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Roundabout capacity in South Africa

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Gap acceptance and follow-up times are critical parameters in determining the capacity of roundabouts. A major national research project was undertaken by the South African National Roads Agency Ltd (SANRAL) into the design, capacity and operations of roundabouts. This paper provides an overview of the findings and presents the models that were developed to inform the capacity analysis of roundabouts in South Africa.

Three important aspects of capacity are addressed, namely i) critical gap acceptance, ii) saturation follow-up headways, and ii) capacity, models. The research was based on data collected using drone video recordings at a total of about 90 roundabouts across the country.

Keywords: Roundabout capacity gap acceptance

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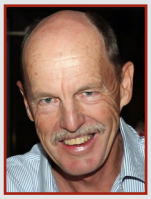

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INTRODUCTION

SANRAL established a research panel and programme covering a range of focus areas including future transportation needs, legislation, economics, environment, communications, transportation planning, road safety, traffic, pavements, geotechnical, structures and drainage.

One of the research projects focussed on the design and operations of roundabouts. The purpose of this paper is to present some of the findings of this research and specifically the following capacity parameters:

- **Critical gaps of local drivers:** These are the minimum gaps between vehicles that drivers would typically accept, measured either in seconds (time-based gaps) or metres (distance-based gaps).
- **Saturation follow-up headway:** This is the average headway (measured in seconds) between successive vehicles entering the roundabout when a queue of vehicles departs from the yield line.
- **Capacity models for roundabouts:** The development of local analytical models to determine the capacity of the different approach lanes to roundabouts.

STUDY APPROACH

The study was based on data from drone video recordings at various roundabouts throughout South Africa. Geometric data was obtained from scaled aerial photographs while the traffic data was extracted using video analysis software from a cloud-based service provider (DataFromSky).

The video analytics software captures the following data for each vehicle in each frame of a video:

- The position (x-y coordinates) of the vehicle
- Vehicle speeds, tangential and lateral accelerations.
- Vehicle classification (light and heavy vehicles).

All the capacity parameters measured during this study were derived from the above data. For example, gaps accepted and rejected by drivers were determined using the positions of conflicting vehicles, distances to the conflict points, and the speeds of the vehicles. Headways were determined using the times at which video frames were recorded.

It was also necessary to determine the vehicle positions relative to the geometry of the roundabouts. Since vehicles do not always follow marked lanes, an approach was adopted in which typical vehicle paths were determined from the trajectory plots of all vehicles. A computer algorithm was developed to "snap" the individual vehicle paths to the nearest typical vehicle path. These snapped positions along the typical paths were then used to determine the positions of the vehicle relative to the geometry of the roundabout.

An extensive set of software was developed for the analysis of data collected using the video recordings. This software

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allows linking and relating the vehicle movement data to the geometric elements and includes various algorithms for the analysis of the collected data. Details of the software are provided in the project research reports.

ROUNDABOUTS INCLUDED IN THE STUDY

During the project, more than 4 800 roundabouts were identified country wide. These range from mini circles in residential areas to large roundabouts on national roads. In comparison, there are nearly 15 000 signalised intersections across the country.

A total of about 120 roundabouts were selected from various locations across the country for the study. From these, about 90 were suitable for the capacity investigation. These varied in size from 25 m to 95 m inscribed (outer) diameter with three to six approaches.

Although a substantial number of roundabouts were included in the study, there were some roundabout configurations for which there were insufficient data for deriving gap acceptance parameters. Only the following roundabout configurations were investigated:

- Single-lane approaches to single-circulating lane roundabouts
- Double-lane approaches to double-circulating lane roundabouts.

It is proposed that the models developed for the above configurations should also be used for the following configurations:

- Single-lane approaches to double-circulating lane roundabouts
- Double-lane approaches to single-circulating lane roundabouts.

GAP ACCEPTANCE MODELS

There are two types of models used for estimating the capacity of priority-controlled intersections such as roundabouts (Rodegerdts *et al* 2007), namely gap acceptance models and empirical regression models.

Gap acceptance models are based on the acceptance and rejection of gaps in the conflicting traffic stream. Empirical regression models are based on a regression analysis of the capacity flow as a function of the conflicting flow.

The following gap acceptance models are discussed in this section:

- Tanner (1962, 1967)
- Akçelik *et al* (1999)
- Wu (2001).

The following notation is used in the discussion of these models:

c = Capacity flow per approach lane (vehicles per second)
q = Conflicting flow rate (vehicles per second)
q_i = Conflicting flow rate in stream i
q_p = Conflicting platoon flow rate
p_f = Proportion followers
p_{fi} = Proportion followers in stream i
n_f = Average platoon length (vehicles)
n = Number of conflicting streams
t_c = Average critical gap (seconds)
h_f = Average following headway in the conflicting flow (seconds)
h_s = Average saturation follow-up headway (seconds)

Tanner (1962) formula

The most well-known capacity formula was developed by Tanner in 1962 and extended in 1967. This formula applies to priority-controlled intersections and can therefore also be used for roundabouts.

The original Tanner (1962) formula only made provision for a single conflicting stream with near-random arrivals. The conflicting headways were assumed to follow an exponential distribution with provision for a minimum headway (h_f) in the stream. The formula is as follows:

$$c = \frac{q \cdot (1 - h_f \cdot q)}{1 - e^{h_s \cdot q}} \cdot e^{-(t_c - h_f) \cdot q}$$

Extended Tanner (1967) formula

The formula was extended by Tanner (1967) for use with multiple conflicting streams and allowing for platooning of the conflicting traffic. The capacity of a priority-controlled intersection can be significantly affected by these two factors. The extended formula effectively replaced the opposing flow rate with a "platoon flow rate":

$$c = \frac{q_p \cdot \Pi(1 - h_f \cdot q_i)}{1 - e^{-h_s \cdot q_p}} \cdot e^{-(t_c - h_f) \cdot q_p}$$

The formula for the total platoon flow rate is the sum of the platoon flow rates of individual conflicting traffic streams, as follows:

$$q_p = \sum \frac{(1 - p_{fi}) \cdot q_i}{1 - h_f \cdot q_i}$$

Tanner formula (1967) applied to double-lane roundabouts

The Tanner (1967) formula requires the conflicting flow rate and proportion of followers for each conflicting stream. In practice, this data is not generally available for double-lane roundabouts. The assumption can, however, be made that the conflicting flow is equally split between the two conflicting streams and the proportion of followers is the same for both streams. Based on these assumptions, the formula can be simplified as:

$$c = \frac{q_p \cdot (1 - h_f \cdot q/n)^n}{1 - e^{-h_s \cdot q_p}} \cdot e^{-(t_c - h_f) \cdot q_p}$$

with the platoon flow rate given by:

$$q_p = \frac{(1 - p_f) \cdot q}{1 - h_f \cdot q/n}$$

Akçelik *et al* (1999) formula

A capacity model was developed by Akçelik *et al* (1999) and is used in the aaSIDRA software package (Akçelik & Besley 2004). The formula is as follows:

$$c = \frac{1}{h_s} \cdot \left[1 - h_{fn} \cdot q + \frac{h_s}{2} \cdot (1 - p_f) \cdot q\right] \cdot e^{-(t_c - h_{fn}) \cdot q_p}$$

The formula for the platooned flow rate q_p is as for the extended Tanner (1967) formula. The following headway h_{fn} is taken as 2 seconds for a single-lane and 1.2 seconds for a double-lane roundabout.

Wu (2001) formula

The following formula developed by Wu (2001) is used in the German Capacity Manual (FGSC 2001):

$$c = \frac{1}{h_s} \cdot (1 - h_f \cdot q/n)^n \cdot e^{-(t_c - h_s/2 - h_f) \cdot q_p}$$

The formula for the platooned flow rate q_p is as for the extended Tanner (1967) formula.

COMPARISON OF GAP ACCEPTANCE MODELS

The different gap acceptance capacity models were compared and evaluated using a microscopic simulation program specifically developed for this purpose. This program is based on the same assumptions used by Tanner (1967) in the development of the extended formula. These assumptions are:

- Lengths of vehicles are ignored and vertical queuing is assumed.
- Conflicting vehicle arrivals follow the travelling queue distribution with a

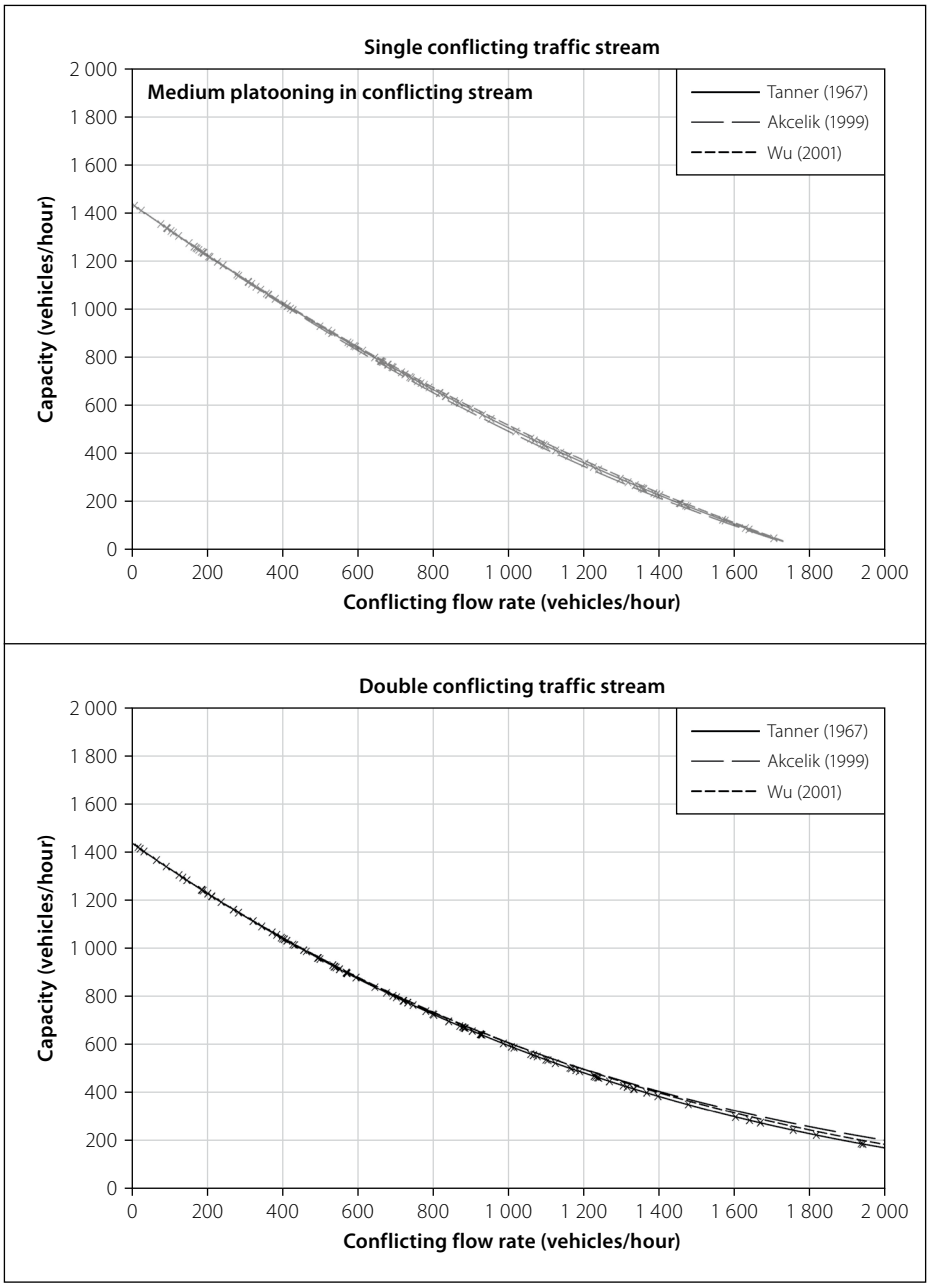

Figure 1 Comparison of capacity models – medium platooning of circulating stream

constant following headway and an exponentially distributed inter-platoon headway (more information on this distribution is given later in this paper).

- A continuous queue of vehicles was generated on the entry to the roundabout.
- The decision to accept or reject a gap was made immediately when the vehicle arrived at the yield line. If the gap is accepted, the vehicle departs immediately. If not, the vehicle waits for the next gap, and the process is repeated until a gap is accepted.
- During a gap, vehicles depart at a constant saturation follow-up headway.

Simulations were undertaken for different levels of platooning in the conflicting stream. An example of a comparison for medium levels of platooning is shown in Figure 1. The comparison showed a remarkable correlation between the simulation and the different capacity models. The Akçelik *et al* (1999) formula deviated slightly for high levels of platooning on double-lane roundabouts, but such levels of platooning are not typically found in roundabouts. Based on this comparison, it can be concluded that any of the formulae can be used for the capacity analysis of roundabouts. The Tanner (1967) formula, however, is the most well known and is therefore recommended for local application.

AVERAGE CONFLICTING FLOW FOLLOWING HEADWAYS

The gap acceptance capacity models make provision for the size of the following headway in the conflicting traffic stream. The following headway was determined as the average of all headways shorter than a threshold value of 3 seconds, and an average of 2 seconds was obtained.

It was found that following headways are slightly shorter at larger roundabouts compared to smaller roundabouts. However, including roundabout size to determine the average headway introduces unnecessary complexity. It is therefore proposed that an average following headway of 2 seconds be used for all roundabouts. This implies that the flow rate on the circulating roadway of a roundabout cannot exceed a maximum of 1 800 vehicles per hour per lane.

PLATOONED CONFLICTING FLOWS

All three gap-acceptance models provide for platooning in the conflicting flow. Studies have shown that such platooning can have a significant impact on the capacity of priority-controlled intersections (Van As & Joubert 2002).

Many traffic models assume random arrivals. The models often also assume that vehicles can be treated as single points and that vehicle length and follower headways (in a platoon or queue) can be ignored (taken as zero). The effect of this assumption is that a queue of vehicles is effectively treated as a vertical queue.

In reality, vehicles do have finite lengths resulting in some minimum inter-arrival headway. There is also often a lack of passing opportunities which results in the platooning of vehicles. The usual assumption is that such platoons may arrive randomly, but the headways within a platoon no longer follow the exponential distribution. The headways between platoons, however, can be assumed to follow the exponential distribution (Van As & Joubert 2002).

This assumption may not be true in signalised networks where platoons are formed by queueing at signals. The platoons then arrive more regularly, and the assumption of random arrivals is no longer valid.

The inter-arrival headways in a traffic stream consisting of platoons with exponentially distributed inter-platoon headways are usually modelled by a "travelling queue" (Van As & Joubert 2002). This distribution was first used by Tanner (1962, 1967) for the analysis of priority-controlled intersections. It has subsequently been described by Cowan (1975) and has become known as the Cowan M3 model (Akçelik & Chung 1994).

The above model is used to convert a traffic stream consisting of random platoons into an equivalent stream consisting

of random single points. The individual platoons are then handled as points (vertical queues) in the same way individual vehicles are treated as points. The traffic flow rate is then converted to an equivalent platoon flow rate using the following formula:

$$q_p = \frac{q/n_f}{1 - h_f \cdot q/n}$$

The division by the average platoon length n_f converts the vehicle flow rate to platoon flow rate. The division by the $1 - h_f \cdot q/n$ term removes the follower headways from the traffic stream, converting the stream to an equivalent point process.

The average platoon length is related to the proportion of followers by means of the following formula:

$$n_f = \frac{1}{1 - p_f}$$

The platoon flow rate can then be written as a function of the proportion of followers in the following form, as used in all three capacity models and as provided for in the extended Tanner (1967) formula:

$$q_p = \frac{(1 - p_f) \cdot q}{1 - h_f \cdot q/n}$$

The introduction of platooning in capacity analysis introduces various complications in the analysis of priority-controlled intersections and roundabouts. This issue was therefore investigated to determine the extent to which such platooning occurs at roundabouts.

The proportion of followers in the conflicting or circulating traffic stream was determined at various roundabouts. The proportions are shown in Figure 2 as a function of the traffic flow rate in the stream. Also shown in the figure is a relationship that was fitted by means of regression analysis using the following function:

$$p_f = (h_f \cdot q/n)^{f_p}$$

In which:

p_f = Proportion followers
q = Traffic flow rate (vehicles/second/lane)
h_f = Average follower headway (2 seconds)
f_p = Platooning factor obtained from regression
n = Number of lanes

It is of particular interest and importance to note that the proportion followers is nearly linearly related to the flow by means of the following formula ($f_p \approx 1$):

$$p_f \approx h_f \cdot \frac{q}{n}$$

Replacing this term in the formula for determining the platoon flow rate results in the following:

$$q_p \cong q$$

This implies that a stream of platooned conflicting or circulating traffic at a roundabout is nearly equivalent to a stream of traffic with no platooning and that such platooning does not have to be considered in the determination of the capacity of a roundabout. This is a significant simplification of the analysis of roundabouts.

CRITICAL GAP OBSERVATIONS

Critical gaps were derived from measured accepted and rejected gaps. These gaps were measured when a driver had to decide to either accept or reject a gap. The time gaps were determined from the distance at which the conflicting vehicle was from the conflict point and the speed of the conflicting vehicle.

Determination of the critical gap is a complex problem since several short gaps may be rejected before accepting a gap which may be shorter than a previously rejected one. Also, the observed rejected gaps are not necessarily the maximum that will be rejected by the driver, nor is the accepted gap necessarily the minimum.

The critical gaps are derived using only the largest gap that was rejected by a driver as well as the gap that was accepted. Smaller rejected gaps do not provide any additional information of the gap acceptance behaviour of drivers.

The so-called "lag" acceptance in which drivers accepted the first available gap was not considered since no information is available on the gaps that were rejected by these drivers.

Gaps are the headways between consecutive conflicting vehicles when crossing

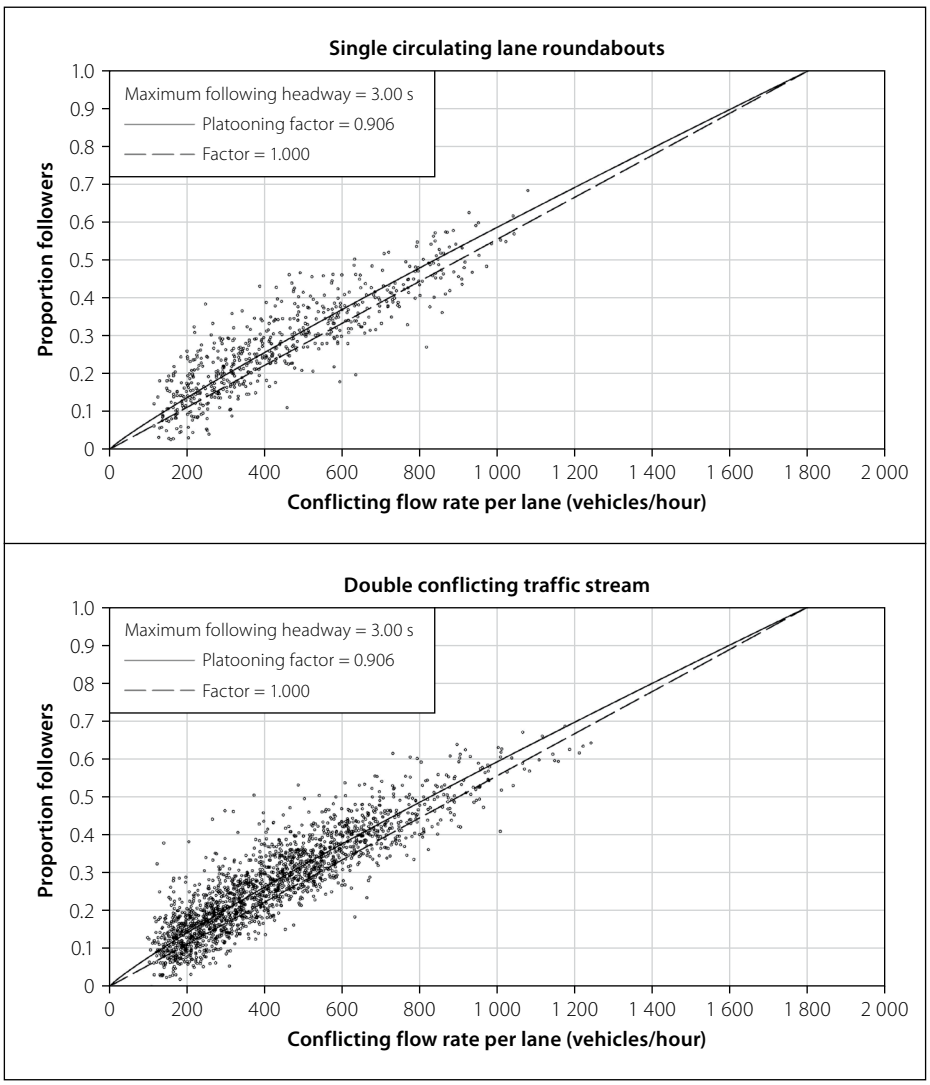

Figure 2 Proportion of followers in the conflicting stream (2.7 second follower threshold)

the conflict point. These gaps, however, are not a true reflection of the actual gap sizes that were rejected and accepted. A conflicting vehicle may either accelerate or decelerate after the entering driver decides to accept or reject a gap which would result in the actual time gap being shorter or longer than the gap evaluated by the driver. A method was therefore used to determine the gap times based on the position and speed of the conflicting vehicle at the time the driver had to decide on whether to accept or reject a gap (and not the time at which the conflicting vehicle passed the point of conflict).

Fitting the critical gap distribution

Various methods for estimating the average critical gap are available. The method used in this study is based on the maximum likelihood method (Miller 1971; Troutbeck 2014). The method assumes that critical gaps follow a lognormal distribution and then uses maximum likelihood methods to determine the average (and standard deviation) of the distribution.

The likelihood that a sample of n drivers having rejected a largest gap of r_i and accepted a gap of a_i is the following:

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

In which:

r_i = Largest gap rejected by driver i
a_i = Gap accepted by the driver
n = Sample size
F() = Critical gap distribution

Calculations can be simplified if the logarithm of the above likelihood function is used:

$$\sum_{i=1}^{n} \mathrm{Ln}(F(a_i) - F(r_i))$$

The parameters of the critical gap distribution are determined as those that maximise the above log-likelihood. Iterative methods are available for this purpose. However, in this study, use was made of the "golden section" method (Press *et al* 1992) to numerically search the parameters that would maximise the log-likelihood function.

The method of measuring gap acceptance allowed the measurement of both time (in seconds) and distance (in metres) gaps. For both types of gaps, it was assumed that critical gaps follow a lognormal distribution. Examples of the fitted lognormal distributions are provided in Figure 3.

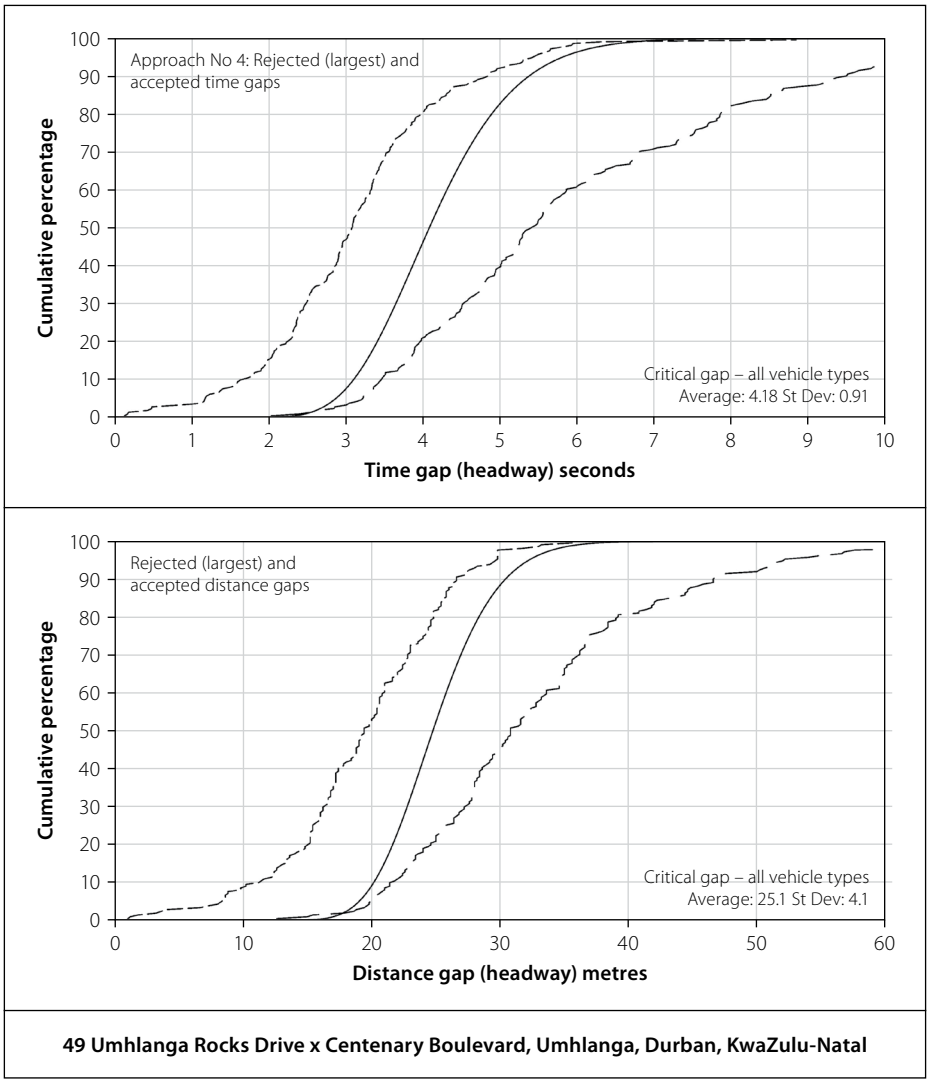

Figure 3 Example of log-normal critical gap distributions for time- and distance-based gaps

The figure shows the distributions of the largest rejected gaps and the accepted gaps (rejected gaps are typically always smaller than accepted gaps). The figure also shows the averages and the standard deviations of the fitted distributions (as obtained for the fitted lognormal distribution).

Concerns with the maximum likelihood methodology

There are concerns with the use of the maximum likelihood method for determining critical gaps. The main concern is illustrated in Figure 3, which shows that there is a considerable separation between the distributions of the rejected and accepted gaps.

The method effectively attempts to determine the critical gaps from measurements that are typically smaller and larger than the actual critical gaps. These two values are often relatively far apart for most observations, which has an impact on the accuracy of the method.

A second concern is that the method depends strongly on the assumption that the critical gaps follow a lognormal distribution. No data is available on whether the critical gaps in fact follow such a distribution.

An alternative method for deriving the critical gaps was therefore used for determining the critical gap. This method involved the use of regression analysis to fit the Tanner (1967) capacity formula to actual observed capacities. The critical gap in the formula is then used as the regression parameter in the analysis. This alternative method should predict capacities that are much closer to the actual observed capacities (but not necessarily actual critical gaps).

Factors affecting critical gaps

In a study of critical gaps in Australia (Troutbeck 1989), it was found that the critical gap was related to various factors such as the size of the roundabout and the circulating traffic flow (or congestion) at a roundabout.

While several roundabouts were investigated during this study, the video recordings of the different roundabouts were of limited duration. There was sufficient data at most of the roundabouts to determine an average critical gap for each roundabout, but the sample sizes were usually too small to investigate the possible correlation between the critical gaps and the traffic volumes. Congestion at roundabouts may affect the critical gaps, but traffic volumes at most of the roundabouts investigated during the project were relatively low.

It was, however, possible to investigate the impact of the size of a roundabout on critical graphs. It was found that the critical gap is not significantly related to the radius and that a constant critical gap can be used for all roundabout sizes (within the range of sizes investigated in the study).

The observations also showed that there is not a significant difference between the critical gaps for light and heavy vehicles and that it is therefore not necessary to differentiate between vehicle types. Normally it would be expected that the critical gaps of heavy vehicles would be longer than those of light vehicles. The reason why this has not been found during the study is probably the lower operating speeds that make it safer to accept shorter gaps and which allow forcing into a shorter gap, causing the conflicting vehicle to slow down.

Distance-based critical gaps are generally not used in the capacity analysis of roundabouts or other intersections, but it is of interest to investigate these gaps to determine whether they should not be considered in the analysis. The results of the study, however, did show that drivers do not only base their decisions on distance but also take the speed of conflicting vehicles into account.

Measured critical gaps

Critical gaps were determined by means of the maximum likelihood and regression methods. For double-lane roundabouts, the critical gaps based on the two methods are close. For single-lane roundabouts, there was a slight difference in the results.

Table 1 Recommend critical gaps

Circulating lanes	Approach lane	Critical gap (s)
1	Single	4.50
2(*)	Single and left lane	3.80
2(*)	Right lane	4.10

(*) Use parameters also for roundabouts with two approach lanes and one circulating lane

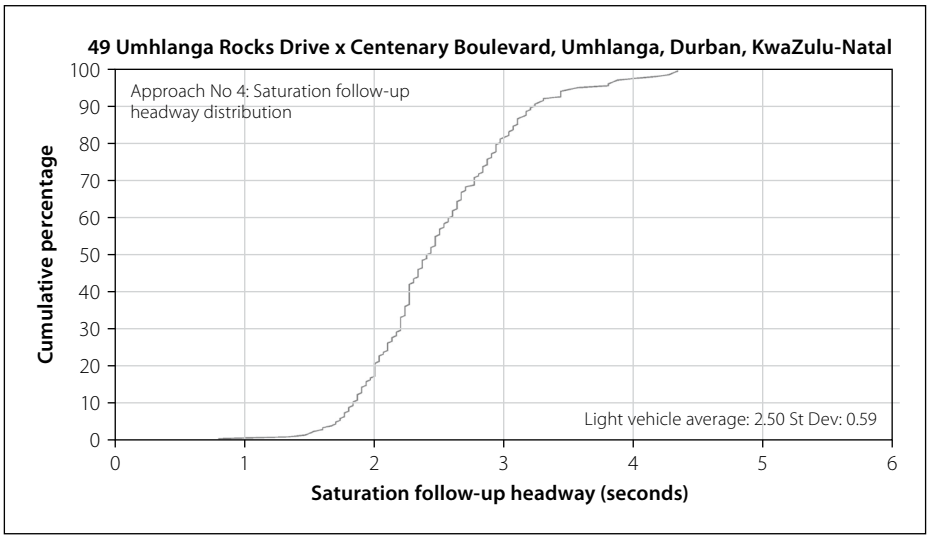

Figure 4 Example of a saturation follow-up headway distribution at a roundabout

The recommended critical gaps were therefore selected as an intermediate value between the gap acceptance observations and the capacity observations. The critical gaps are provided in Table 1 for use in South Africa.

SATURATION FOLLOW-UP HEADWAYS

A key parameter in determining the capacity of a roundabout is the saturation follow-up headway. This headway is defined as the average headway in a continuous stream of vehicles that enters a roundabout while there is no conflicting traffic. These headways were only determined for vehicles that followed the first vehicle accepting a gap and that formed part of a departing queue of vehicles from the approach.

An example of an observed distribution of saturation follow-up headways is provided in Figure 4. The distribution shows that the saturation follow-up headways can typically vary between 1.5 and 3.5 seconds.

An investigation was undertaken to determine whether the saturation follow-up headway was affected by the roundabout size. No such relationship was found, which means that a constant follow-up headway can be used for all roundabout sizes (within the range investigated in this study).

It was also found that the difference between the saturation follow-up headways for light and heavy vehicles is insignificant. Therefore, it is not necessary to differentiate between vehicle types when analysing roundabout capacities. This is again a finding that is unexpected, but it appears as if drivers of heavy vehicles might be more aggressive than those of light vehicles.

There was also little variation in the saturation follow-up headways at all the

Table 2 Highway Capacity Manual capacity parameters (TRB 2016)

Number of circulating lanes	Approach lane	Capacity at zero conflicting flow	Follow-up headway h_s	Parameter f Veh/hr units	Parameter f Veh/s units
1	Single	1380	2.61	0.00102	3.672
2	Single	1420	2.54	0.00085	3.060
2	Left lane	1420	2.54	0.00085	3.060
2	Right lane	1350	2.67	0.00092	3.312

Table 3 Parameters of the fitted exponential regression model

Number of circulating lanes	Approach lane	Capacity at zero conflicting flow	Follow-up headway h_s	Parameter Veh/s units
1	Single	1440	2.50	4.379
2(*)	Single/left lane	1440	2.50	2.949
2(*)	Right lane	1440	2.50	3.469

(*) Use parameters also for roundabouts with two approach lanes and one circulating lane

roundabouts that were investigated. A constant saturation follow-up headway of 2.5 seconds is therefore proposed for all roundabouts. This implies that the maximum capacity of a single-entry lane to a roundabout is 1 440 vehicles per hour per lane (3600/2.5).

REGRESSION CAPACITY MODELS

Empirical regression models are based on regression analysis of capacity flow as a function of conflicting flow. The capacity flow rate was measured from the video recordings as the number of vehicles that depart as part of a queue of vehicles departing from an approach lane of a roundabout divided by the time that it takes for the queue to depart.

The following two empirical regression models are discussed in this section:

a. Highway Capacity Manual exponential regression model (TRB 2016)
b. Linear-exponential regression model developed during this study.

The following notation is used in the discussion of these models:

- c = Capacity flow per approach lane (vehicles per hour)
- q = Total conflicting flow rate (vehicles per hour)
- h_f = Following headway in the conflicting flow (seconds)
- n = Number of conflicting streams
- h_s = Saturation follow-up headway (seconds)
- f = Regression parameter

Exponential regression model

The Highway Capacity Manual (TRB 2016) uses an exponential regression method to estimate the capacity of a roundabout:

$$c = \frac{3600}{h_s} \cdot e^{-f \cdot q/3600}$$

The parameters of the HCM model are provided in Table 2. Two values are provided for the parameter f. The first is applicable when the conflicting rate is

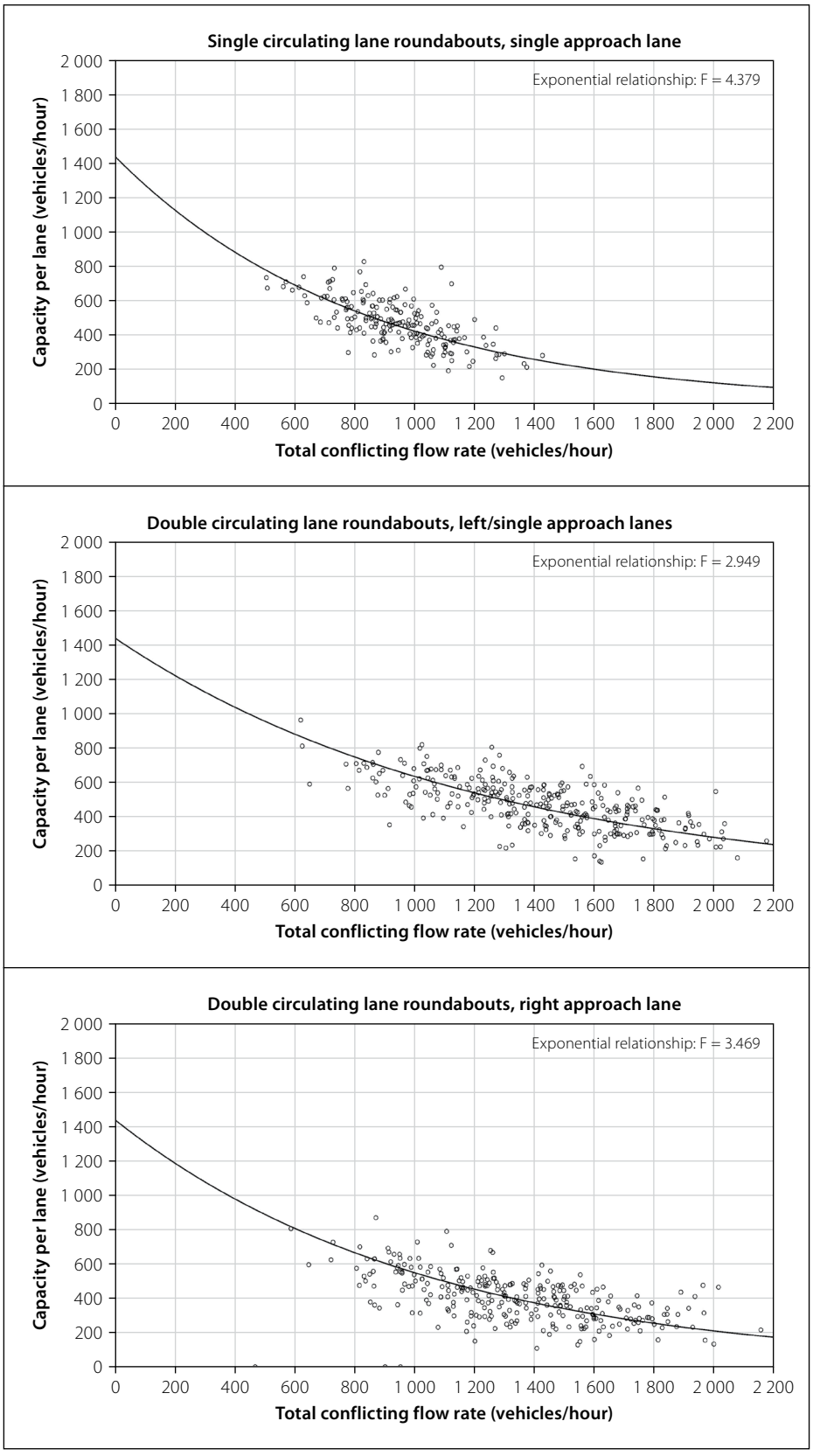

Figure 5 Capacity by lane types based on exponential models

Table 4 Parameters of the linear-exponential regression model

Number of circulating lanes	Approach lane	Capacity at zero conflicting flow	Follow-up headway h_s	Following headway h_f	Parameter Veh/s units
1	Single	1440	2.50	2.00	1.476
2(*)	Single/left lane	1440	2.50	2.00	0.394
2(*)	Right lane	1440	2.50	2.00	1.044

(*) Use parameters also for roundabouts with two approach lanes and one circulating lane

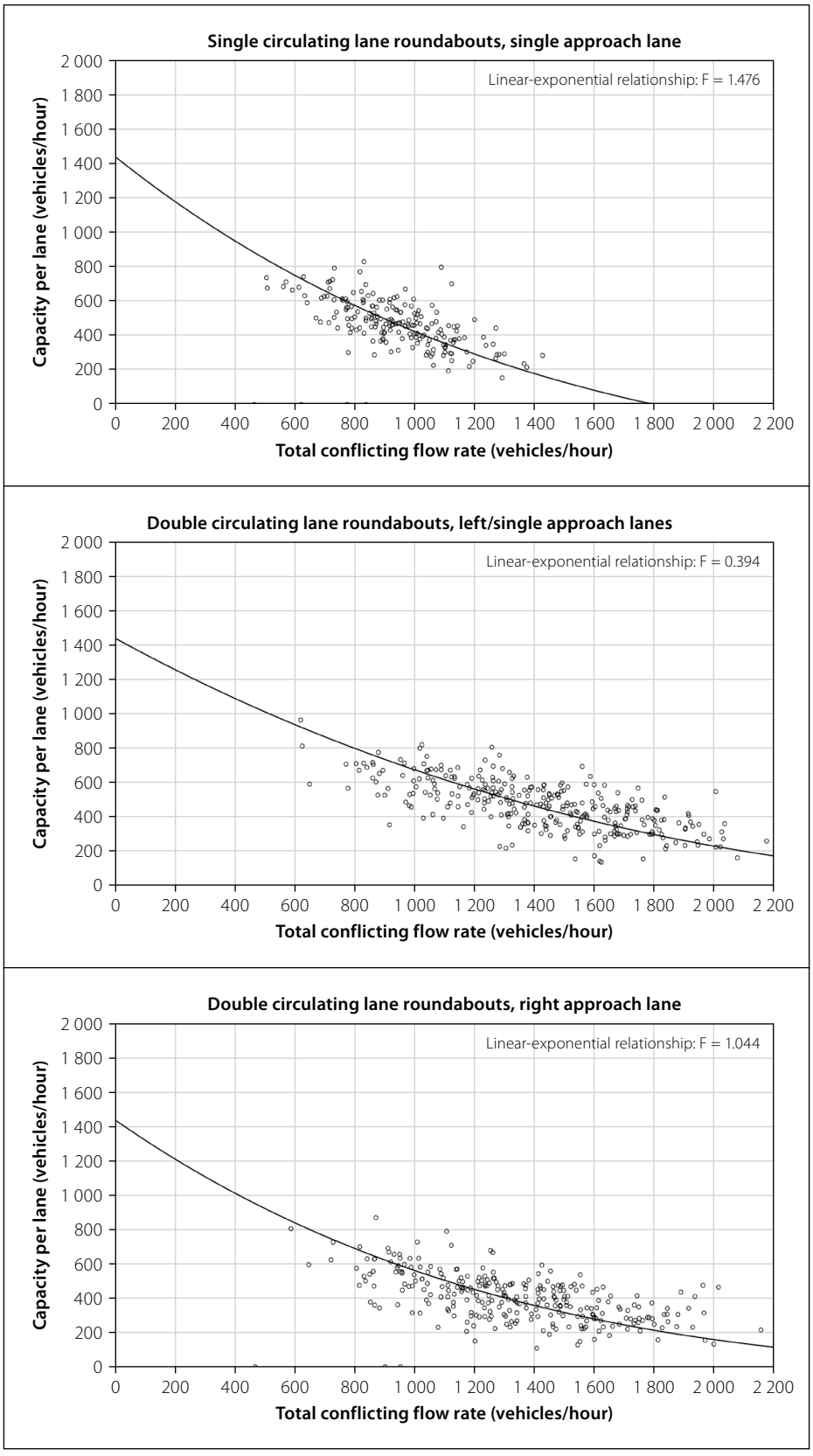

Figure 6 Capacity by lane types based on linear-exponential models

used in units of vehicles per hour, while the second one is used when the conflicting rate is used in units of vehicles per second.

The exponential regression model was fitted to the capacity observations that were undertaken during this study. The results are shown in Figure 5 together with the observations. The parameters of the model are shown in the figure and are also provided in Table 3. The parameters are fairly close to those of the Highway Capacity Manual for double-lane roundabouts, but higher for single-lane roundabouts. This indicates that the capacity of local single-lane roundabouts is slightly lower than those in the USA but about the same for double-lane roundabouts.

Linear-exponential regression model

An alternative regression equation to estimate capacity per approach lane was developed during the study based on the Wu (2001) formula, expressed as follows:

$$c = \frac{3600}{h_s} \cdot \left(1 - \frac{h_f \cdot q}{3600 \cdot n}\right)^n \cdot e^{-f \cdot q/3600}$$

This model was fitted to the capacity observations by means of regression analysis. The results are shown in Figure 6 together with the observations. The parameters of the model are shown in the figure and are also provided in Table 4.

Comparison of capacity models

A comparison of the different fitted regression models is provided in Figure 7. The Highway Capacity Manual method (TRB 2016) together with the Tanner (1967) formula are also shown. The figure shows that there is a relatively close correlation between these models for lower conflicting flows. For higher conflicting flow rates, the exponential regression model predicts a higher capacity than the other models.

The exponential regression model probably provides a more accurate reflection of actual operations under high traffic

volumes. The capacity observations do show that relatively high capacities have been measured for some double-lane roundabouts at high conflicting flow rates. The traffic volumes at the single-lane roundabouts investigated during this study carried relatively low volumes of traffic, but it is likely that similar capacities would also be found for such roundabouts.

The term "limited priority" is used by Troutbeck and Kako (1997) to describe the situation in which the circulating stream vehicles are sometimes forced to slow down to accommodate the entering vehicles. Kimber (1980) used the term "gap-forcing behaviour" to describe the situation. According to Troutbeck and Kako (1997), the operations are then more related to merging than to gap acceptance. The merging operation is more efficient, allowing more vehicles to utilise the merging area more effectively than using gap acceptance. This leads to higher capacities at higher conflicting flows. The gap-forcing behaviour of drivers may lead to higher capacities but is likely to increase the risk of collisions.

Road authorities and designers should not rely on the capacity created by gap-forcing behaviour in the evaluation of roundabouts. To prevent such designs, the COTO (2012) TMH 16 Manual for traffic impact assessments introduced the requirement that, for new developments, the sum of the entering flow and conflicting flow must not be designed to exceed a total of 1 300 vehicles/hour for a single- and 1 600 vehicles/hour for double-lane roundabouts.

It is therefore proposed that the additional capacity resulting from gap-forcing not be utilised in the design of roundabouts and that such behaviour be discouraged. This implies that it is more appropriate to use the linear exponential relationship to determine capacities at roundabouts.

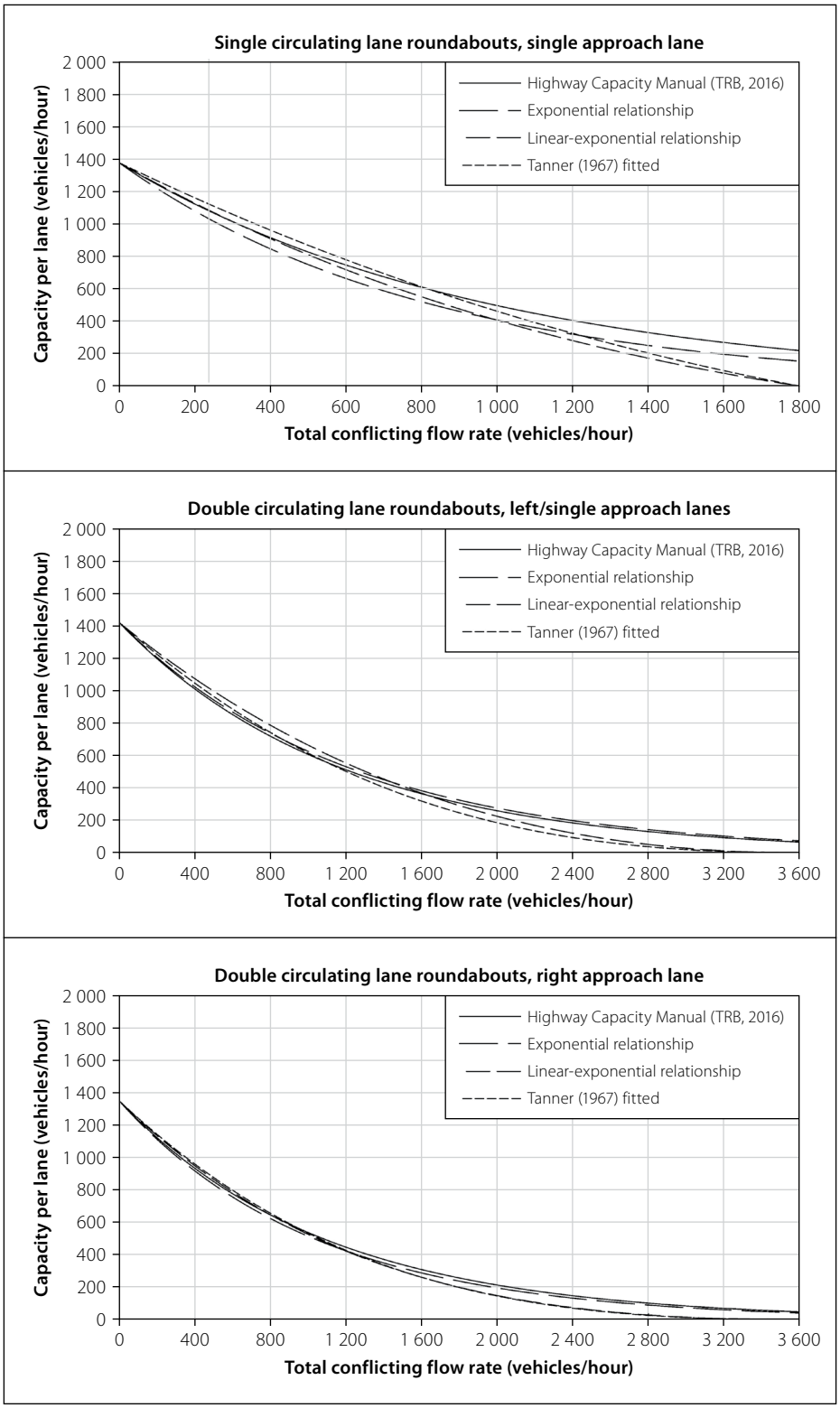

Figure 7 Capacity by lane type–comparison of models

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to develop analytical models that can be used for the capacity analysis of roundabouts in South Africa. These models were developed from data observed using drone video recordings at various roundabouts countrywide which varied in size from 25 m to 95 m inscribed diameter with three to six approaches. The main findings and recommendations of the study are outlined below.

Critical gaps

Critical gaps were determined using both the maximum likelihood method and regression of the Tanner (1967) formula to fit observed capacity flows. Based on the two methods, the critical gaps provided in Table 1 are proposed for use in South Africa.

Saturation follow-up headways

An average follow-up headway of 2.5 seconds was obtained for all roundabouts regardless of size and for both light and heavy vehicles. This implies a maximum capacity of 1 440 vehicles per hour for a single approach lane to a roundabout.

Capacity of roundabouts

Various capacity models were evaluated, including both gap acceptance and regression models. The gap acceptance models showed a remarkable degree of correlation between simulated capacities and those based on the gap acceptance models. Any

of the models that were evaluated can therefore be used. Since the Tanner (1967) model is the most well known it is recommended for use when it is necessary to utilise a gap acceptance-based model.

Two regression models were also evaluated, namely the exponential model used by the Highway Capacity Manual (TRB 2016) and the linear-exponential model developed during this study. A comparison of the best-fit linear-exponential model and Highway Capacity Manual model showed lower capacities for approach lanes to single-lane roundabouts while they are approximately the same for double-lane roundabouts.

A comparison of the different fitted models, including both the gap acceptance models and the regression models, showed that there is close correlation among the different models under low conflicting flows. At higher conflicting flows, the exponential regression model predicts higher capacities than the other models.

The exponential regression model may provide a more accurate reflection of actual traffic operations at high conflicting volumes. However, these higher capacities are the result of "gap-forcing" behaviour of drivers. This behaviour, however, is undesirable and may lead to increased conflicts which may result in accidents. Road authorities and roundabout designers should therefore not rely on these higher capacity estimates in the design and evaluation. It is proposed that the linear-exponential model be used for the capacity analysis of roundabouts in South Africa.

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