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turbo roundabouts; roundabouts capacity, HCM 2010

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THE APPLICATION OF HCM 2010 IN THE DETERMINATION OF CAPACITY OF TRAFFIC LANES AT TURBO ROUNDABOUT ENTRIES

Summary. The main aim of this study was to verify whether it is possible to utilize the model contained in the HCM 2010 methodology for evaluation of traffic capacity of the lanes at the entries to turbo roundabouts in Poland. The models contained in the HCM 2010 methodology were compared with the empirical values obtained for traffic capacity of the traffic lanes at the entries to turbo roundabouts with values of traffic capacity determined based on the author's own models developed based on the data collected at turbo roundabouts located in Poland. The comparison demonstrated a moderate consistency of the compared values of traffic capacity.

ZASTOSOWANIE METODY HCM 2010 DO WYZNACZANIA PRZEPUSTOWOŚCI PASÓW RUCHU NA WLOTACH ROND TURBINOWYCH

Streszczenie. Głównym celem artykułu było sprawdzenie, czy możliwe jest wykorzystanie modelu zawartego w metodzie HCM 2010 do szacowania przepustowości pasów ruchu na wlotach rond turbinowych w Polsce. Modele zawarte w metodzie HCM 2010 porównywano z empirycznymi wartościami przepustowości pasów ruchu na wlotach rond turbinowych oraz z wartościami przepustowości wyznaczonymi z modeli autorskich, skonstruowanych na podstawie danych zebranych na rondach turbinowych zlokalizowanych w Polsce. Pozwoliło to na stwierdzenie umiarkowanej zgodności porównywanych wartości przepustowości.

1. INTRODUCTION

Modern models for the determination of traffic capacity at the entries to roundabouts and the methodologies using these models are mainly developed based on the gap acceptance theory (analytical and semi-probabilistic) and the results of regression analysis for the empirical data (static empirical models). There are also simulation models which allow for taking into consideration the dynamic characteristics of individual vehicles, complex geometrical situations and a number of other determinants, which affect the processes of acceptance of headways in the mainstream. These models have been used to develop many more or less known models and methodologies used for the calculation of traffic capacity.

In the USA, the calculation of traffic capacity is based on the methodology presented in HCM 2010 [20]. Five major revisions of this method were published in 1950-2010. The chapters of the most recent version of HCM 2010 were based on the studies by L. Rodegerdts et al. [18]. The studies were ordered by *the American Association of State Highway and Transportation Officials in Cooperation* *with the Federal Highway Administration*. One effect of these studies is non-complex models that allow for evaluation of traffic capacity in lanes at the entries to the roundabouts. These models have been shown to be characterized by better fit to empirical traffic capacity compared to the models used in the previous HCM 2000 version.

The HCM 2010 methodology gained worldwide popularity and after necessary adaptation it is used for evaluation of traffic conditions at roundabouts all over the world. The attempts to adapt the HCM 2010 methodology to local national conditions have been presented in studies by A. Gazzarri, M. Martello, A. Pratelli and R. Souleyrette for the roundabouts located in the northern part of Italy [4] and G. Castellano, V. Depiante, J. Galarraga [2] for the roundabouts located in Cordoba in Argentina. Furthermore, there have also been studies that were aimed at the adaptation of the HCM 2010 methodology in individual U.S. states, e.g. Georgia state—the study by L. Schmitt [19] and the study by Ch. Barry [1]. However, these studies have mainly concerned the calibration of the HCM 2010 methodology for single-lane and two-lane roundabouts. Therefore, it should be of interest whether they can be used for the description of traffic capacity at the entries to the turbo roundabouts, which are a relatively new form of roundabouts.

Numerous scientific studies (e.g. [8 - 10, 12, 13, 15 - 17]) have demonstrated that single-lane roundabouts represent the most secure form of intersections. Furthermore, turbo roundabouts are considered as safe solutions for the multi-lane roundabouts, which was demonstrated in studies: [7], [11], [14]. Turbo roundabouts were first designed by L. Fortuijn in 1998 in the Netherlands. L. Fortuijn proposed several designs of traffic organization in the area of the roundabout depending on the number of entries and number of traffic lanes at the entries and on the circular roadway and the presence or absence of lanes for the traffic outside the circular roadway. Due to the likelihood of the presence of turbo roundabouts at a close distance from each other, they can be additionally divided according to location with respect to other turbo roundabouts into single-lane or two-lane (multi-lane) turbo roundabouts. The specific names of each turbo roundabout are connected with the direction of the dominant traffic stream in the area of the intersection. The main factors that determine the choice of a specific type of turbo roundabout in concrete road and traffic conditions include the dominant direction, value of traffic stream intensities, mean time loss for the drivers when passing the intersection, land conditions (limitations) and investment costs. Individual types of turbo roundabouts are schematically presented in Fig. 1.

Due to their benefits, turbo roundabouts are also designed in Poland. In the beginning of 2016, their number reached nearly 100. The turbo roundabouts present in Poland can be divided into two groups. The first group is turbo roundabouts with elevated lane separators, whereas the second group encompasses turbo roundabouts with lane separators in the form of a single continuous line of P-2 type. Replacing the elevated lane separators with only a continuous line is usually explained by potential difficulties in the clearing of snow from the roadway under winter conditions. However, these simplifications are dangerous and little effective. In winter, with snow covering the road, horizontal road signs are invisible or insufficiently legible for vehicle drivers and may lead to dangerous traffic situations and, consequently, to road accidents in the area of roundabouts.

This paper analyses the opportunities for application of the HCM 2010 methodology for evaluation of traffic capacity at the entries to turbo roundabouts located in Poland. The analyses were conducted for 11 cases of turbo roundabouts with elevated lane separators.

2. TRAFFIC CAPACITY FOR LANES AT THE ENTRIES TO ROUNDABOUTS ACCORDING TO HCM 2010

The models contained in the HCM 2010 methodology used for the calculation of traffic capacity for the lanes at the entries to roundabouts were developed based on the regression analysis for the empirical data obtained from examinations carried out in roundabouts in the USA. These models are non-linear with respect to the theoretical fundamentals of the gap acceptance theory. It is possible to determine traffic capacity with the accuracy of a traffic lane at the roundabout entries. The models were defined for different variants of traffic organization around roundabouts and adopt the following form [14]:

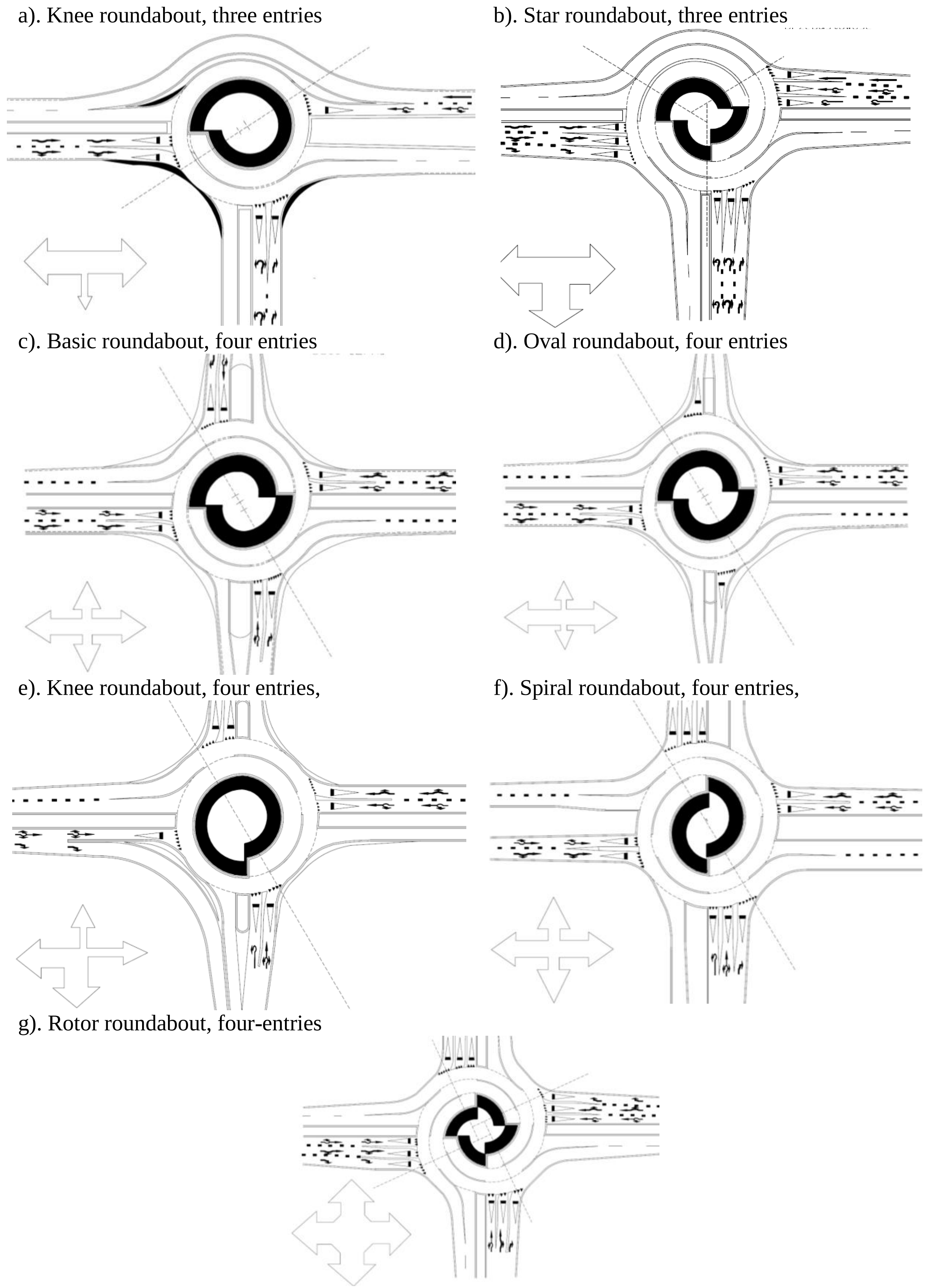


Fig. 1. Types of turbo roundabouts according to L. Fortuijn [3]
Rys. 1. Typy rond turbinowych według L. Fortuijna [3]

- for the entry to the single-lane roundabout and the traffic lane at the two-lane entry to the roundabout for a single-lane circular roadway:

$$C_{pwl} = 1130 \cdot e^{\left(-1{,}0 \cdot 10^{-3}\right) \cdot Q_{nwl}} \quad [pcu/h] \tag{1}$$

where: C_{pwl} – capacity of the entry lane, Q_{nwl} – conflicting flow,

- for the traffic lane at the one-lane entry for two traffic lanes on the circular roadway:

$$C_{wl} = 1130 \cdot e^{\left(-0{,}7 \cdot 10^{-3}\right) Q_{nwl}} \quad [pcu/h] \tag{2}$$

where: C_{wl} – capacity of the entry lane.

- for the left and right traffic lane at the two-lane roundabout entry for two traffic lanes on the circular roadway:

$$C_{P} = 1130 \cdot e^{\left(-0{,}70 \cdot 10^{-3}\right) \cdot Q_{nwl}} \quad [pcu/h] \tag{3}$$

$$C_{L} = 1130 \cdot e^{\left(-0{,}75 \cdot 10^{-3}\right) Q_{nwl}} \quad [pcu/h] \tag{4}$$

where: C_P – capacity of the right entry lane, C_L – capacity of the left entry lane,

- for the separated lane for traffic that occurs outside the circular roadway where drivers at the exit are obliged to give way to drivers of vehicles that leave the circular roadway with a single-lane exit:

$$C_{wpwl} = 1130 \cdot e^{\left(-1{,}0 \cdot 10^{-3}\right) Q_{wy}} \quad [pcu/h] \tag{5}$$

where: C_{wpwl} – traffic capacity of the separated roadway at the entry *wl* for the traffic outside the circular roadway, Q_{wy} – traffic volume at the exit *wy* from the roundabout,

- for the separated lane for traffic that occurs outside the circular roadway where drivers at the exit are obliged to give way to drivers of vehicles that leave the circular roadway with a two-lane exit:

$$C_{wpwl} = 1130 \cdot e^{\left(-0{,}7 \cdot 10^{-3}\right) Q_{wy}} \quad [pcu/h] \tag{6}$$

A general form of the above relationships was also presented in the HCM 2010, allowing for the calibration of the models for local movement conditions in a specific country, region and city, adopting the following form [14]:

$$C = A \cdot e^{-B \cdot Q_{nwl}} \; [pcu/h] \tag{7}$$

$$A = \frac{3600}{t_f} \; [-] \tag{8}$$

$$B = \frac{t_g - \frac{t_f}{2}}{3600} \; [-] \tag{9}$$

where: C – capacity, *A, B* – model parameters, t_f – follow-up time, t_g – critical gap.

The final form of the gap acceptance model depends mainly on behaviours of traffic users, expressed in this case through such parameters as critical headway (t_g), follow-up headway (t_f) and local habits. Therefore, according to the form of the model contained in the HCM 2010, model validity and accuracy of traffic capacity calculations determine these two parameters, i.e. t_g and t_f.

3. DESCRIPTION OF THE INVESTIGATION AND MEASUREMENTS PHASES

Opportunities for using the HCM 2010 methodology to evaluate traffic capacity for the lanes at the entries to turbo roundabouts in Poland were analysed for 11 cases of turbo roundabouts with elevated lane separators. Characterization of the research site with the presentation of the measurements is shown in Table 1.

The measurements of traffic lane capacity at turbo roundabout entries were carried out in saturated conditions. The capacity of traffic lanes at turbo roundabout entries was appointed by counting vehicles entering the main roadway of roundabouts after waiting at the entry at the appropriate time headway in the traffic flow moving on the main roadway of the roundabout. Capacity calculations were taken into account only at those time intervals during which fully saturated conditions occurred in the traffic lane at the entry. Due to the lack at analyzed training grounds sufficiently long periods of saturation within which can be designated fifteen-minute time intervals, five-minute time intervals were adopted in the analysis. The length of five-minute time interval was designed as t_s. Counting of vehicles took place from the moment of entry of the first vehicle forming a queue until the exit of the last vehicle that was standing in the queue in five minutes. In the five-minute time intervals, vehicles from the traffic lanes at the roundabout entry used all acceptable headways in the traffic flow (Q_{nwl}) on the main road of the roundabout. During t_s period the vehicles entering the main road of the roundabout and the vehicles on the main road of the roundabout were counted. Vehicles in the time intervals t_s were calculated to the value of capacity according to the formula:

$$C_{Le} = Q_L \cdot \frac{3600}{t_s}\left[\frac{veh}{h}\right],\ C_{Pe} = Q_P \cdot \frac{3600}{t_s}\left[\frac{veh}{h}\right] \tag{10}$$

where: $C_{Le,}$ C_P – empirical value of capacity respectively left and right traffic lane at turbo roundabout entry, $Q_{L,}$ Q_P – the number of vehicles entering to the main roadway of the turbo roundabout, t_s – the length of saturation (five-minute time intervals).

Table 1

Characterization of the research site

No.	Roundabout location, names of the intersecting streets	Turbo roundabout characteristics [m]	Sample size *n*	Scope of variability of empirical traffic capacity [pcu/h]	
				from	to
1.	Bielsko Biała, Niepodległości Street (2 entries), Kryształowa Street (1 entry), Krausa Street (1 entry)	R_1 = 11,0, l_{jr}= 4,5-9,0	158	248	1246
2.	Kalisz, Częstochowska Street (2 entries), Księżnej Jolanty Street (1 entry)	R_1 = 13,0, l_{jr}= 10,0	47	169	908
3.	Bielsko Biała, Piekarska Street (2 entries), Lwowska Street (2 entries)	R_1 = 13,0, l_{jr}= 5,0-10,0	261	88	1452
4.	Bielsko Biała, PCK Street (2 entries), Sempłowskiego Street (2 entries)	R_1 = 15,0, l_{jr}= 4,5-9,0	123	334	1125
5.	Bielsko Biała, PCK Street (2 entries), Broniewskiego Street (2 entries)	R_1 = 15,0, l_{jr}= 4,5-9,0	112	269	1349
6.	Tarnów, Czysta Street (1 entry), Kwiatkowskiego Street (1 entry), Mościckiego Street (1 entry), W. Wody Street (1 entry)	R_1 = 17,0, l_{jr}= 5,0-10,0-15,0	28	411	1146
7.	Puławy, Żyrzyńska Avenue (1 entry), 100-lecia P. Polskiego Avenue (1 entry), Partyzantów Avenue (1 entry)	R_1 = 18,0, l_{jr}= 5,0-10,0	34	565	1022
8.	Zabrze, G. Bruno Street (1 entry), Mielżyńskiego Street (1 entry), Korfantego Avenue (2 entries)	R_1 = 19,0, l_{jr}= 4,5-9,0	147	611	1457
9.	Stalowa Wola, Kwiatkowskiego Street (1 entry), Bojanowska Street (2 entries)	R_1 = 19,0, l_{jr}= 6,5-13,0	93	156	1348
10.	Zabrze, Korfantego Avenue (2 entries), Gdańska Street (2 entries)	R_1 = 20,0, l_{jr}= 4,5-9,0	271	132	1453
11.	Płock, Dobrzyńska Street (2 entries), Gałczyńskiego Street (1 entry), Na skarpie Street (1 entry)	R_1 = 21,0, l_{jr}= 5,0-10,0	52	298	1419

Next, the obtained values of capacity expressed in real vehicles were converted to value of capacity in passenger car unit according to the following formula:

$$C_L = \frac{C_{Le}}{f_c}\left[\frac{pcu}{h}\right],\ C_P = \frac{C_{Pe}}{f_c}\left[\frac{pcu}{h}\right] \tag{11}$$

where: f_c – coefficient of the heavy vehicle impact.

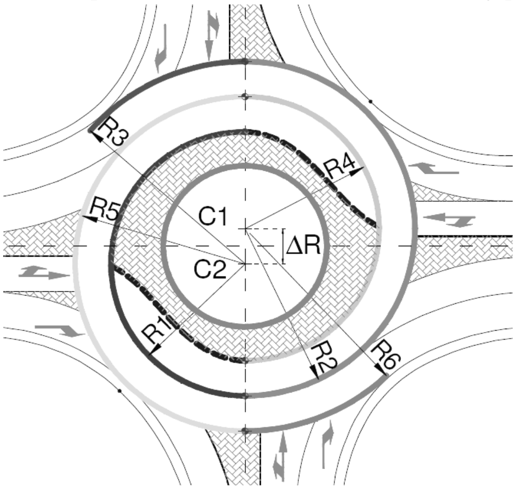
4. AUTHOR'S OWN RESEARCH

Among all the possible traffic organizations in the area of the entry and roundabout circular roadway at the entry, further analysis focused on the case with two traffic lanes at the entry and two at the circular roadway, with one of them starting at the level of the entry (western entry in Fig. 1a, western and eastern entries in Fig. 1c and Fig. 1d and southern in Fig. 1e). With this layout of traffic lanes on the circular roadway, drivers of vehicles from the entry are actually obliged to give way to the vehicles moving on only one traffic lane on the circular roadway. Therefore, traffic capacity for the left and right traffic lane at the entry used the relationship derived from the HCM 2010 methodology presented with number 1.

At the first stage, the empirical traffic capacities for the traffic lanes at the entries to the turbo roundabouts were compared with traffic capacities evaluated from the author's models construed based on the data collected from the turbo roundabouts located in Poland (these models were discussed in detail in the study [6]) and the model presented in the HCM 2010 methodology (Equation 1). A comparison was carried out with the accuracy of a traffic lane at the roundabout entries. The results of the comparisons for two selected turbo roundabouts with extreme values of circular roadway radius R1[1] are presented in Fig. 2.

Equation 1 expresses the dependency of lane traffic capacity at the roundabout entry only on the value of main traffic volume for the entry. Furthermore, using these models allows for the determination of the values of final traffic capacities separately for the left and right traffic lane at the entry with respect to a greater number of characteristics and determinants of traffic streams. These models have the following form [6]:

[1] According to the Dutch guidelines presented e.g. in study [5], the circular roadway in turbo roundabouts are designed as arcs with different centerpoints and different radii, schematically presented in the figure below.



where: R1, R2, R3, R4, R5, R6 – radii of the circular roadway in the turbo roundabout [m].

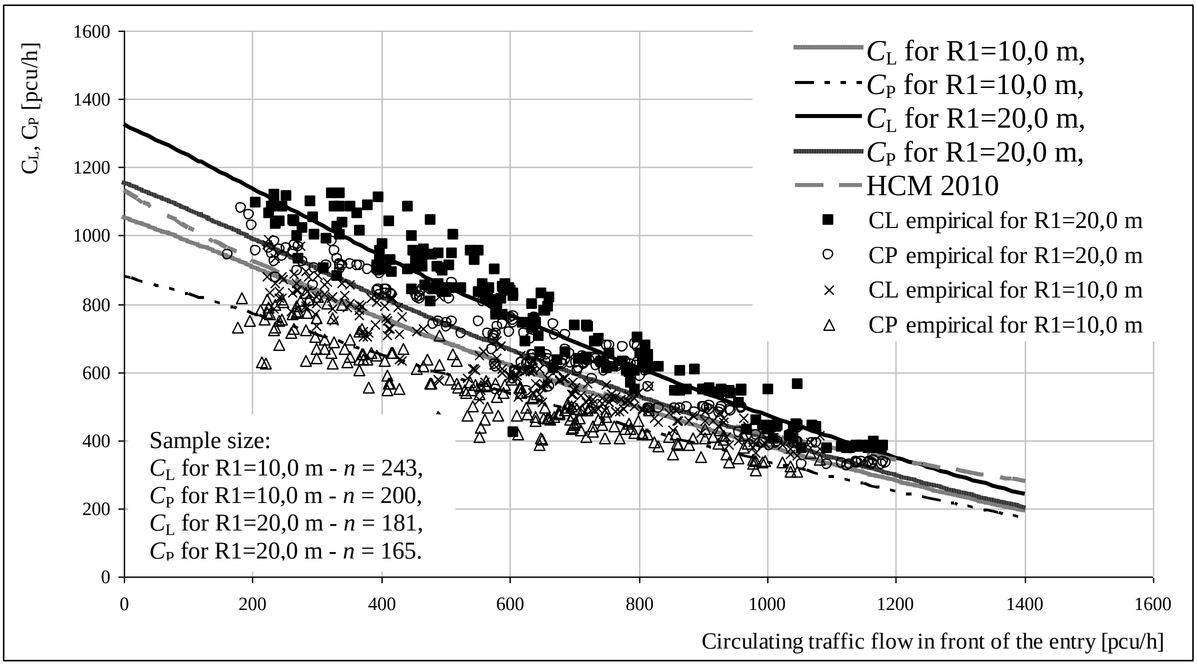


Fig. 2. Traffic capacities for the right and left traffic lane at the entries to turbo roundabouts with elevated lane separators with R_1=10,0 m and R_2=20,0 m

Rys. 2. Przepustowości prawego i lewego pasa ruchu na wlotach rond turbinowych z wyniesionymi ponad powierzchnię jezdni separatorami pasów ruchu o R_1=10,0 m oraz R_2=20,0 m

- for the right traffic lane at the entry to the turbo roundabout:

$$C_{oP} = \begin{cases} 1{,}02 \cdot 3600 \cdot t_f^{-1} = \dfrac{1{,}02 \cdot 3600}{t_f} \quad [pcu/h] & for \quad Q_{nP} = 0\,[pcu/h] \\[2ex] \dfrac{1{,}02 \cdot Q_{nP} \cdot e^{-\left[\frac{Q_{nP}}{3600 - Q_{nP} \cdot t_p} \cdot (t_g - t_p)\right]}}{1 - e^{-\left[\frac{Q_{nP}}{3600 - Q_{nP} \cdot t_p} \cdot t_f\right]}} = \dfrac{1{,}02 \cdot Q_{nP} \cdot e^{-\frac{Q_{nP} \cdot (t_g - t_p)}{3600 - Q_{nP} \cdot t_p}}}{1 - e^{-\frac{Q_{nP} \cdot t_f}{3600 - Q_{nP} \cdot t_p}}} \quad [pcu/h] & for \quad 1 < Q_{nP} \le 100\,[pcu/h] \\[2ex] \dfrac{1{,}02 \cdot Q_{nP} \cdot \phi \cdot e^{-\left[\frac{\phi \cdot Q_{nP}}{3600 - Q_{nP} \cdot t_p} \cdot (t_g - t_p)\right]}}{1 - e^{-\left[\frac{\phi \cdot Q_{nP}}{3600 - Q_{nP} \cdot t_p} \cdot t_f\right]}} = \dfrac{1{,}02 \cdot Q_{nP} \cdot \phi \cdot e^{-\frac{\phi \cdot Q_{nP} \cdot (t_g - t_p)}{3600 - Q_{nP} \cdot t_p}}}{1 - e^{-\frac{\phi \cdot Q_{nP} \cdot t_f}{3600 - Q_{nP} \cdot t_p}}} \, [pcu/h] & for \quad Q_{nP} > 100\,[pcu/h] \wedge Q_{nP} < C_{jr} \\[2ex] \cong 0\,[pcu/h] & for \quad Q_{nP} \cong C_{jr} \end{cases} \tag{12}$$

where: C_{OP} – base capacity for right lane on entry, Q_{nP} – traffic volume on main road of roundabout major for vehicles from right lane on roundabout entry, C_{jr} – capacity of the main road of roundabout, t_g – critical gap, t_f – follow-up time, t_p – minimal headway between vehicles on the main road of roundabout, φ – the proportion of vehicles moving freely.

- for the left traffic lane at the entry:

$$C_{oL}=\begin{cases} 1{,}02\cdot 3600\cdot t_f^{-1}=\dfrac{1{,}02\cdot 3600}{t_f}\quad [pcu/h] & for \quad Q_{nL}=0\,[pcu/h] \\ \dfrac{1{,}02\cdot Q_{nL}\cdot e^{-\left[\frac{Q_{nL}}{3600-Q_{nL}\cdot t_p}\cdot(t_g-t_p)\right]}}{1-e^{-\left[\frac{Q_{nL}}{3600-Q_{nL}\cdot t_p}\cdot t_f\right]}}=\dfrac{1{,}02\cdot Q_{nL}\cdot e^{-\frac{Q_{nL}\cdot(t_g-t_p)}{3600-Q_{nL}\cdot t_p}}}{1-e^{-\frac{Q_{nL}\cdot t_f}{3600-Q_{nL}\cdot t_p}}}\quad [pcu/h] & for \quad 1<Q_{nL}\le 100\,[pcu/h] \\ \dfrac{1{,}02\cdot Q_{nL}\cdot\phi\cdot e^{-\left[\frac{\phi\cdot Q_{nL}}{3600-Q_{nL}\cdot t_p}\cdot(t_g-t_p)\right]}}{1-e^{-\left[\frac{\phi\cdot Q_{nL}}{3600-Q_{nL}\cdot t_p}\cdot t_f\right]}}=\dfrac{1{,}02\cdot Q_{nL}\cdot\phi\cdot e^{-\frac{\phi\cdot Q_{nL}\cdot(t_g-t_p)}{3600-Q_{nL}\cdot t_p}}}{1-e^{-\frac{\phi\cdot Q_{nL}\cdot t_f}{3600-Q_{nL}\cdot t_p}}}\,[pcu/h] & for \quad Q_{nL}>100\,[pcu/h]\wedge Q_{nL}<C_{jr} \\ \cong 0\,[pcu/h] & for \quad Q_{nL}\cong C_{jr} \end{cases}$$

(13)

where: C_{OL} – base capacity for left lane on entry, Q_{nL} – traffic volume on main road of roundabout major for vehicles from left lane on roundabout entry, other symbols without change.

Fig. 2 shows that the values of traffic capacities determined based on the model presented in the HCM 2010 methodology differ both from empirical values of traffic capacities and traffic capacities determined from the models described by Equations 12 and 13. Therefore, at the next stage of analyses, calibration of the model from the HCM 2010 methodology using Equation 1 to the empirical data that describe the conditions on the left and right traffic lane at turbo roundabout entries in Poland was based on relationships 7, 8, 9. The models used for calibration were positively verified for Polish conditions and allowed for the determination of values of critical headways and follow-up headways. The calibrated models that allow for the determination of traffic capacity for the right and left traffic lane are presented in Table 2 and in Fig. 3 and Fig. 4.

Evaluation of the quality of fit for the models from the HCM 2010 methodology used for determination of traffic capacity for the right and left lanes at turbo roundabout entry was performed by evaluation of the values of absolute errors δ_C [%] for individual measurements using the following relationship:

$$\delta_C=\left|\frac{C_M^i-C_E^i}{C_E^i}\right|\cdot 100\ [\%] \tag{14}$$

where: δ_C – absolute error, C_M^i – *i*-traffic capacity for the lane at the entry determined from the model, C_E^i – *i*-empirical traffic capacity.

Values of relative errors were determined from:

$$\mu_C=C_M^i-C_E^i\ [pcu/h] \tag{15}$$

where: μ_C – relative error.

Table 2

Results obtained for the calibration of models derived from the HCM methodology to Polish conditions for the right and left traffic lane at the entry to the turbo roundabout

Roundabout number	t_g [s]	t_f [s]	*A*	*B*	Lane traffic capacity at the entry [pcu/h]	Coefficient of determination R^2 [-]	Equation number
Right traffic lane at the turbo roundabout entry							
1.	4,25	4,07	884	0,000616	$884 \cdot e^{\left(-0{,}61 \cdot 10^{-3}\right) Q_{nP}}$	0,63	(14)
2.	4,22	3,88	929	0,000635	$929 \cdot e^{\left(-0{,}63 \cdot 10^{-3}\right) Q_{nP}}$	0,50	(15)
3.	4,22	3,88	929	0,000635	$929 \cdot e^{\left(-0{,}63 \cdot 10^{-3}\right) Q_{nP}}$	0,80	(16)
4.	4,19	3,68	979	0,000654	$979 \cdot e^{\left(-0{,}65 \cdot 10^{-3}\right) Q_{nP}}$	0,61	(17)
5.	4,19	3,68	979	0,000654	$979 \cdot e^{\left(-0{,}65 \cdot 10^{-3}\right) Q_{nP}}$	0,79	(18)
6.	4,16	3,48	1036	0,000673	$1036 \cdot e^{\left(-0{,}67 \cdot 10^{-3}\right) Q_{nP}}$	0,64	(19)
7.	4,15	3,37	1067	0,000683	$1067 \cdot e^{\left(-0{,}68 \cdot 10^{-3}\right) Q_{nP}}$	0,60	(20)
8.	4,13	3,27	1100	0,000692	$1100 \cdot e^{\left(-0{,}69 \cdot 10^{-3}\right) Q_{nP}}$	0,58	(21)
9.	4,13	3,27	1100	0,000692	$1100 \cdot e^{\left(-0{,}69 \cdot 10^{-3}\right) Q_{nP}}$	0,53	(22)
10.	4,11	3,17	1136	0,000702	$1136 \cdot e^{\left(-0{,}70 \cdot 10^{-3}\right) Q_{nP}}$	0,56	(23)
11.	4,09	3,07	1174	0,000711	$1174 \cdot e^{\left(-0{,}71 \cdot 10^{-3}\right) Q_{nP}}$	0,51	(24)
Left traffic lane at the turbo roundabout entry							
1.	4,13	3,42	1053	0,000671	$1053 \cdot e^{\left(-0{,}67 \cdot 10^{-3}\right) Q_{nL}}$	0,66	(25)
2.	4,08	3,29	1096	0,000677	$1096 \cdot e^{\left(-0{,}67 \cdot 10^{-3}\right) Q_{nL}}$	0,50	(26)
3.	4,08	3,29	1096	0,000677	$1096 \cdot e^{\left(-0{,}67 \cdot 10^{-3}\right) Q_{nL}}$	0,72	(27)
4.	4,04	3,15	1144	0,000684	$1144 \cdot e^{\left(-0{,}68 \cdot 10^{-3}\right) Q_{nL}}$	0,74	(28)
5.	4,04	3,15	1144	0,000684	$1144 \cdot e^{\left(-0{,}68 \cdot 10^{-3}\right) Q_{nL}}$	0,61	(29)
6.	3,99	3,00	1200	0,000691	$1200 \cdot e^{\left(-0{,}69 \cdot 10^{-3}\right) Q_{nL}}$	0,53	(30)
7.	3,97	2,93	1230	0,000695	$1230 \cdot e^{\left(-0{,}69 \cdot 10^{-3}\right) Q_{nL}}$	0,55	(31)
8.	3,94	2,85	1264	0,000699	$1264 \cdot e^{\left(-0{,}69 \cdot 10^{-3}\right) Q_{nL}}$	0,78	(32)
9.	3,94	2,85	1264	0,000699	$1264 \cdot e^{\left(-0{,}69 \cdot 10^{-3}\right) Q_{nL}}$	0,66	(33)
10.	3,92	2,77	1299	0,000703	$1299 \cdot e^{\left(-0{,}70 \cdot 10^{-3}\right) Q_{nL}}$	0,50	(34)
11.	3,89	2,69	1338	0,000708	$1338 \cdot e^{\left(-0{,}70 \cdot 10^{-3}\right) Q_{nL}}$	0,62	(35)

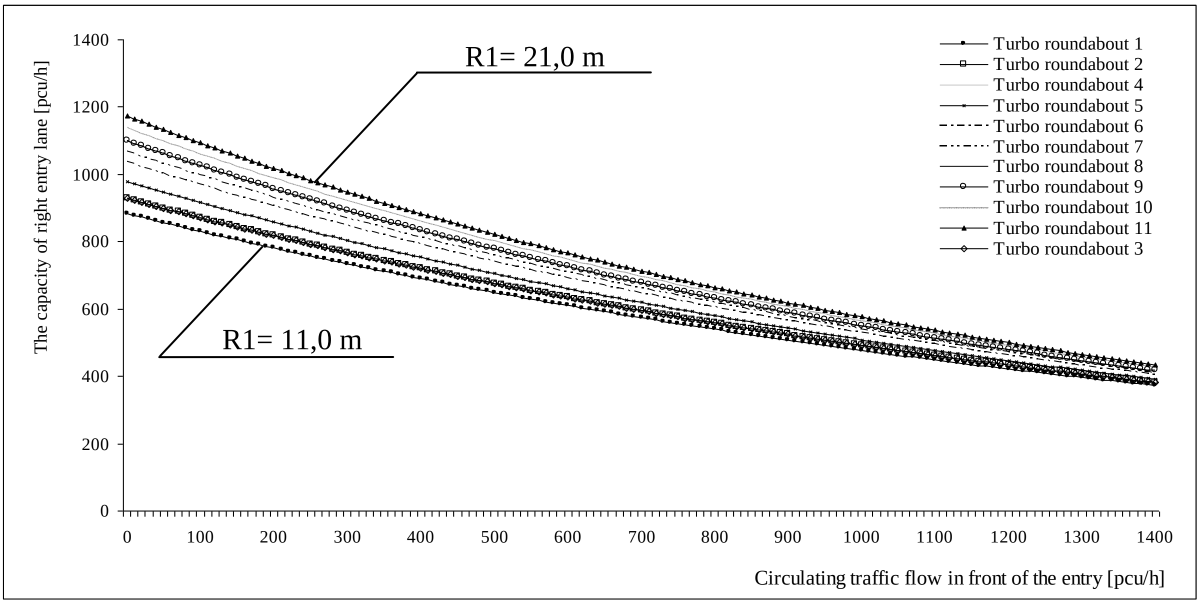


Fig. 3. Models from the HCM 2010 methodology calibrated to Polish conditions that allow for the determination of traffic capacity for the right lane at the turbo roundabout entry

Rys. 3. Skalibrowane do polskich warunków modele z HCM 2010, pozwalające wyznaczyć przepustowości prawego pasa ruchu na wlocie ronda turbinowego

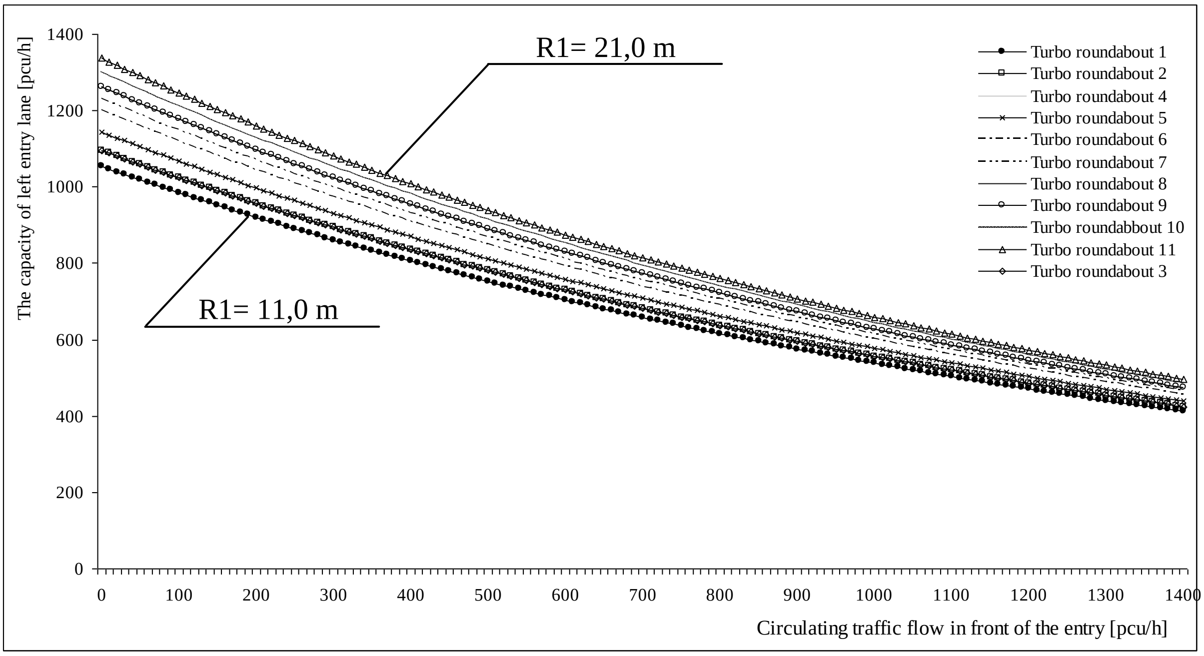


Fig. 4. Models from the HCM 2010 methodology calibrated to Polish conditions that allow for determination of traffic capacity for the left lane at the turbo roundabout entry

Rys. 4. Skalibrowane do polskich warunków modele z HCM 2010, pozwalające wyznaczyć przepustowości lewego pasa ruchu na wlocie ronda turbinowego

Table 3 presents a comparison of mean values of relative and absolute errors for the left and right traffic lanes for turbo roundabouts examined. The results obtained from the verification show certain differences between empirical data and the model from the HCM methodology calibrated to Polish conditions. Mean absolute error for the left lane at the entry was 17,44%, whereas this value for the right lane was 17,64%. Furthermore, mean relative errors were 71 [pcu/h] for the left lane and 82 [pcu/h] for the right lane. The results obtained in the study revealed a moderate consistency of traffic capacity values evaluated based on the model from the HCM 2010 methodology calibrated to Polish conditions with empirical traffic capacities for the lane at the entries to the turbo roundabouts. The best consistency of the results was obtained for the main traffic volumes $Q_n \leq 600$ [pcu/h] (values of absolute errors in all cases were lower than 10,00%). Above the values of main traffic volumes $Q_n > 600$ [pcu/h], the differences between the compared values of traffic capacity are substantially greater. In all these cases, the values of absolute errors are greater than 10,00 %.

Table 3

The mean values of relative and absolute errors for the left and right traffic lane for examined turbo roundabouts

L.p.	*Left traffic lane at the turbo roundabout entry*		*Right traffic lane at the turbo roundabout entry*	
	$\bar{\delta}_C$ [%]	$\bar{\mu}_C$ [pcu/h]	$\bar{\delta}_C$ [%]	$\bar{\mu}_C$ [pcu/h]
1.	16,44	86	15,79	83
2.	19,31	94	19,24	98
3.	14,57	38	17,68	71
4.	17,22	62	16,33	62
5.	15,76	41	18,81	87
6.	19,11	57	19,25	95
7.	18,82	69	17,57	85
8.	17,43	78	18,22	60
9.	16,69	93	15,33	84
10.	19,04	70	17,90	95
11.	17,48	97	17,87	77
Average value	17,44	71	17,64	82

5. CONCLUSIONS

The results presented in this paper lead to the following conclusions:

- values of traffic capacities determined based on the model presented in the HCM 2010 methodology differ both from empirical values of traffic capacities and traffic capacities determined from the models presented in Equations 12 and 13
- calibration of the model from the HCM 2010 methodology to Polish conditions yielded moderate consistency of the model with values of empirical traffic capacities obtained for traffic lanes at the entries to turbo roundabouts in Poland. In all the roundabouts examined, mean absolute error for the left lane at the entry was 17,44%, whereas this value for the right lane was 17,64%. Mean relative errors were 71 [pcu/h] for the left lane and 82 [pcu/h] for the right lane. Furthermore, coefficient of determination for the right lane at the turbo roundabout entry is $R^2 \in (0{,}50;0{,}80)$, whereas this value for the left traffic lane is $R^2 \in (0{,}50;0{,}78)$
- the best consistency of the results was obtained for the main traffic volumes $Q_n \leq 600$ [pcu/h] (values of absolute errors in all cases were lower than 10.00%). Above the values of main traffic volumes $Q_n > 600$ [pcu/h], the differences between the compared values of traffic capacity are substantially greater. In all these cases, the values of absolute errors are greater than 10.00%

- a comparison of the model from the HCM methodology calibrated to Polish conditions with the models defined by Equations 12 and 13 also reveals certain differences in traffic capacities. These differences are mainly caused by different functional forms of the models. The model from the HCM methodology was construed based on the exponential function, whereas the models defined by Equations 12 and 13 represent the arrangement of two different distributions of the random variable adopted for different ranges of the main traffic capacity, i.e. for Q_n=0 pcu/h, $1 < Q_n \leq 100$ pcu/h, $Q_n > 100\,[pcu/h] \wedge Q_n < C_{jr}$ and for $Q_n \cong C_{jr}$). Division of the range of values of main traffic capacities into ranges offers opportunities for a more accurate adjustment of the form and shape of the function to the form of the empirical data in the analysed range
- the above conclusion shows that the use of the model contained in the HCM 2010 methodology for evaluation of traffic capacity for lanes at turbo roundabout entries in Poland requires a more detailed research carried out in a bigger research site. This research should focus on calibration of the model from the HCM 2010 methodology to empirical data that represent traffic and road conditions that occur in turbo roundabouts in Poland.

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