CAPACITY OF 2-LANE ROUNDABOUTS

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ABSTRACT

The number of roundabouts has increased significantly in Denmark over the last two decades. The majority of roundabouts are single-lane roundabouts (used in rural and urban areas), but due to increasing traffic volumes, more and more roundabouts in rural areas are now being built as 2-lane roundabouts.

In Denmark, the capacity of roundabouts is traditionally based on gap acceptance theory and a number of previous studies have measured critical gap and follow up times for varies types of roundabouts in order to set up a general capacity model to be used in Denmark.

This presentation will mainly focus on 2-lane roundabouts and will be based on a new study from 2-lane roundabouts (mainly with "turbo design") that was completed in 2008. The results from the study include new values for critical gap and follow up times to be used in 2-lane roundabouts. The study also re-estimates the values for passenger car units (pcu) for two different categories of heavy vehicles. The new pcu-values indicate that capacity of roundabouts is more influenced by heavy vehicles than previously expected. The study also estimates the effect on capacity from exiting vehicles (vehicles leaving the roundabout at the adjacent arm). It is well known, that high traffic volumes of exiting vehicles reduce the capacity of entering vehicles. The results indicate that the capacity is reduced by up to 20% in situations with high traffic volumes of exiting vehicles. Empirical data from observed capacity at 2-lane roundabouts have been used to test different theoretical and empirical capacity models. In general, the theoretical capacity models seem to have certain limitations when it comes to describing the observed data. Methods to overcome these limitations are sought and will be presented.

Finally, an analysis of drivers lane use when entering roundabouts has been examined. The majority of entering drivers use the right lane (outer lane), even at high traffic volumes. It is assumed that better signing and marking might lead to a more balanced use of the entrance lanes, which could lead to higher capacity.

1. INTRODUCTION

Denmark like many other European countries has used roundabouts for decades. While roundabouts earlier mainly were built as 1-lane roundabouts, the number of 2-lane roundabouts has increased significantly over the last 10 years in Denmark. Due to increasing traffic flows, 1-lane roundabout are now being extended to 2-lane roundabouts and new roundabouts in rural areas are often constructed as 2-lane roundabouts.

The increased used of 2-lane roundabouts have lead to greater demand for knowledge concerning safety, capacity and traffic operation of 2-lane roundabouts. Several studies have been conducted over the years regarding these issues and this paper will try to summarise some of the findings regarding traffic operation and capacity of the entry lanes at 2-lane roundabouts.

2. GEOMETRIC DESIGN

2-lane roundabouts are in most cases situated in rural areas. Under normal conditions no facilities for cyclists or pedestrians are found. However, if separate cycle tracks are present, the cycle tracks will be recessed in a distance of 10-20m from the roundabout. At the crossing, cyclist will have to give way. Figure 1 shows a typical 2-lane roundabout with an outer diameter of 55 m. (diameter of central island is 40 m.). The roundabout has 2-way separate cycle tracks outside the roundabout.

FIGURE 1. Typical 2-lane roundabout with separate cycle tracks outside the roundabout.

Two different types of lane markings are used, see figure 2. Design 1 is the turbo-marking (figure 2, left) and Design 2 is the traditional roundabout marking (figure 2, right). The turbo-marking is characterized by a forced exit lane in the major travelling direction. The major road has two entry and two exit lanes, while the minor road only has 1 entry/exit lane. The width of the central island on the major arms is approx. 5 m. The majority of 2-lane roundabouts in Denmark use the Design 1 marking.

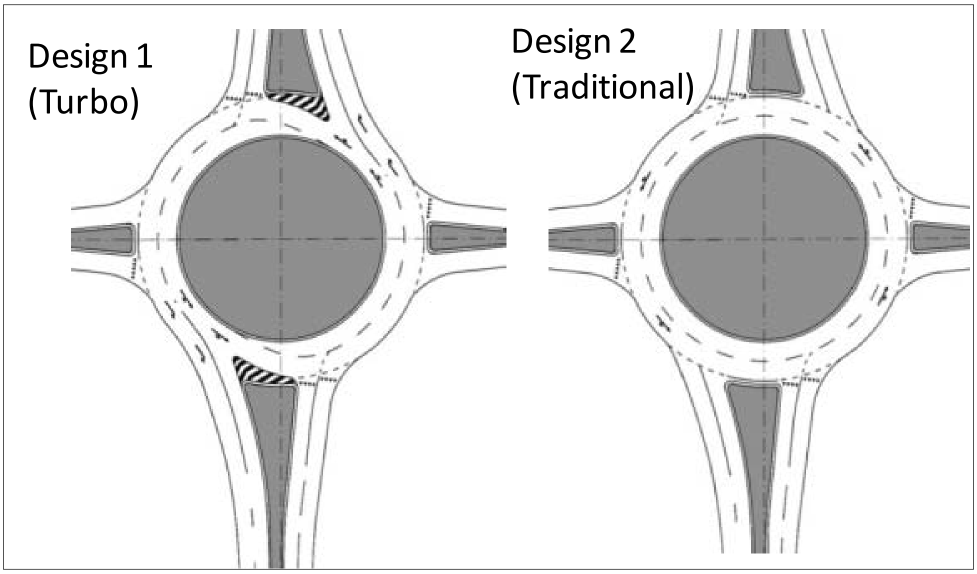

FIGURE 2. Example of two different markings designs.

2. CAPACITY OF ENTRY LANE

In Denmark, the capacity of roundabouts are usually based on gap acceptance theory by use of Tanners gap acceptance formula, which use the critical gap and follow up time in order to estimate the basic capacity of the entry lane, see formula below. The method is described in the Danish Capacity Manual [1].

$$G = \frac{q_c \, . \, e^{-\left(\frac{q_c \, . t_g}{3600}\right)}}{1 - e^{-\left(\frac{q_c \, . t_f}{3600}\right)}}$$

where

G	=	basic capacity of entry lane (pcu/h)
q_c	=	circulating traffic flow (pcu/h)
t_g	=	critical gap (sec)
t_f	=	follow up time (sec)

In order to study the capacity of 2-lane roundabouts, the driver behaviour in a total of five Danish roundabouts has been studied by use of video recordings. The study includes five Design 1 entries and two Design 2 entries.

2.1 Estimation of critical gap and follow up times

A study conducted in 2008 estimated critical gap and follow up times for 2-lane roundabouts [2]. A total of 256 follow up times for passenger cars has been measured; 202 follow up times for the right entry lane and 52 for the left entry lane. The average follow up time has been estimated to 2.7 sec for the right entry lane and 2.6 sec for the left entry lane. No significant difference could be found between Design 1 and Design 2 markings. The distribution of the observed follow up times is shown in figure 3.

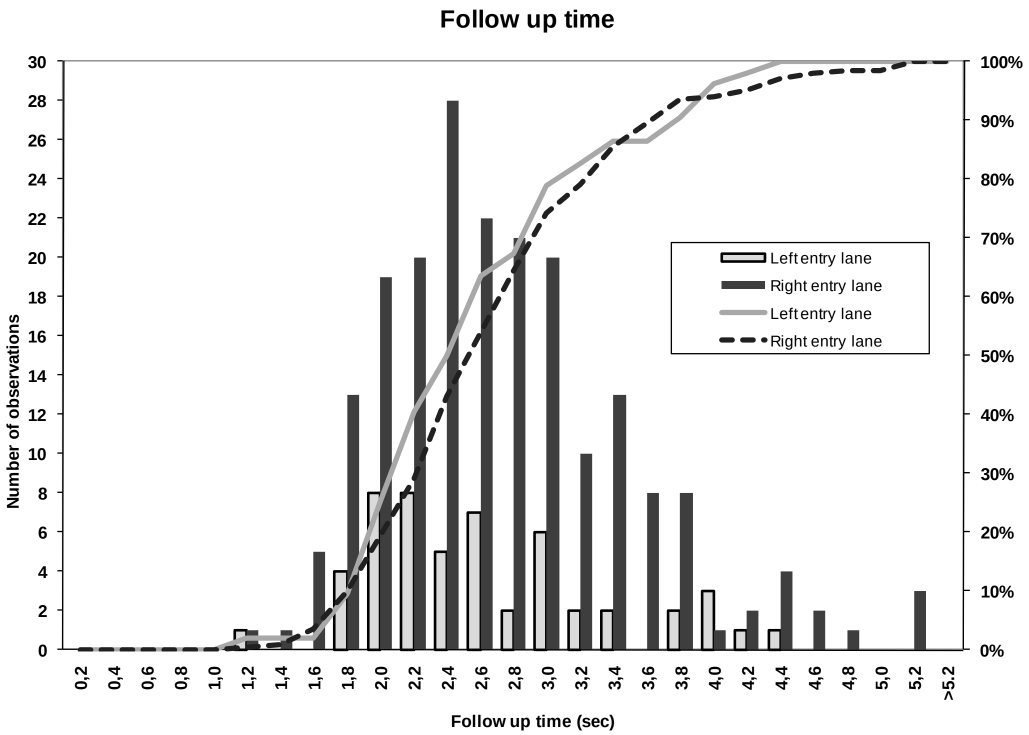

FIGURE 3. Observed follow up times for passenger cars in right and left entry lane.

A general observed phenomenon is that the follow up time depends on the car position in the queue at the entry lane. The average follow up time between car1 and car2, is 3.1 sec (see table 1) while shorter follow up times are observed between cars positioned further down the queue. This indicates, that when five cars enter the roundabout in the same gap, the average follow up time is considerable lower compared to a situation when only two cars enters the roundabout in the same gap. The gap acceptance theory does not take this into account and only use average follow up times.

TABLE 1. Observed follow up time by car position in queue

	Follow up time			
	Pas. Car 1 and 2	Pas. Car 2 and 3	Pas. Car 3 and 4	Pas. Car 4 and 5
Average follow up time	3.1 sec	2.5 sec	2.4 sec	2.2 sec

The critical gap has been estimated by use of Kärbers method and is based on 1810 observations of accepted/rejected gap and delayed lags. Table 2 shows the observed critical gap for passenger cars by marking design and entry lane. No difference in critical gap for right/left lane can be found for marking Design 1, and only 0.1 sec for marking Design 2. Marking Design 2 seems to have longer critical gaps compared to Design 1. The difference is not significant however, and a general critical gap of 4.0 sec is now recommended for 2-lane roundabouts (according to the Danish Capacity Manual [1])

TABLE 2. Observed critical gaps for 2-lane roundabouts (passenger cars)

Marking Design	Entry lane	No.: acc/reject gaps	Critical gap
Design 1	Right	266/358	3.9 sec
	Left	282/432	3.9 sec
Design 2	Right	64/112	4.2 sec
	Left	121/175	4.1 sec

Figure 4 shows the estimated entry capacity for 2-lane roundabouts (tf=2.7 sec, tc=4.0 sec) with one or two circulating lanes. It is assumed that 67% of the vehicles use the right entry lane and 33% use the left entry lane. In comparison, the capacity of 1-lane roundabouts is also shown (results from a previous study where tf=3.0 sec, tc=4.7 sec).

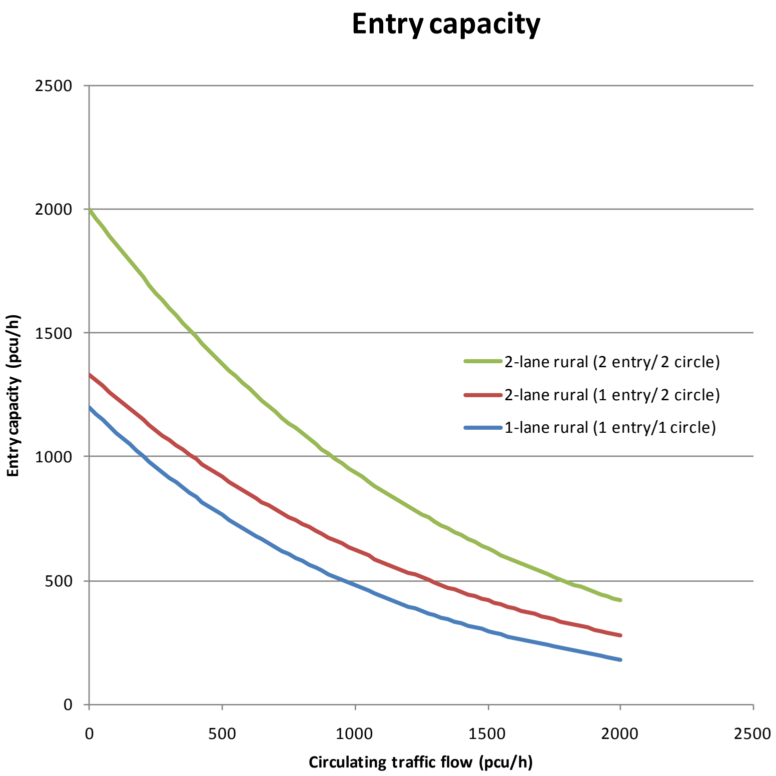

FIGURE 4. Entry capacity at 1- and 2-lane roundabouts

2.2 Passenger car units (pcu) for heavy vehicles in 2-lane roundabouts.

The normal procedure for capacity estimation is to convert all traffic flows into passenger car units (pcu) in order to take the influence of heavy vehicles into account. The pcu-values have been studied recently [3] based on driving behaviour for different categorised of heavy vehicles in 2-lane roundabouts with lane entries on level.

Follow up time and critical gap have been measured for two heavy vehicle categories: truck/bus (length 8-13m) and semitrailer/truck with trailer (length 13-22m).

The measured follow up times for heavy vehicles are shown in table 3. As mentioned earlier, the follow up time for passenger cars were measured to 2.6 sec giving 1.7-2.4 higher follow up times for heavy vehicles compared to passenger cars. It should be mentioned that the number of observed follow up times for heavy vehicles are limited and large variations are found in data.

TABLE 3. Observed follow up times for heavy vehicles.

Vehicle type	No.: (observations)	Follow up time		
		Average	15%-fraktile	85%-fraktile
Truck/bus	63	4.3 sec	3.4 sec	5.4 sec
Semitrailer/truck w. trailer	74	6.1 sec	4.6 sec	7.7 sec

Table 4 shows the critical gap for the different vehicle categories when entering the roundabout. Passenger car against passenger car has the lowest critical gap (4.0 sec), while semitrailer/truck w. trailer against passenger cars has the highest critical gap (5.9 sec). Passenger cars have larger critical gap towards circulating heavy vehicles compared to circulating passenger cars. The reason for this might be the fact that drivers are more careful/cautious when entering the roundabout in front of a heavy vehicle. In general, the critical gap for heavy vehicles is 1.2-1.4 times longer compared to passenger cars.

TABLE 4. Estimated critical gap for different vehicles categories.

Entering vehicle	Critical gap for entering vehicle against:	
	Passenger car	Truck/bus/semitrailer/truck w. trailer
Passenger car	4.0 sec	4.4 sec
Truck/bus	4.9 sec	5.3 sec
Semitrailer/truck w. trailer	5.9 sec	5.3 sec

Based on the observed follow up times and critical gaps for heavy vehicles, the pcu-value has been estimated, see table 5. The estimation is based on entering traffic flow with 100% passenger cars compared to entering traffic flow consisting of 100% heavy vehicles using the relevant critical gap and follow up times. The large spread in pcu values for entering semitrailer/truck with trailer depends on the actual traffic situation. In situations with high circulating traffic flows, the pcu-value would be approx. 3.0. With low circulating traffic flow, the pcu-value would be somewhat smaller. An average pcu-value for the entering flow is shown in () in table 5. The pcu-values for the circulating traffic flow are estimated on headways for heavy vehicles compared to headways for passenger cars in the circulating traffic flow.

TABLE 5. Estimated pcu-values for heavy vehicles.

Vehicle type	PCU-values	
	Entering flow	Circulating flow
Truck/bus	1.6-1.8 (1.7)	1.5
Semitrailer/truck w. trailer	2.3-3.0 (2.5)	1.9

3. EMPIRICAL DATA

In addition to the theoretical follow up times and critical gaps, empirical data on the traffic operation have been collected in a few selected roundabouts. The empirical data has been used to verify the gap acceptance model and to study the influence of exiting traffic on capacity. The empirical data are collected in periods with permanent queue in the entry lane. During these short periods (approx. 1 min in average) the number of entering vehicles, the number of circulating vehicles (in front of the entrance lane) and the number of exiting vehicles in the adjacent arm has been observed, see figure 5.

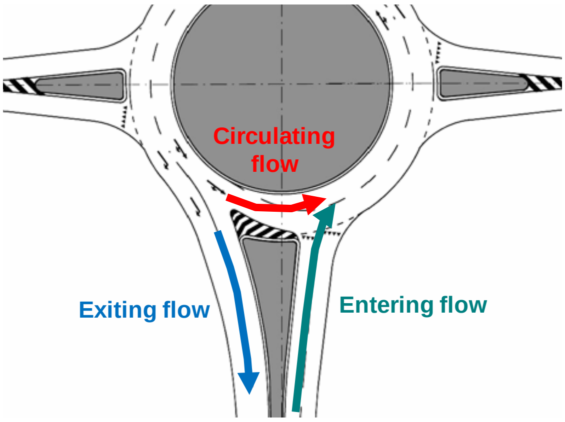

FIGURE 5. Observed traffic volumes.

For each time period, the observed traffic volumes have been converted to pcu-values covering 15 min intervals. A total of 336 observations are registered for marking Design 1 and 148 observations for marking Design 2. In the following, only Design 1 will be presented.

Figure 6 shows the empirical data for traffic operation in right lane – Design 1 roundabouts. Each dot represents observed traffic volumes for a single time period (approx 1 min. in average) converted to pcu-values pr 15 min. Different colours represent different roundabouts. First of all, the figure shows a non-linear relationship. The best fit is described by an exponential function. The thick blue line is the gap-acceptance model with tg=4.0 sec and tf=2.6 sec. The model seems to underestimate the capacity at low circulating traffic flows and overestimate the capacity at high circulating traffic flows.

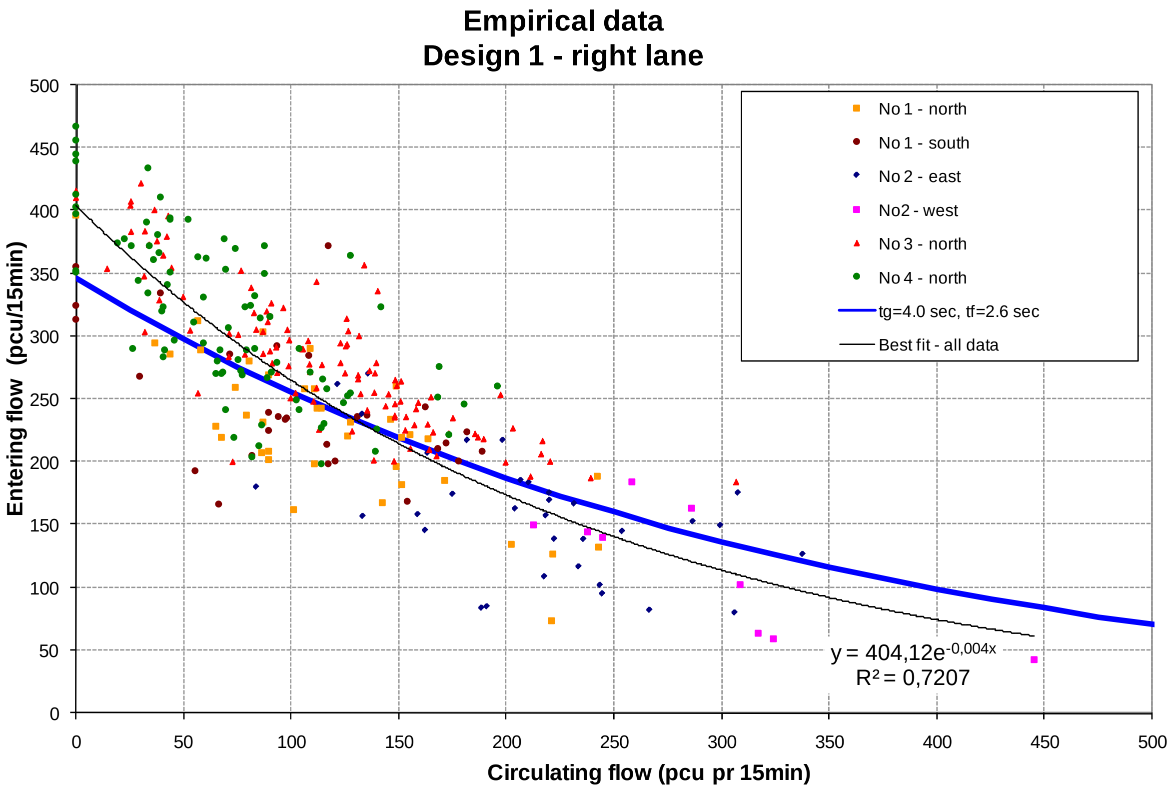

FIGURE 6. Empirical data from right lane in type 1 design roundabouts.

Other theoretical capacity models have been tested on the empirical data set [5]. If tg=4.0 sec and tf=2.6 sec in the tested models, very little difference in “goodnees of fit” was observed between the models. A simple linearly fit or a polynomial fit were just as good, or even better. A general problem for all the theoretical models is underestimation of capacity at low circulating traffic flows. This indicates that the follow up time (tf) might be too high. If tg=4.6 sec and tf=2.3 sec, better fit are obtained by most of the models.

3.1 Modified capacity model

Based on the empirical data, a modified theoretical model, that takes into account the variance in follow up times and the influence of exiting traffic from adjacent arm has been developed. As mentioned earlier, the observed average follow up time (tf) is 2.6 sec, but varies depending on the number vehicles entering the same gap. Low tf-values (approx. 2.0 sec) are found when more than 4 vehicles use the same gap and higher tf-values (>3 sec) are found when only 2 vehicles use the same gap.

It has also been observed that driver behaviour among entering vehicles are influenced by the amount of vehicles leaving the roundabout at the adjacent arm, producing lager follow up times and thereby lower capacity. The effect from exiting vehicles on capacity is shown in table 6. The table summarises the empirical data for entering vehicles depending on circulating flow and exiting flow. The table shows that entering traffic flow is reduced, not only when the circulating flow increases, but also when the exiting flow is increased. For example, when the exiting flow is increased from 0-50 to 100-150 pcu per 15 min, the entering flow is reduced by approx. 10%.

TABLE 6. Entering flow (pcu pr 15 min) by circulating and exiting flow – empirical data.

Circulating flow (pcu pr 15 min)	Exiting flow from adjacent arm (pcu pr 15 min)							
	0-50	50-100	100-150	150-200	200-250	250-300	300-350	>350
0-50	372	381	389	358	308	348		301
50-100	338	292	282	303	248	252	242	226
100-150	268	281	252	261	235	198		
150-200	238	192	217	195	170			
200-250	120	187	139	179	160			
250-300	94	148	137					
300-350	125	88						

In order to have a model that takes into account the variations in capacity due to exiting and circulating flows, the equation below have been developed. The formula estimates the follow up time (tf) as a function of circulating and exiting flow. Figure 7 shows the estimated entry capacity at different flow values by use of the formula when tg=4.0 sec in the gap acceptance formula. The effect form exiting flow on capacity is clearly shown.

$$t_f = 1.8 + (0.004 \cdot q_e) \cdot (1 - 0.0013 \cdot q_c) + 0.005 \cdot q_c$$

where
t_f = follow up time (sec)
q_c = circulating flow (pcu pr 15 min)
q_e = exiting flow (pcu pr 15 min)

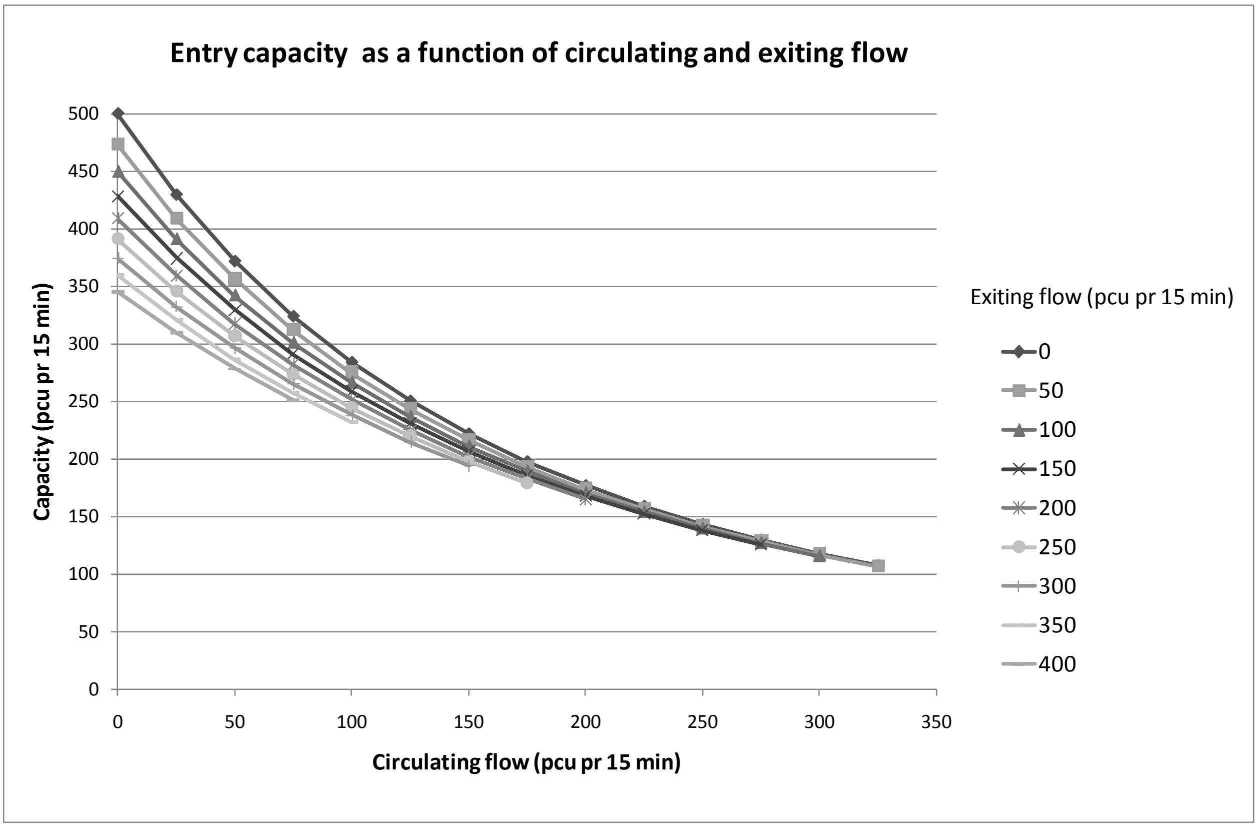

FIGURE 7. Capacity of entry lane at different circulating/exiting flow levels.

The modified capacity model seems to fit the empirical data better than other theoretical models. However, further studies are needed to verify this model before general use.

4. LANE USE

It is well known, that some drivers find it difficult to use 2-lane roundabouts. They feel uncomfortable and insecure, mainly because the drivers are uncertain when it comes to choosing the right lane in the roundabout. This is particular the case with driver that are unfamiliar the roundabout (not local traffic). From a level of service, capacity and road safety perspective, it is important that drivers use 2-lane roundabouts correctly. In a study from 2008 based on four different roundabouts [4], driver’s choice of lane at the entry, through the roundabout (circulating lanes) and at exit lane has been studied.

The four observed roundabouts had either a “lane use-sign” placed 100-150 m before the roundabout, showing the correct lane use to different destinations when driving through the roundabout, or signs placed on a portal at the entrance (above each entry lane), see figure 8 for examples.

It should be noted that the four analyzed roundabouts are very different in terms of geometry.

Results from the study shows that drivers mainly use the right entry lane, regardless that the left lane also could be used to their destination. In average, 50%-90% of the drivers choose the right entry lane. However, the numbers varies with regard to traffic density and unfortunately no significant difference in lane use could be related to present signing. It was found that the share of drivers choosing the left lane is increased up till approx. 30-40% at high traffic volumes. In the Danish Capacity manual, the recommended share of drivers using the right entry lane is 2/3, and 1/3 for the left entry lane.

The results also show, that approx. 3-5% of the drivers that wish to make a left turn in the roundabout, chooses the right entry lane, which forces the driver to change lane inside the roundabout. The observations also showed a number of “very late” lane changes when drivers want to leave the roundabout.

Better signing and marking might help drivers to choose the correct lane in the roundabout and also to use both entry lanes and thereby increase the capacity.

FIGURE 7. Two different signing concepts at the entrance to the 2-lane roundabout. Left – “lane use-sign” and right – use of portals.

5. CONCLUSION

The number of roundabouts has increased significantly over the last 10-20 years, mainly due to their good safety performance. The use of 2-lane roundabouts on major rural roads with large traffic volumes is now quite common which calls for updated knowledge concerning traffic operation at 2-lane roundabouts.

This paper summarises the most important findings regarding traffic operation at 2-lane roundabouts in rural areas in Denmark.

The capacity of the entrance lane is traditionally based on gap acceptance theory, and updated values for critical gap and follows up time to be used in the Danish Capacity Manual (DCM), has been estimated for 2-lane roundabouts. The results are based on observations from a limited number of roundabouts. Two different roundabout designs has been studied (turbo and traditional) but only minor differences in critical gap and follow up time were found.

The critical gap for entering passenger cars against circulating passenger cars has been found to be 4.0 sec. and the follow up time was found to be 2.7 sec.

Critical gap for entering heavy vehicles against circulating passenger cars was found to be 4.9 sec and 5.9 sec for truck/bus and semitrailer/truck w. trailer respectively. The corresponding follow up times were 4.3 sec and 6.1 sec for the two vehicle categories. Based on these results, new pcu-values for heavy vehicles in roundabouts have been estimated. The pcu-value for entering truck/bus was in average 1.7 and in average 2.5 for semitrailer/truck w. trailer. These values are somewhat higher than stated in the current DCM.

Empirical data has been collected to verify the gap acceptance models. The study shows that the gap acceptance model fits the empirical data quite well, but the models have some limitations that need to be studied in further details.

Some drivers find it difficult to drive through 2-lane roundabouts, particular choosing the correct lane for their destination. Studies show that the majority of entering vehicles choose the right lane regardless their destination. Better signing and marking strategies should be considered to help drivers in 2-lane roundabouts and to improve traffic operation in general.

6. REFERENCES

1 Danish Capacity Manual (*Kapacitet og Serviceniveau- Vejregelforslag)*, 2008

2 Capacity of 2-lane roundabout (*2-sporede rundkørlser – Vurdering af kapacitet i tilfartssporet*). Belinda la Cour Lund, Poul Greibe, Trafitec, 2007

3 Estimation of pcu-values for heavy vehicles in 2-lane roundabouts (*Vurdering af personbilækvivalenter i 2-sporede rundkørlser)*, Poul Greibe, Belinda la Cour Lund, Trafitec, 2009

4 Lane use in 2-lane roundabouts (*Trafikantadfærd i 2-sporede rundkørsler – sporbenyttelse og konfliktende adfærd*), Belinda la Cour Lund, Poul Greibe, Trafitec, 2008

5 Examination of capacity models (*En begrænset undersøgelse af kapacitetsmodeller for vigepligt*), Workingpaper – not published. Henning Sørensen, The Danish Road Directorate, 2009