Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 120 **2023**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2023.120.1

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Al Hasanat, H., Janos, J. Development of roundabouts empirical capacity model – case study of Hungary. *Scientific Journal of Silesian University of Technology. Series Transport*. 2023, **120**, 5-16. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2023.120.1.

Haitham AL HASANAT[1], Juhasz JANOS[2]

DEVELOPMENT OF ROUNDABOUTS EMPIRICAL CAPACITY MODEL – CASE STUDY OF HUNGARY

Summary. Roundabouts are commonly used worldwide because they offer several advantages over traditional intersections. The capacity that a roundabout can handle is an important factor in ensuring smooth traffic flow at a particular location. Therefore, various models have been developed to describe traffic conditions and driver behaviour at different sites or countries. However, existing models cannot be directly applied to other countries without proper calibration of the models to ensure an accurate estimation of capacity. In this study, five roundabouts in Hungary were selected to develop a general capacity model and compare it with international models. First, all sets of entry and circulating data were obtained from video recordings of each roundabout entry. These data were used to develop a model for each entry and then for each roundabout separately. Finally, all the data sets from all sixteen entries were used to develop a general capacity model (GM). The general capacity model (GM) was compared with the Highway Capacity Manual (HCM) 2016, the Brilon-Bondzio, and the Brilon-Wu models. The maximum capacity of the general capacity model (GM) was 1390 pcu/h, slightly higher than the maximum capacity of the HCM 2016 model of 1380 pcu/h. The percentage differences between the generated general capacity

[1] Department of Highway and Railway Engineering, Faculty of Civil Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary. Email: haitham.alhasanat@gmail.com. ORCID: https://orcid.org/0000-0001-9678-9146
[2] Department of Highway and Railway Engineering, Faculty of Civil Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary. Email: juhasz.janos@emk.bme.hu. ORCID: https://orcid.org/0000-0001-6795-4181

model (GM), HCM 2016, Brilon-Bondzio, and Brilon-Wu models were +0.71%, +12.4%, and +10.7%, respectively.
Keywords: roundabout, single-lane, regression, capacity, comparison

1. INTRODUCTION

A roundabout is a circular intersection in which traffic circulates around the central island, and entering traffic must yield to circulating traffic before entering. Roundabouts are very popular throughout Europe and other parts of the world, and are becoming more popular in North America due to their proven safety record and ability to reduce delays compared to traditional intersections [1]. Modern roundabouts have been very popular and widely used in Hungary since the 1990s [2]. Also, roundabouts as compared to signalized intersections are safer because of fewer conflict points and the lower speed at the entry or on the circulatory roadway [3].

Since existing roundabout capacity models cannot be transferred to other countries without proper calibration due to different driver behavior. Therefore, an accurate estimate of roundabout capacity, delay, and performance is important. Hence, a proper calibration is vital to perfectly describe the traffic condition or drivers' behavior at that location. Roundabout capacity models can be grouped into three categories: gap acceptance models, empirical models, and microscopic models. Gap acceptance models, such as the Highway Capacity Manual (HCM) model [4], are based on driver behavior. Empirical models, such as the UK capacity model [5], are based on the relationship between traffic volumes and the roundabout's geometry. Microscopic models, on the other hand, focus on the interactions between vehicles and their movements, considering factors like gap acceptance, car following, and lane changing. [6]. These models are used by traffic engineers to design and evaluate the performance of roundabouts in order to ensure that they can handle the traffic demand in a safe and efficient manner [4], [6]-[9].

Accordingly, Kimber [5] recommends using empirical models because they take into account the various factors that can affect driver behavior and produce more reliable results.

The most widely recognized capacity model is the HCM 2016 model, which is expressed mathematically in (1)

$$C_{e,pce} = 1380e^{(-1.02*10^{-5})v_{c,pce}} \quad (1)$$

Where
$C_{e,pce}$ = lane capacity adjusted for heavy vehicles (pc/h); and
$v_{c,pce}$ = conflicting flow rate (pc/h).

Subsequently, Brilon-Bondzio developed a linear capacity model for Germany [10], [11], the developed model of Brilon-Bondzio is expressed as (2)

$$C = A - B.Q_C \quad (2)$$

Where
A and B can be obtained from
Q_C = circulating flow.

Tab. 1
List of parameter values for the Brilon-Bondzio entry capacity model

No. of circle lane	No. of entry lane	A	B
3	2	1409	0.42
2	2	1380	0.50
2-3	1	1250	0.53
1	1	1218	0.74

Another recognized capacity model is the model developed by Brilon-Wu, which is used in the German Highway Capacity Manual (GHCM) [12]. The capacity mode of GHCM is expressed mathematically in (3)

$$C = 3600\,.\,(1 - \frac{\Delta.\frac{Q_c}{3600}}{n_c})^{n_c}.\frac{n_e}{T_f}\,.\,exp[-Q_c\,/3600.\,(T_c - \frac{T_f}{2} - \Delta)] \tag{3}$$

Where
Q_c = circulating flow in passenger car unit (pcu/h);
n_c = number of circulatory lanes;
n_c = number of entry lanes;
T_c = critical gap, which is 4.1 seconds;
T_f = follow-up time, which is 2.9 seconds;
Δ = minimum headway between the vehicles circulating in the circle, which is 2.1 seconds.

The purpose of this study is to generate a general model (GM) for Hungary, estimating the entry capacity of single-lane roundabouts using an empirical regression model, and compare it with the international models.

2. METHODOLOGY

In this research, five single-lane roundabouts were selected in different locations in Hungary, including Budapest, Vac, Solymárvölgy, Biatorbágy. The selection was based on the presence of high traffic volumes. The selected roundabouts are in urban and rural areas. Pedestrian traffic is significantly low; therefore, it is neglected in this study. Field data was collected using a video camera recorder. The recorded videos were taken during t peak hours, and they are the main source of data. The camera recorder was fitted on a 4 m long pole placed at a specific location to ensure a clear view of all entries (see Fig. 1). An example of the recorded videos is shown in Fig. 2

This paper is divided into three main parts.

- ❖ Data acquisition:
  - Roundabout selection based on traffic volumes,
  - Determining the peak hour for each roundabout, and
  - Video recording of the selected roundabout.
- ❖ Data extraction and verification:
  - Traffic data extraction from the recorded videos,

- Traffic data verification by deleting the outliers, and
- Converting all vehicle types into passenger car unit (pcu).

❖ Model development:

- Data processing,
- Performing regression analysis to collected data, and
- Comparison of the generated general model with the international models.

The performed regression analysis was conducted in three steps.

- Step 1 entry capacity model for each entry was developed.
- Step 2 entry capacity model for each roundabout individually was generated.
- Step 3 all collected sets of data from all roundabouts were used to generate a general model (GM) for this case study. Then, a comparison between the generated model and the international models is studied.

Fig. 1. The camera setup at one of the investigated roundabouts

Fig. 2. A screenshot for one of the recorded roundabouts

3. DATA COLLECTION

The selected roundabouts of this study are provided in Tab. 2. Each roundabout has four entries, and only the one with the highest observed traffic is considered. Hence, data was collected for a total of 16 entries. For each entry, data was collected manually at 1-min intervals. The use of 1-min interval rather than a longer period was introduced in NCHRP report 572 [13], and was used by other researchers [14]. The collected data contains the number of entering vehicles and the number of circulating vehicles in front of the entry at the same time interval.

Tab. 2

All selected roundabouts' locations, types and numbers of entries

Roundabout no.	Roundabout type	Location	Latitude	Longitude	No. of entries
R1	Singe-lane	Pasaréti tér	47.52391	18.99338	4
R2	Singe-lane	Pusztaszeri körönd	47.4608	18.95833	4
R3	Singe-lane	Vac	47.37861	18.92618	4
R4	Singe-lane	Solymárvölgy	47.37819	18.92191	4
R5	Singe-lane	Biatorbágy	47.46066	18.939	4

For all traffic data, all vehicle types were converted into passenger car unit pcu. There are three different types of vehicles according to the Hungarian guidelines [15].

- Light vehicles (motorcycle, passenger car, minibus, light commercial vehicle up to 3.5t of load),
- Heavy vehicles (trucks from 3.5t of load, buses),
- Articulated vehicles (vehicles with trailerers, semi-trailer vehicles, articulated buses).

The values used to convert different vehicle types into passenger car unit are listed in Tab. 3

Tab. 3

Passenger car unit for different vehicle types in Hungarian guidelines

Vehicle type	PCU value
Light vehicles	1
Heavy vehicles	2
Articulated vehicles	3

The statistical characteristics of the collected data is shown in Tab. 4. There are a total of 388 observations collected from recorded videos.

4. DATA ANALYSIS AND RESULTS

After the collection of all entry and circulating traffic data, a statistical analysis was conducted to investigate the correlation between the entry capacity and circulating traffic of the studied roundabouts. This analysis aimed to provide insights into the dynamic behavior of traffic flow and the capacity utilization of the roundabouts. In this study, the roundabout capacity model proposed by W. Brilon and B. Stuwe [8] was employed to quantitatively evaluate the capacity of the studied roundabouts. The model is based on mathematical equations that estimate the entry capacity of a roundabout as a function of traffic parameterers (circulating traffic flow). The mathematical relationship between entry capacity and circulating flow is exponential and is expressed as follows in Eq. 4.

$$q_e = A * e^{(-B*q_c/10000)} \quad (4)$$

Where
q_e= the maximum entry traffic possible in passenger car unit (pcu) per hour,
q_c= the traffic circulating in front of the entry in pcu per hour,
e = base of the natural logarithm, and
A and B are the constants determined by regression.

Tab. 4

Descriptive statistics of entry capacity, circulating traffic flow, and inscribed diameter of the studied roundabouts

Variables	Observations	Mean	Std. dev.	Min	Max
Entry capacity (pcu/h)	388	703.2632	281.103	60	1320
Circulating traffic (pcu/h)	388	627.3158	272.2072	30	1290
Inscribed Diameter (m)	5	37.8	18.1989	22	60

Tab. 5 presents the results of the statistical analysis conducted to estimate the capacity of the studied roundabouts using the roundabout capacity model proposed in Eq. 4. The table includes the number of observations, the inscribed diameter, A and B regression constants, and the coefficient of determination (R^2) for each entry. The values of R^2 range from 0.847 to 0.455 for all entries, which indicates a moderate to high correlation between the observed and estimated capacity values. Additionally, all the results were found to be statistically significant, which means that there is a statistically significant relationship between the observed and estimated values.

In order to develop a model for the capacity of each roundabout, the same methodology used to develop the entry-capacity model for each entry was applied. This involved using all sets of data from all entries to estimate the capacity of each roundabout. The data was then fitted to an exponential equation, similar to the one used for the entry-capacity model, to establish the relationship between the entry and circulating flows for each roundabout.

The results are presented in

Fig. 3, which shows the exponential relationship between entry and circulating flows for all roundabouts. The coefficient of determination (R^2) for each roundabout (R1 to R5) was also calculated, with values ranging from 0.61 to 0.72. These values indicate that there is a good correlation between the observed and estimated values.

The regression constant "A" is an important parameter in the roundabout capacity model, as it represents the maximum entry capacity that can be achieved under ideal conditions. The values of A for the studied roundabouts were found to range from 1244 to 1449 pcu/h.

Tab. 5

Characteristics of the investigated roundabouts
and the results of entry capacity models for each entry

Roundabout No	Entry no.	Inscribed diameter (m)	A	B	R^2	No. of observations
R1	A	24	1419	0.00134	0.578	23
	B		1255	0.00132	0.575	27
	C		1356	0.00133	0.611	31
	D		1300	0.00106	0.631	31
R2	A	22	1266	0.00087	0.572	29
	B		1338	0.00137	0.565	29
	C		1299	0.00127	0.455	29
	D		1630	0.00169	0.784	21
R3	A	28	1459	0.00131	0.558	11
	B		1637	0.00147	0.644	11
	C		1112	0.00114	0.504	11
	D		1207	0.00087	0.763	11
R4	A	55	1414	0.00116	0.847	29
	B		1681	0.00101	0.767	28
R5	A	60	1523	0.00107	0.654	34
	B		1456	0.00110	0.762	33
Total						388

presents a summary of the key characteristics of the statistical results for the smallest and largest roundabouts among the studied roundabouts.

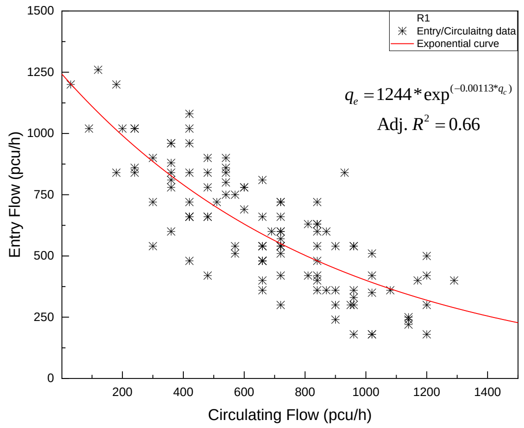
Tab. 6

Key characteristics of R2 and R5 of different inscribed diameter

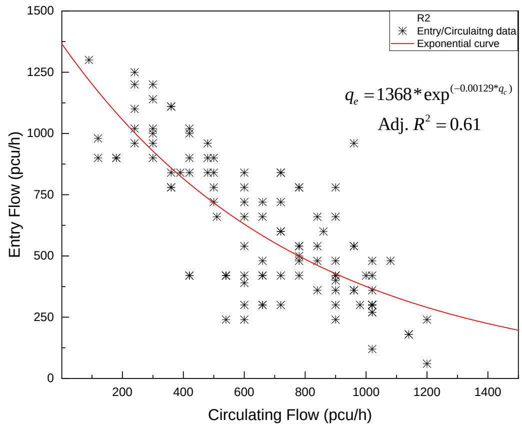
Roundabout No.	Constants	Value	Standard error	t-value	Prob>|t|	Adj. R-Square	% difference
R2	A	1368	76.86664	17.79149	0	0.61	5.75%
	B	-0.00129	1.04E-04	-12.38979	0		
R5	A	1449	65.01215	22.28949	0	0.72	
	B	-0.00103	9.05E-05	-11.38952	0		

An examination of the data shows that there is a positive correlation between the inscribed diameter of the roundabout and the entry capacity, as can be seen in Fig. 4. In this study, the capacity of the roundabout with the larger inscribed diameter is approximately 5.75% higher than the capacity of the roundabout with the smaller inscribed diameteThis observation is consistent with the findings of other researchers in the field, as reported in publications [14][16][17].

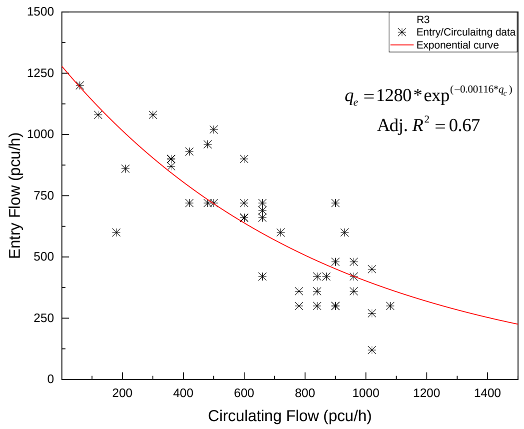
This is further supported by the trend line depicted in Fig. 5, which illustrates the relationship between inscribed diameter and entry capacity for a sample of roundabouts. The trend line indicates a positive correlation between inscribed diameter and entry capacity, with an increase in inscribed diameter resulting in a corresponding increase in entry capacity. The positive correlation between inscribed diameter and entry capacity can be explained by the fact that larger roundabouts generally have wider entries, a wider circulating path, and a longer entry-entry distance, which allows for a larger number of vehicles to enter and circulate on the roundabout.



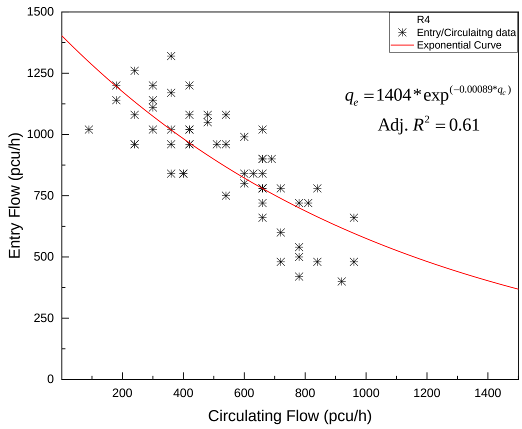
R1



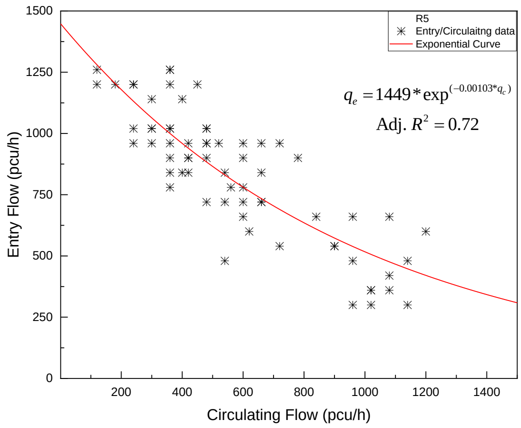
R2



R3



R4



R5

Fig. 3. Entering flow versus circulating flow at R1 to R5

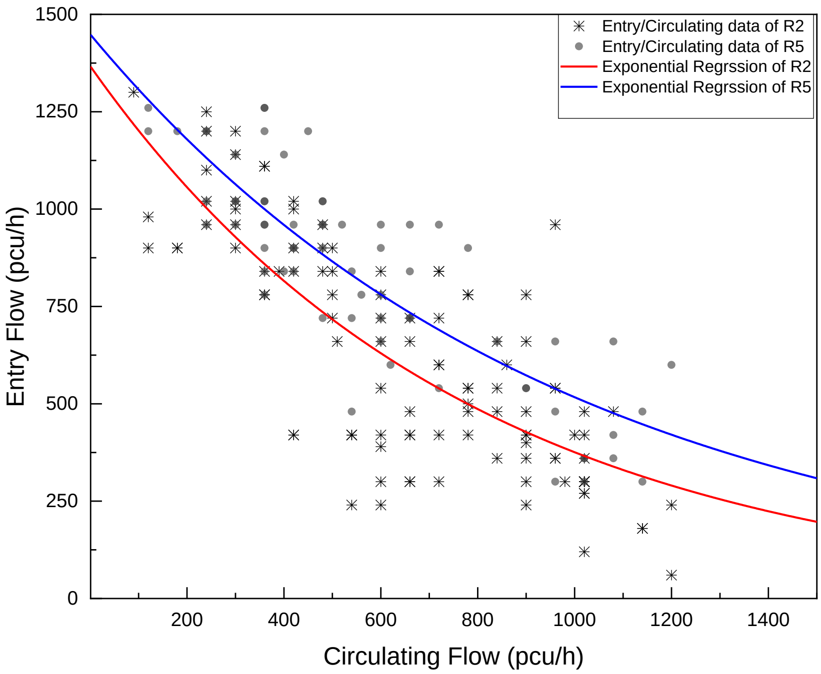


Fig. 4. A comparison between the smallest and largest selected roundabouts

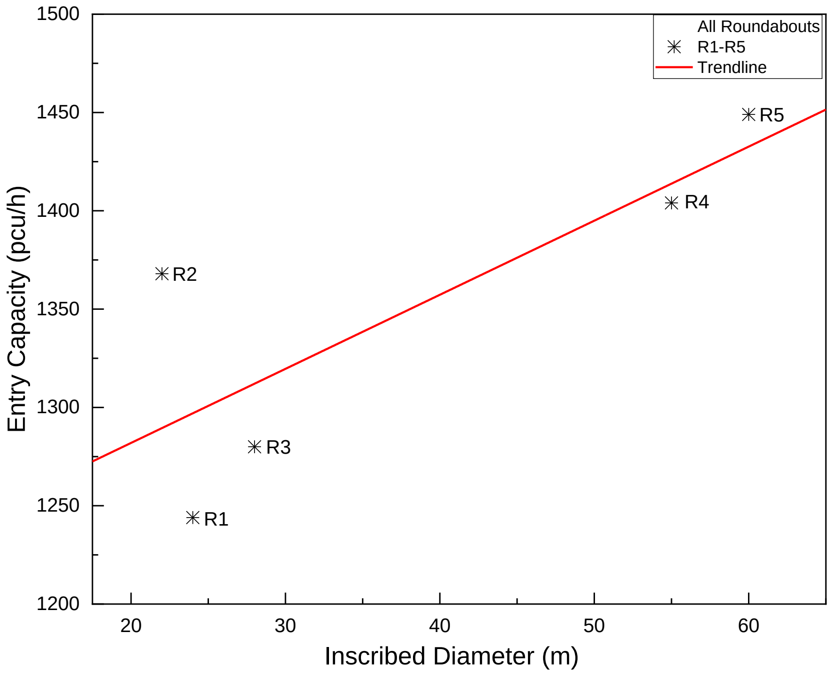


Fig. 5. Entry capacity versus inscribed diameter

A general capacity model (GM) was developed using the data collected for all roundabouts, as depicted in Fig. 6. The GM has an R2 value of 0.63, indicating a strong correlation between the independent and dependent variables. Furthermore, the model is statistically significant. The mathematical representation of the GM is provided in Equation (5).

$$q_e = 1390 * e^{(-0.0016 * q_c)} \quad (5)$$

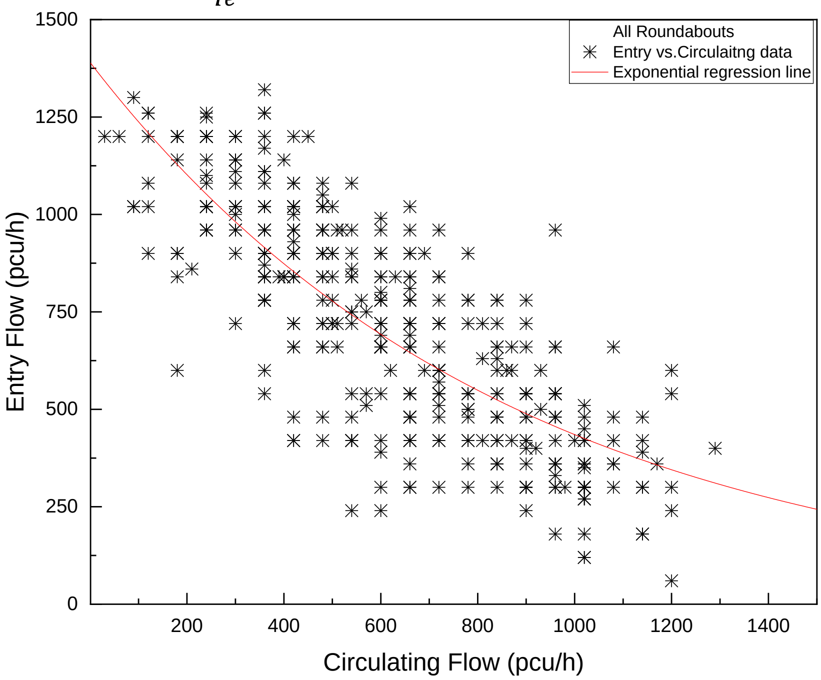


Fig. 6. Entry flow versus circulating flow of all roundabouts

After arriving at the final form of the model, the general capacity model (GM) was used as a benchmark for comparison with other international models in this study. Fig. 7 presents a comparison of the GM with the Highway Capacity Manual (HCM) 2016, Brilon-Bondzio, and Brilon-Wu models. The GM has a maximum entry capacity of 1390 pcu/h, which is only slightly higher than the maximum entry capacity of the HCM 2016 model of 1380 pcu/h. On the other hand, the maximum entry capacities of the Brilon-Bondzio and Brilon-Wu models are 1218 pcu/h and 1241 pcu/h respectively, which are significantly lower than the GM capacity.

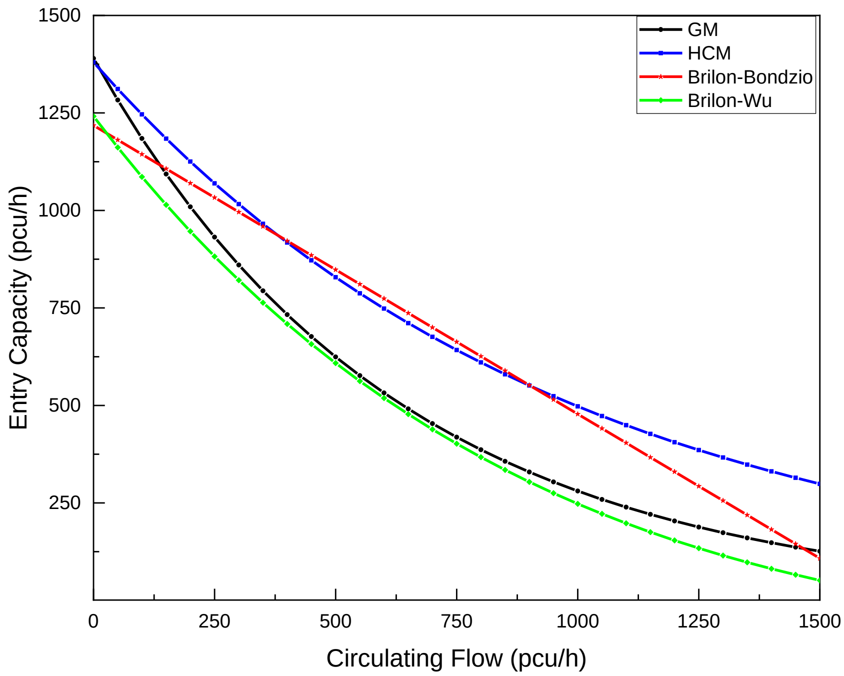


Fig. 7. Comparison between GM and international capacity models

Tab. 7 provides a detailed comparison of the GM, HCM, Brilon-Bondzio, and Brilon-Wu models, including the percentage difference between each model's maximum entry capacity.

Tab. 7

Percentage difference between the GM and other international models

Model	GM	HCM 2016	Brilon-Bondzio	Brilon-Wu
Max. entry capacity	1390	1380	1218	1241
% difference		0.71%	12.4%	10.7%

4. CONCLUSION

To develop an entry-capacity model for Hungarian roundabouts, an empirical method based on regression analysis was applied using the collected data of the selected roundabouts. The model was first developed for each individual entry and then for each roundabout as a whole. Finally, a general model was created using all of the collected data from all sixteen entries. The results of this analysis led to the following conclusions:

- A general entry-capacity model for Hungarian roundabouts was developed using the collected data. The model's coefficient of determination, R2, was 0.63, which is encouraging given that the data was manually extracted.
- The general model developed using the collected data resulted in a capacity that was about 0.71% higher than the capacity predicted by the Highway Capacity Manual (HCM) 2016 model.
- The general model (GM) developed using the collected data predicts a significantly higher entry capacity than the models developed by Brilon-Bondzio and Brilon-Wu, with a percentage difference of +12.4% and +10.7% respectively.
- The analysis showed that as the inscribed diameter of a roundabout increases, capacity also increases. This is consistent with the findings of previous studies on the subject.

One limitation of this study is the limited amount of data available from existing roundabouts. To improve the reliability of the general model (GM) developed in this study, it would be necessary to collect data from a larger sample of roundabouts. Therefore, further research is needed in this area. Additionally, the model developed in this study is only applicable to single-lane roundabouts. It would be interesting to study other types of roundabouts and compare the results of different models to the developed GM model in this study. Despite these limitations, the research methodology and results are transferable to other countries with similar driving behaviors.

References

1. Polus A., S.S. Lazar, M. Livneh. 2003. “Critical Gap as a Function of Waiting Time in Determining Roundabout Capacity”. *J Transp Eng* 129(5): 504-509. DOI: 10.1061/(ASCE)0733-947X(2003)129:5(504).
2. Hóz E., K. Temesiné Tóth. 2010. “New Planning Regulations for Roundabouts. Hungarian Review of Transport Infrastructure”. *Közlekedésépítési Szemle* 10: 10-15.
3. Nambisan S.S., V. Parimi. 2007. “A comparative evaluation of the safety performance of roundabouts and traditional intersection controls”. *ITE Journal (Institute of Transportation Engineers)* 77(3): 18-25.
4. Transportation Research Board. *The Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis (HCM)*. Washington, DC: The National Academies Press. 2016.
5. Kimber R.M. “The Traffic Capacity of Roundabouts”. 1980. Available at: https://trl.co.uk/publications/the-traffic-capacity-of-roundabouts.
6. Valdez M., R.L. Cheu, C. Duran. 2011. “Operations of Modern Roundabout with Unbalanced Approach Volumes”. *Transportation Research Record* 2265(1): 234-243. DOI: https://doi.org/10.3141/2265-26.
7. Kimber R.M. 1989. “Gap-acceptance and empiricism in capacity prediction”. *Transportation Science* 23(2): 100-111. DOI: https://doi.org/10.1287/trsc.23.2.100.
8. Brilon W., B. Stuwe. 1993. “Capacity and Design of Traffic Circles in Germany”. *Transportation Research Record* 1398: 61-67. Available at: https://onlinepubs.trb.org/Onlinepubs/trr/1993/1398/1398-009.pdf.
9. Yap Y.H., H.M. Gibson, B.J. Waterson. 2013. “An International Review of Roundabout Capacity Modelling”. *Transp Rev* 33(5): 593-616. DOI: https://doi.org/10.1080/01441647.2013.830160.

10. Werner Brilon. 1991. "Intersections without Traffic Signals II ". *Proceedings of an International Workshop*. 18-19 July, 1991. Bochum, Germany.
11. Brilon W., N. Wu, L. Bondzio. 1997. "Unsignalized Intersections in Germany-a State of the Art 1997". *Third International Symposium on Intersections Without Traffic Signals*. Portland, Oregon. 1997-7-21 to 1997-7-23.
12. Brilon W., N. Wu. 2006. *Guidelines for the construction of roundabouts.* Merkblatt für die Anlage von Kreisverkehren.
13. Rodegerdts L., et al. 2007. *NCHRP REPORT 572: Roundabouts in the United States*. Washington, D.C. Transportation Research Board, National Research Council.
14. Al-Masaeid H.R., M.Z. Faddah. 1997. "Capacity of Roundabouts in Jordan". *Transp Res Rec* 1572(1): 76-85. DOI: https://doi.org/10.3141/1572-10.
15. Hungarian Road and Rail Society. 2021. "Design of Roundabouts". Budapest, Hunagry.
16. Macioszek E. 2020. "Roundabout Entry Capacity Calculation – A Case Study Based on Roundabouts in Tokyo, Japan, and Tokyo Surroundings". *Sustainability* 12(4): 1533. DOI: https://doi.org/10.3390/SU12041533.
17. Robinson B., et al. 2000. "Roundabouts: an informational guide". U.S. Dept. of Transportation, Federal Highway Administration. Washington, D.C. Available at: https://www.fhwa.dot.gov/publications/research/safety/00067/00067.pdf.

Received 26.01.2023; accepted in revised form 05.05.2023