A COMPARISON OF TWO ROUNDABOUT CAPACITY MODELS

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ABSTRACT

This paper presents the results of a detailed comparison of two roundabout capacity models, namely a model developed by the first author of this paper based on her research conducted in Poland (referred to as the Macioszek model) and the model used in the SIDRA INTERSECTION software based on roundabout research conducted in Australia (referred to as the SIDRA Standard model due to other model options in the software). Both models are lane-based analytical models based on gap acceptance theory with an empirical basis, and both models use Cowan's bunched exponential distribution of circulating road headways. On the other hand, the two models use different capacity and headway distribution equations, and they are calibrated for different traffic conditions in two different countries. Comparisons of entry lane capacity estimates from the two models for one-lane and for two-lane roundabouts are presented. Analyses indicated that the entry lane capacities at one-lane roundabouts in Poland are lower but close to those in Australia whereas the entry lane capacities at two-lane roundabouts in Poland are much lower than those in Australia. Calibrating the SIDRA Standard model using data for 21 one-lane roundabouts and 12 two-lane roundabouts resulted in capacity estimates with very good match to driving conditions in Poland.

Keywords: One-lane roundabouts, Two-lane roundabouts, Capacity, Gap Acceptance

INTRODUCTION

Different methods exist around the world to determine roundabout entry capacity. The methods differ in the modeling approach used, model level of detail (lane-based or approach-based), model parameters used to represent driver behavior and roundabout geometry, model calibration methods as well as the levels of model complexity. The analytical models of roundabout capacity can be divided into two groups:

- models (semi-probabilistic) based on gap acceptance theory, and
- statistical models (empirical) based on regression analysis of field data.

The models based on gap acceptance theory represent driver behaviour through *headway distributions* of traffic on the circulating road, and *critical gaps* and *follow-up headways* of drivers on roundabout approaches. The critical gaps and follow-up headways are fixed values in some models, or they are adjusted as a function of the roundabout geometry and flow conditions to varying degrees in other models. The headway distributions and entry characteristics of gap-acceptance based analytical models are calibrated using empirical data *(1-13)*.

The statistical (empirical) models use regression and correlation tools to identify independent variables that determine capacity values. These models may or may not relate to driver characteristics directly and interpretation of some statistically significant parameters may be difficult *(10-18)*. Note that the references to the roundabout capacity model in the US Highway Capacity Manual *(10-13)* are repeated in both the analytical (gap-acceptance) and the statistical (empirical) model groups above. Akçelik refers to this model as "a non-linear empirical (exponential regression) model with a theoretical basis in gap-acceptance methodology" *(4, 5)*.

In relation to the model level of detail relevant to both groups of roundabout capacity models, it is important to distinguish between *lane-based methods* which model capacity of individual entry lanes (allowing for differences in entry circulating lane characteristics and unequal lane use cases) and *approach-based methods* which aggregate all entry lanes and model capacity of the approach as whole.

This paper presents the results of a detailed comparison of two analytical roundabout capacity models based on gap-acceptance theory. These are a model developed by the first author of this paper based on her research conducted in Poland (referred to as the *Macioszek model*) *(19-21)* and the model used in the SIDRA INTERSECTION software based on roundabout research conducted in Australia (referred to as the *SIDRA Standard model* due to other model options in the software) *(2-6)*.

Both the Macioszek model and the SIDRA Standard model for roundabout capacity are lane-based analytical models based on gap acceptance theory with an empirical basis, and both models use Cowan's bunched exponential distribution of circulating road headways *(22)*. On the other hand, the two models use different capacity and headway distribution equations, and they are calibrated for different traffic conditions in two different countries. The results of comparative analysis of capacity estimates from the two models for one-lane and two-lane roundabouts are presented in this article.

In both models, capacity is defined as "the maximum sustainable flow rate that can be achieved during a specified time period under given (prevailing) road, traffic and control conditions", measured as "the traffic volume of vehicles entering to the circulating road at saturated conditions at the entry when drivers at the entry use all acceptable gaps in the circulating traffic flow", and estimated as "the maximum queue discharge rate reduced by time lost due to interruption caused by lack of acceptable gaps in the circulating road". The gap-acceptance method uses the the follow-up headway (t_f) parameter as the queue discharge headway and determines the proportion of time when the vehicles can depart from the queue as a function of the circulating stream headway distribution and the critical gap (t_c) parameter *(3-5)*.

The paper presents comparisons of capacity estimates from the Macioszek and SIDRA Standard models for 21 one-lane roundabouts and 12 two-lane roundabouts in Poland which formed the basis of the Macioszek model development. At two-lane roundabout entries, the comparisons of entry lane capacities depend on entry lane flows. The entry lane flow estimates from the SIDRA INTERSECTION software were used for comparisons presented in this paper. The comparisons were limited to conditions where demand flows are below capacity in order to simplify the comparison process.

THE MACIOSZEK MODEL

The Macioszek model is structured to determine the *initial capacity* for one-lane and two-lane roundabouts under ideal conditions at the roundabout, i.e. without the influence of heavy vehicles and pedestrians. The actual entry capacity can then be estimated allowing for heavy vehicles and pedestrians.

The Macioszek model is a lane-based analytical model based on gap acceptance theory with an empirical basis. In the modeling process, a stepwise function of gap acceptance by drivers entering the roundabout is assumed. The model uses two different *circulating stream headway distributions* to be applied according to the range of the circulating flow rate, Q_{nwl}:

- *Shifted exponential distribution* for $1 < Q_{nwl} \leq 100$ pcu/h, and
- *Cowan M3 distribution (3, 22)* for 100 pcu/h $< Q_{nwl} < C_{jr}$ (circulating stream capacity).

The model parameters including the *critical gap* and f*ollow-up headway* for drivers entering the roundabout, the *minimum headway* and the proportions of free (unbunched) vehicles for the circulating stream depend on the geometry and flow characteristics of one-lane and two-lane roundabouts. In the case of two-lane roundabouts, these parameters are defined separately for each lane. The mathematical forms of models for estimation of capacity for a one-lane roundabout entry, and the capacity of right and left lanes of a two-lane roundabout entry are not included in this paper due to space limitation. A detailed description of the Macioszek model as well as detailed data and information about the measurement of critical gap and follow-up headway parameters can be found in papers by the first author *(19-21)*.

A summary of survey data from roundabouts in Poland used for calibrating the Macioszek capacity model is given in *Table 1*. The data collection was carried out at 21 one-lane roundabouts and 12 two-lane roundabouts located in urban areas of eight provinces of Poland (Upper Silesian, Lower Silesian, Lubuskie, Małopolskie, Opolskie, Łódzkie, Podkarpackie and Warmia-Mazury). During the surveys, the following characteristics of traffic flows were observed:

- the traffic volumes on the circulating road and on each roundabout entry recorded separately for each entry lane in the case on two-lane roundabouts,
- vehicle types (0.1 to 21.0 % of trucks),
- traffic movements,

- critical gaps by observing the circulating stream headways accepted and rejected by drivers at roundabouts entries, and
- follow-up headways.

The measurements were carried out using digital video cameras during weekday peak periods (*Figure 1*). Surveys were carried out under good weather conditions (no precipitation, good visibility). Data on the geometrical features of each roundabout were also collected.

Figures 2 to 4 show the capacity estimates from the Macioszek model as a function of circulating flow rate for one-lane and two-lane roundabout entries (capacities with no effect of heavy vehicles or pedestrians are shown). The graphs are shown for extreme values of observed data for the inscribed diameter (D_i) and circulating road width (w_c) for one-lane and two-lane roundabout entries as listed in *Table 1*. *Figures 3 and 4* for two-lane roundabouts also show the graphs for average values of these parameters.

Table 1 - Summary of survey data from roundabouts in Poland used for calibrating the Macioszek capacity model

Parameter	One-Lane Roundabouts	Two-Lane Roundabouts
Inscribed diameter (m)	26.0 - 45.0	41.0 - 75.0
Central island diameter (m)	15.0 - 26.0	32 - 63.0
Circulating road width (m)	4.0 - 10.0	8.0 - 11.5
Total entry width (m)	3.0 - 4.0	6.0 - 7.0
Entry radius (m)	6.0 - 15.0	8.0 - 15.0
Total exit width (m)	4.0 - 4.75	4.0 - 4.75
Exit radius (m)	12.0 - 15.0	14.0 - 16.0
Number of intersection arms	4	4
Presence of splitter island	Yes, at all entries	Yes, at all entries
Follow-up headway (s)	2.50 - 3.08	2.20 - 3.72
Critical gap (s)	3.16 - 6.05	4.06 - 4.43
Follow-up headway/Critical gap ratio	0.51 - 0.79	0.54 - 0.84
Circulation flow (veh/h)	186 - 568	246 - 939
Total entry flow (veh/h)	172 - 694	261 - 855
Dominant lane flow (veh/h)	172 - 694	139 - 465
Subdominant lane flow (veh/h)	-	122 - 403

Figure 1 - Traffic surveys using digital video cameras

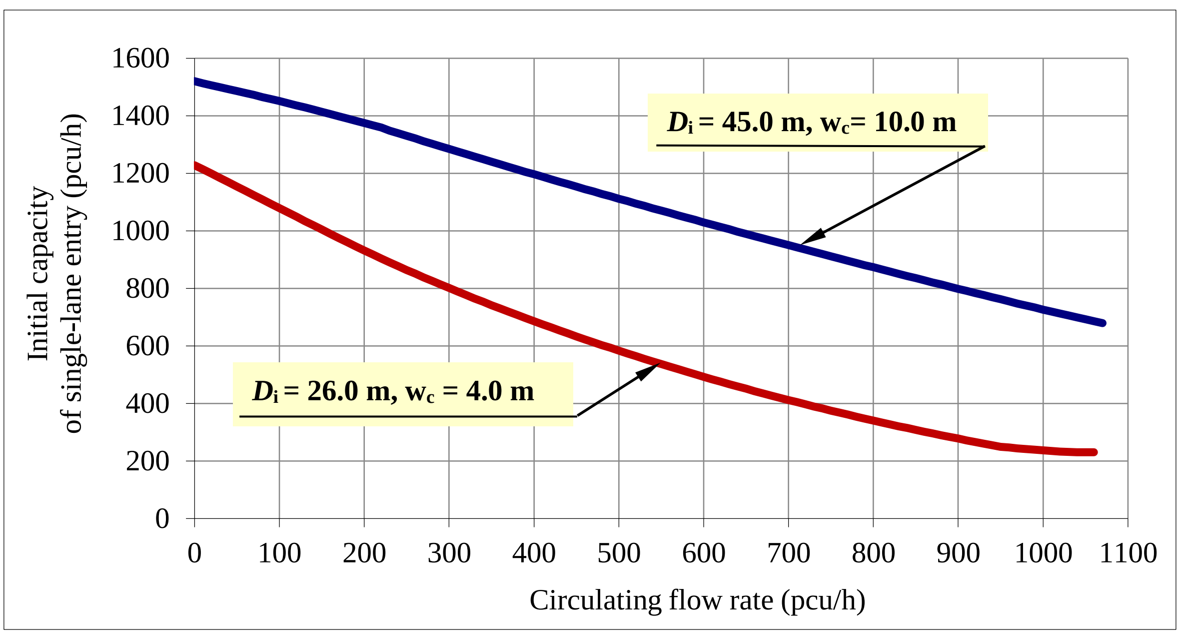

Figure 2 - Capacity estimates for one-lane roundabouts from Macioszek model

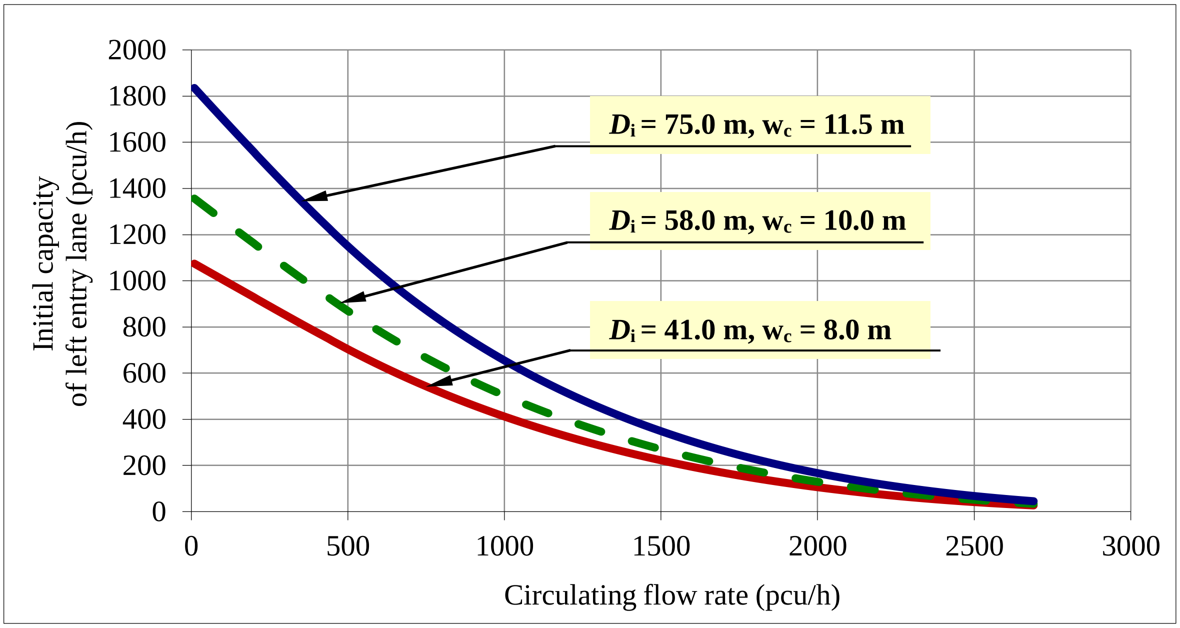

Figure 3 - Capacity estimates for left entry lanes at two-lane roundabouts from Macioszek model

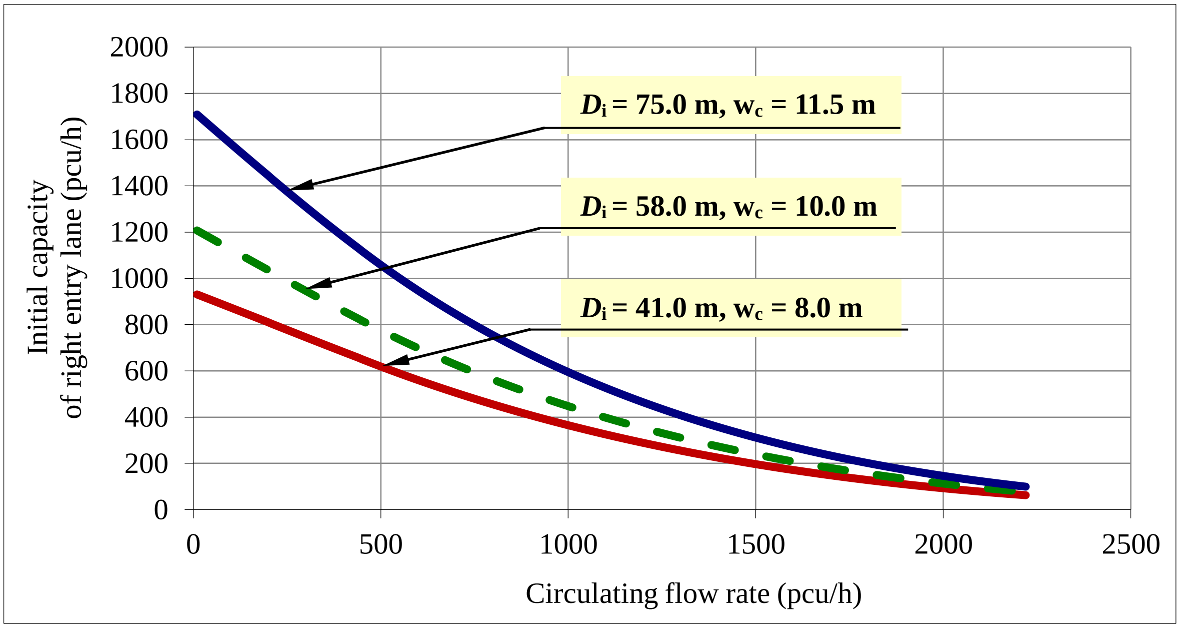

Figure 4 - Capacity estimates for right entry lanes at two-lane roundabouts from Macioszek model

THE SIDRA STANDARD MODEL

The SIDRA Standard roundabout capacity model is a lane-based model that allows for the effects of both roundabout geometry and driver behaviour. The model was originally based on the method developed at the Australian Road Research Board as described in Special Report SR 45 which was introduced into SIDRA INTERSECTION with some variations and extensions *(23, 24)*. The SR 45 method was also incorporated into the older Australian roundabout design guide (AUSTROADS 1993) with some minor modifications *(25, 26)*. A significant addition to the model was provision for handling unbalanced flow conditions *(2).* Subsequently, significant enhancements were introduced in various versions of the SIDRA INTERSECTION software based on further research and development including the handling of roundabout metering signals *(6, 27, 28)*.

The SIDRA Standard roundabout capacity model uses lane-based *gap acceptance* techniques for roundabout capacity and performance analysis based on empirical models used to calibrate gap acceptance parameters. As such, the SIDRA Standard model differs from models which estimate capacity directly from a linear regression equation, e.g. as used in the TRL (UK) "empirical" model *(14-16)*. The HCM Edition 6 (2016) and HCM 2010 roundabout capacity models use an exponential regression model with a structure consistent with gap acceptance modelling *(4, 5)*.

The SIDRA Standard capacity model is based on research on Australian roundabouts, thus reflecting Australian driving characteristics (*Table 2*). In the SIDRA INTERSECTION software, the *Environment Factor* is used as a general parameter to allow for the effects of such factors as driver aggressiveness and alertness (driver response times), standard of intersection geometry, visibility, operating speeds, sizes of light and heavy vehicles, interference by pedestrians, standing vehicles, parking, buses stopping, and so on when such factors are not modeled explicitly.

Table 2 - Summary of survey data from roundabouts in Australia used for calibrating the SIDRA Standard roundabout capacity model

	Total Entry Width (m)	No. of Entry Lanes	Average Entry Lane Width (m)	Circul. Width (m)	Inscribed Diameter (m)	Entry Radius (m)	Entry Angle (°)
Minimum	3.7	1	3.20	6.5	16	4	0
Maximum	12.5	3	5.50	12.0	220	∞	80
Average	8.1	2	3.84	9.6	56	39.0	29
15th percentile	6.4	2	3.34	8.0	28	10.0	0
85th percentile	10.5	3	4.48	11.9	70	39.8	50
Count	55	55	55	55	55	55	55
	Follow-up Headway (s)	Critical Gap (s)	Fol. Hdw / Crit. Gap Ratio	Circul. Flow (veh/h)	Total EntryFlow (veh/h)	Dominant Lane Flow (veh/h)	Subdom. Lane Flow (veh/h)
Minimum	0.80	1.90	0.29	225	369	274	73
Maximum	3.55	7.40	0.92	2648	3342	2131	1211
Average	2.04	3.45	0.61	1066	1284	796	501
15th percentile	1.32	2.53	0.43	446	690	467	224
85th percentile	2.65	4.51	0.79	1903	1794	1002	732
Count	55	55	55	55	55	55	55

The US research *(10-13)* indicates that capacities of roundabouts in the USA are lower compared with Australian roundabouts. As a result, the *SIDRA Standard* capacity model was calibrated for US applications to provide capacity estimates closer to those observed in the USA. For this purpose, the Environment Factor parameter of the model was set to 1.2 for one-lane and two-lane roundabouts on the basis of the roundabout capacity models described in HCM 2010 *(10, 11)* while the value of this parameter for Australian conditions is 1.0. On the basis of the roundabout capacity models described in HCM Edition 6 *(13)*, Environment Factor values of 1.05 and 1.2 are used for one-lane and two-lane roundabouts, respectively.

This paper is the result of an investigation to determine the best values of Environment Factor for the SIDRA Standard model to represent driving conditions for roundabouts in Poland on the basis of comparison with the Macioszek model for single-lane and two-lane roundabouts.

COMPARISON OF MODELS FOR ONE-LANE ROUNDABOUTS

The capacity estimates from the Macioszek and SIDRA Standard models were determined and compared for 21 one-lane roundabouts which had formed the basis of Macioszek model calibration. Initial analyses indicated that entry lane capacities at one-lane roundabouts in Poland are lower but close to those in Australia. The average difference between the capacity estimates from the two models was -6.5% (-56 veh/h) with values in the range -19.7% (-163 veh/h) to 7.6% (69/veh/h),

By calibrating the SIDRA Standard model using all 21 one-lane roundabouts to match the one-lane roundabout capacities observed in Poland (as represented by the Macioszek model), an Environment Factor value of 1.053 was determined.

A summary of model comparison results for one-lane roundabouts using the Environment Factor of 1.053 in the SIDRA Standard model is given in *Table 3* which includes minimum, maximum, average and standard deviation of remaining differences as well as the degrees of saturation (v/c ratios) determined by each model. It is seen that the average difference between the Macioszek model and the SIDRA Standard model using the Environment Factor of 1.053 is reduced to 0.6 % (7 veh/h) after calibration.

Figure 5 presents the results of linear regression analysis for entry lane capacities at one-lane roundabouts after the initial calibration, indicating a good fit for entry lane capacities (R^2 = 0.78). However, residual analysis of data indicated strong correlation of residuals (difference between the capacity estimate from the Macsiszek model and the capacity estimate from the calibrated SIDRA Standard model) with the one lane roundabout inscribed diameter (in the range 26 m to 45 m) as shown in *Figure 6*.

Table 3 - Summary of model comparison results for ONE-LANE roundabouts after calibration using Environment Factor = 1.053

Value	**Difference in capacity estimate from two models *(1)***		**Degree of saturation (v/c ratio)**	
	Percentage	**veh/h**	**Macioszek model**	**SIDRA Standard model**
Average	0.6%	7	0.45	0.45
Minimum	-12.9%	-99	0.18	0.19
Maximum	16.4%	138	0.91	0.90
St. Deviation	8.0%	67	0.14	0.13

(1) Relative difference (%) and absolute difference (veh/h) values are based on (Macioszek Model estimate - SIDRA Standard Model estimate)

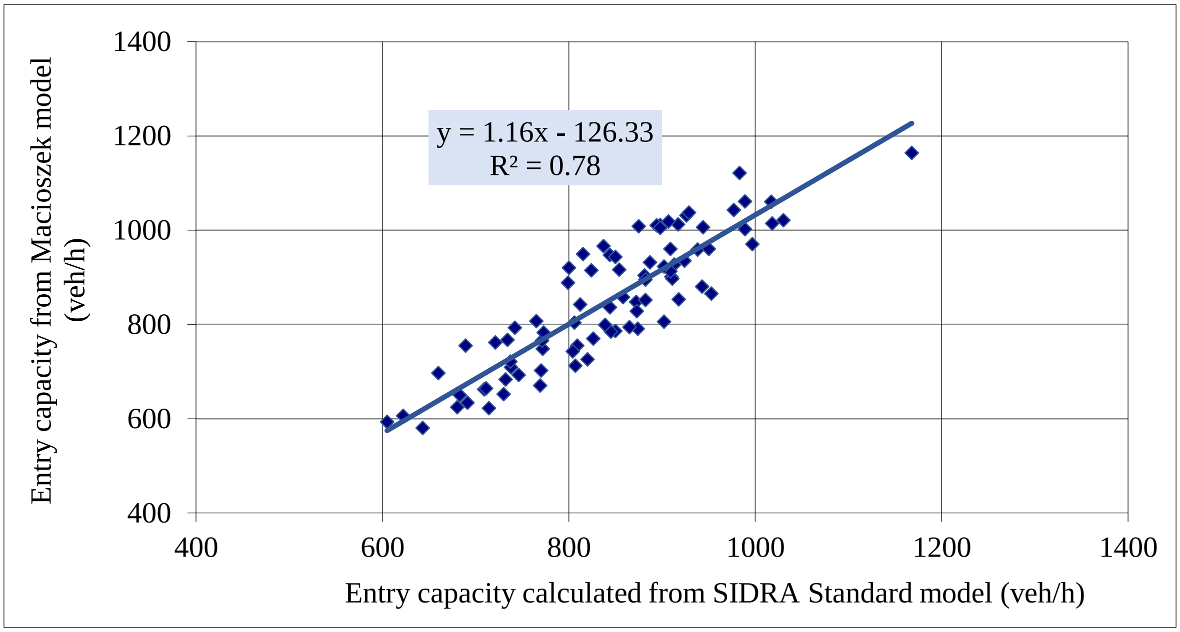

Figure 5 - Results of linear regression analysis between one-lane roundabout entry capacity calculated from the Macioszek model and the SIDRA Standard model using Environment Factor = 1.053

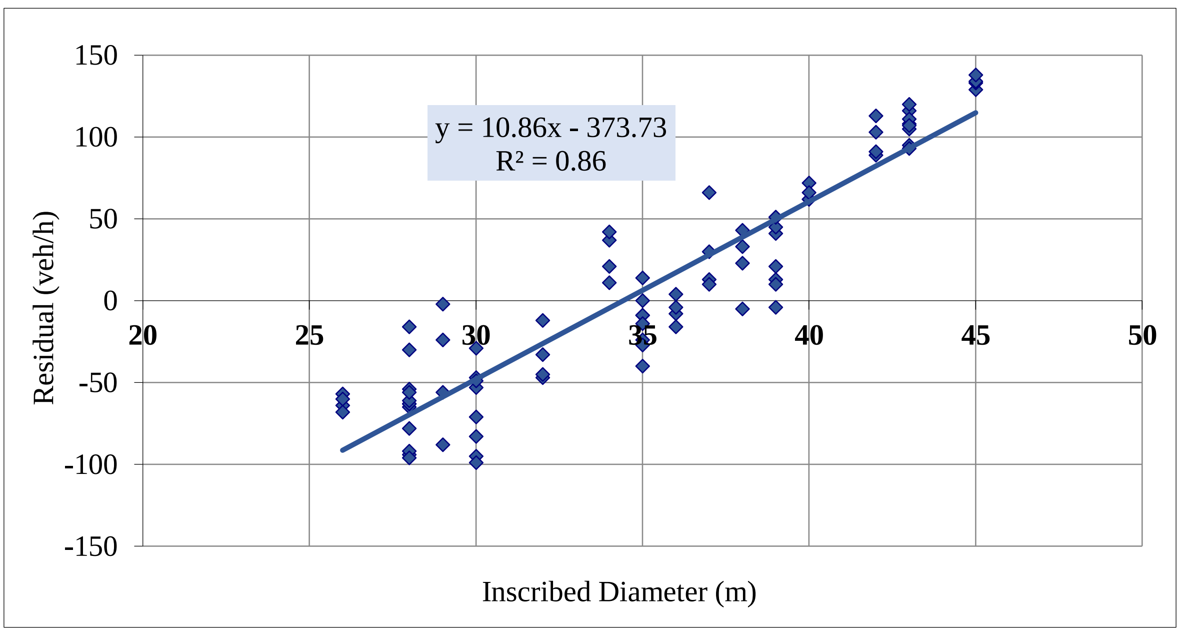

Figure 6 - The impact of one-lane roundabout inscribed diameter on the residuals

In view of the strong correlation of residuals with the roundabout inscribed diameter, the SIDRA Standard model was calibrated for two categories of roundabouts according to the inscribed diameter as follows:

- smaller roundabouts (26 < $D_i \leq$ 35 m): Environment Factor =1.095, and
- larger roundabouts (35 m < $D_i \leq$ 45 m): Environment Factor =1.005.

This was found to improve the overall calibration results as shown in *Table 4* and *Figure 7*. It is seen that the average difference between the Macioszek model and the SIDRA Standard model using two Environment Factors according to inscribed diameter groups is reduced to 0.2 % (2 veh/h).

Table 4 - Summary of model comparison results for ONE-LANE roundabouts after grouped calibration using Environment Factor = 1.095 for 26 < $D_i \leq$ 35 m and 1.005 for 35 < $D_i \leq$ 45 m

Value	**Difference in capacity estimate from two models *(1)***		**Degree of saturation (v/c ratio)**	
	Percentage	**veh/h**	**Macioszek model**	**SIDRA Standard model**
Average	0.2%	2	0.45	0.45
Minimum	-9.3%	1	0.18	0.18
Maximum	12.4%	82	0.91	0.84
St. Deviation	4.8%	41	0.14	0.13

D_i = Inscribed Diameter

(1) Relative difference (%) and absolute difference (veh/h) values are based on (Macioszek Model estimate - SIDRA Standard Model estimate)

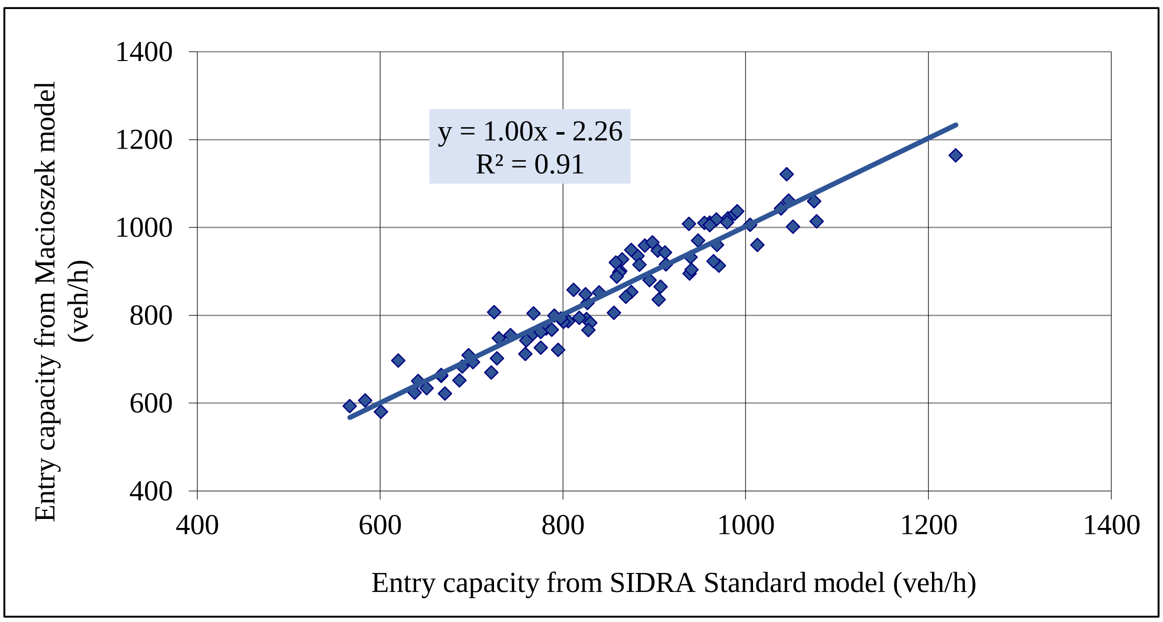

Figure 7 - Linear regression analysis between capacity estimates from the Macioszek and SIDRA Standard models for one-lane roundabouts after grouped calibration using Environment Factor = 1.095 for 26 < $D_i \leq$ 35 m and 1.005 for 35 < $D_i \leq$ 45 m

These results show a satisfactory level of compatibility of the Macioszek and SIDRA Standard capacity models for one-lane roundabouts. A single Environment Factor of 1.05 could be used in the SIDRA INTERSECTION software to match the conditions for one-lane roundabouts in Poland. It is interesting to note that this is the same as the Environment Factor used for one-lane roundabouts to match the model described in the new US Highway Capacity Manual Edition 6 *(13)*.

COMPARISON OF MODELS FOR TWO LANE ROUNDABOUTS

A method similar to the comparison of the Macioszek and SIDRA Standard capacity models for one-lane roundabouts was used to compare the capacity estimates from the two models for 12 two-lane roundabouts which had formed the basis of the Macioszek model calibration. The two-lane roundabouts were analysed in a single group without grouping according to the inscribed diameter.

In the SIDRA Standard model, entry lane capacities and lane flow rates are interdependent for multi-lane roundabout approaches. For this reason, lane flows determined by the SIDRA INTERSECTION software were used in both models in order to limit the model comparison to the comparison of capacity estimates for given lane flows.

The initial analyses showed that the differences in capacity estimates from the two models for two-lane roundabouts are much larger than those for one-lane roundabouts. The average differences were -34.9% (-363 veh/h) for left entry lanes and -31.5% (-278 veh/h) for right entry lanes. The differences for both lanes considered together were in the range -7.1% (-65 veh/h) to -49.4% (469/veh/h). This indicates that entry lane capacities at two-lane roundabouts in Poland are substantially lower than those in Australia.

By calibrating the SIDRA Standard model to match the two-lane roundabout capacities observed in Poland (as represented by the Macioszek model), an Environment Factor value of 1.387 (approximately 1.4) was determined.

A summary of model comparison results for two-lane roundabouts after calibration is given in *Table 5* which includes minimum, maximum, average and standard deviation of remaining differences as well as the degrees of saturation (v/c ratios) determined by each model for individual lanes (separately for left and right entry lanes). It is seen that the average differences between the Macioszek model and the SIDRA Standard model are reduced to 7.1 % (50 veh/h) for left entry lane and -5.1 % (-27 veh/h) for right entry lane after calibration.

Figure 8 shows the results of linear regression analysis for right and left entry lane capacities at two-lane roundabouts after calibration, indicating very good quality of fit for both right and left entry lane capacities (R^2 = 0.93 for left entry lanes and R^2 =0.90 for right entry lanes). *Figure 8* also shows the difference in dominant lane (left entry lane) and subdominant (right entry lane) capacities. This indicates that the dominant lane in Poland is found as the left lane which differs from the US and Australian behaviour. In applying the SIDRAStandard model in the analyses reported in this paper, the left lane was specified as the dominant lane to match the conditions in Poland.

Figure 9 shows the results of linear regression analysis for degrees of saturation (all lanes) at two-lane roundabouts after calibration. This also shows very good quality of fit between the two models.

These results show a satisfactory level of compatibility of the Macioszek and SIDRA Standard capacity models for two-lane roundabouts.

Table 5 - Summary of model comparison results for TWO-LANE roundabouts after calibration using Environment Factor = 1.387

Entry lane	**Value**	**Difference in capacity estimate from two models *(1)***		**Degree of saturation (v/c ratio)**	
		Percentage	**veh/h**	**Macioszek model**	**SIDRA Standard model**
Left	Average	7.1%	50	0.47	0.50
	Minimum	-9.6%	-51	0.26	0.27
	Maximum	29.5%	211	0.86	0.78
	St. Deviation	7.9%	55	0.15	0.14
Right	Average	-5.1%	-27	0.53	0.49
	Minimum	-19.0%	-100	0.29	0.27
	Maximum	19.7%	140	0.96	0.78
	St. Deviation	8.2%	51	0.17	0.14

(1) Relative difference (%) and absolute difference (veh/h) values are based on (Macioszek Model estimate - SIDRA Standard Model estimate)

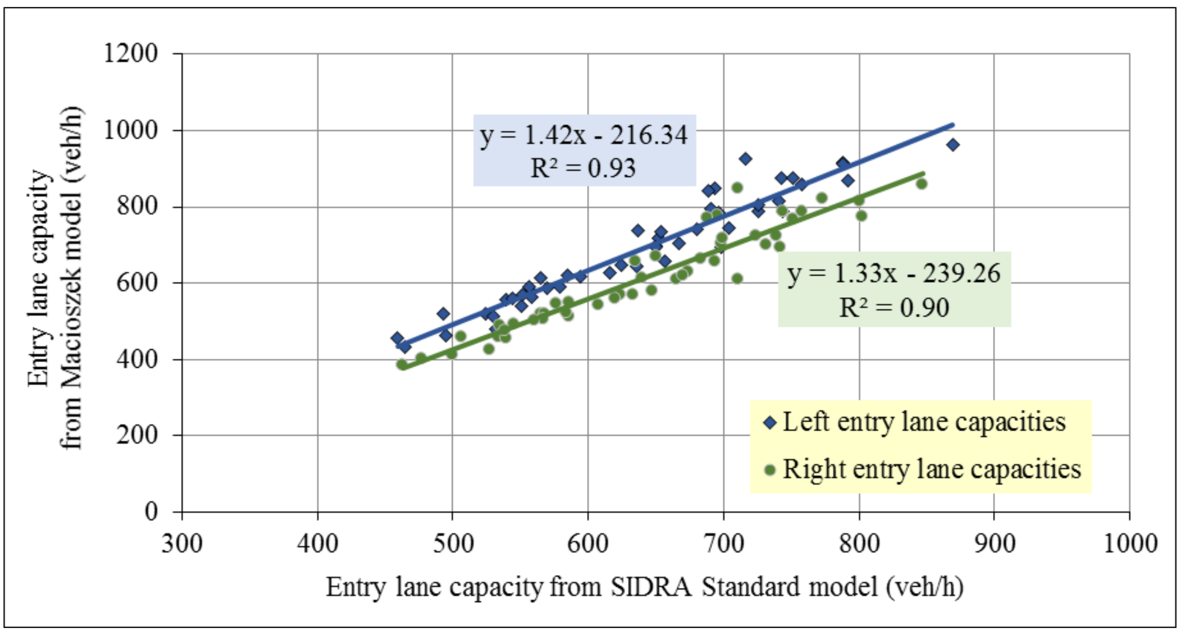

Figure 8 - Linear regression analysis between capacity estimates from the Macioszek and SIDRA Standard models for left and right entry lanes at two-lane roundabouts after calibration using Environment Factor = 1.387

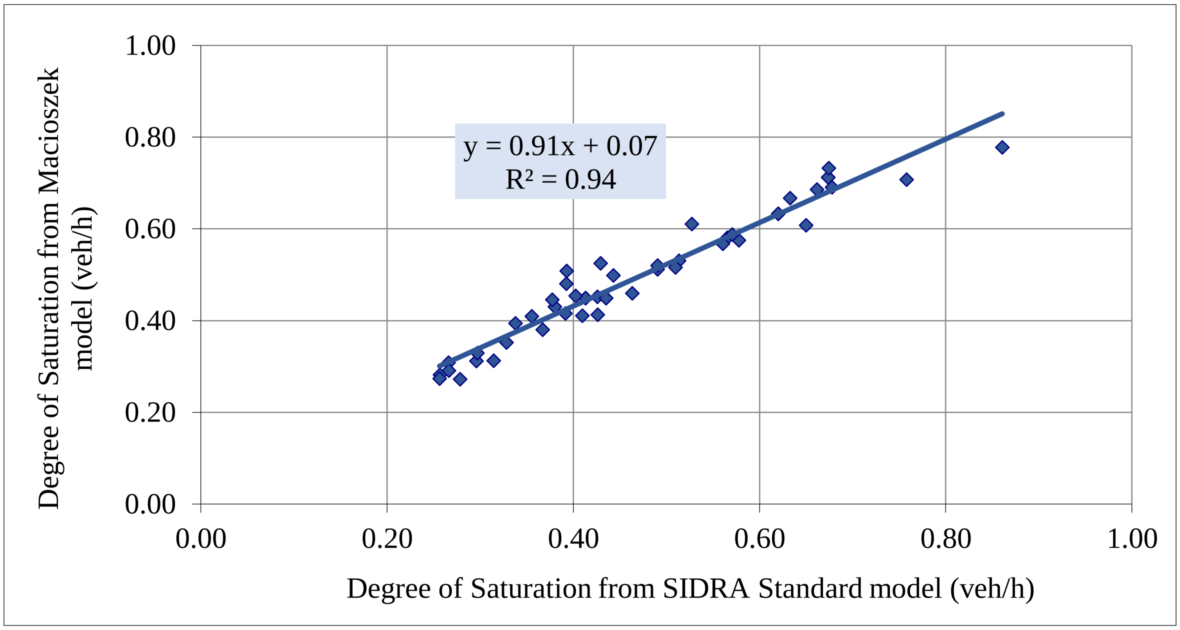

Figure 9 - Linear regression analysis between degree of saturation estimates (all lanes) from the Macioszek and SIDRA Standard models at two-lane roundabouts after calibration using Environment Factor = 1.387

CONCLUSIONS

This paper presents the results of detailed comparison of two roundabout capacity models, namely the Macioszek model developed by the first author of this paper based on her research conducted in Poland and the SIDRA Standard model used in the SIDRA INTERSECTION software developed by the second author of the paper based on roundabout research conducted in Australia. Both models are lane-based analytical models based on gap acceptance theory with an empirical basis, and both models use Cowan's bunched exponential distribution of circulating road headways.

The comparisons of entry lane capacity estimates from the two models for one-lane and for two-lane roundabouts indicated that the entry lane capacities at one-lane roundabouts in Poland are lower but close to those in Australia whereas the entry lane capacities at two-lane roundabouts in Poland are much lower than those in Australia.

Calibrating the SIDRA Standard model using data for 21 one-lane roundabouts and 12 two-lane roundabouts resulted in capacity estimates from this model with very good match to driving conditions in Poland. Analyses showed very good levels of compatibility between the Macioszek and SIDRA Standard capacity models for one-lane and two-lane roundabouts.

It should be noted that the SIDRA Standard model was used with default values of entry lane width (4.0 m), entry radius (20 m) and entry angle (30 degrees) for the analyses reported in this paper. The parameter ranges shown in *Table 1* for roundabouts in Poland indicate lower values of entry lane width (3.0 to 4.0 m for one-lane roundabouts and 3.0 to 3.5 m for two-lane roundabouts) and entry radius (6.0 to 15.0 m for one-lane roundabouts and 8.0 to 15.0 m for two-lane roundabouts), and the entry angle values are not available. The Environment Factor values used to calibrate the SIDRA Standard model for roundabout capacities in Poland would have been lower if the lower values of entry lane width and entry radius (and possibly values of entry angle higher than 30 degrees) were used in the SIDRA Standard model since the capacity estimates would have been closer to the observed values. The effect of these parameters can be the subject of further analysis.

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