ROUNDABOUT CAPACITY STUDY

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ABSTRACT

The South African National Roads Agency Ltd (SANRAL) has established a Research Panel and Programme to undertake research in the transportation field. One of the projects that were undertaken as part of the program was an investigation into the design and operations of roundabouts. This project included, amongst others, a study of traffic operations and the capacity of roundabouts in South Africa. The purpose of the paper is to present the findings of the study.

1. INTRODUCTION

1.1 Background and Objectives

The South African National Roads Agency Ltd (SANRAL) has established a Research Panel and programme to undertake research in the transportation field. The research covers a range of focus areas such as future transportation needs, legislation, economics, environment, communication, transportation planning, road safety, traffic, pavement, geotechnical, structures and drainage.

One of the projects that were undertaken as part of the program was an investigation into 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:

a) Critical gaps. The gaps that drivers are willing to accept.
b) Saturation follow-up headway. Average headway between successive entering vehicles.
c) Capacity of roundabouts. Development of models for determining the capacity of local roundabouts.

1.2 Study Approach

The study was based on data obtained from drone video recordings at various roundabouts throughout South Africa. Geometry data were obtained from scaled aerial photographs while the traffic data were extracted using video analysis software. The videos were analysed and georeferenced using video analytics software using a cloud-based service provider (DataFromSky (DfS), www.datafromsky.com).

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

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

All the capacity parameters were derived from the above data. For example, gaps accepted and rejected were determined using 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.

1.3 Roundabouts Included in the Study

A total of about 120 roundabouts were selected from various locations across the country for the study. From these, about 90 roundabouts were suitable for the capacity study.

Data were available for the development of capacity relationships for the following roundabout configurations.

Single-lane approaches (entries) to single circulating -lanes.
Double-lane approaches to double circulating -lanes.

2. CAPACITY ACCEPTANCE MODELS

2.1 Introduction

Internationally there are mainly two types of models used for estimating the capacity of priority-controlled intersections such as roundabouts (Rodegerdts et al., 2007):

a) Gap acceptance models.
b) 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 regression analysis of observed capacity flows as a function of conflicting flows.

2.2 Tanner (1962) Formula

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, but with provision for a minimum headway in the stream as follows:

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

In which:

c = Capacity flow per lane (vehicles per second)
q = Conflicting flow rate (vehicles per second)
t_c = Average critical gap (seconds)
h_f = Following headway in the conflicting flow (seconds)
h_s = Saturation follow-up headway (seconds)

2.3 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:

$$c = \frac{q_p \cdot \prod(1 - h_f \cdot q_i)}{1 - e^{-h_s \cdot q_p}} \cdot e^{-(t_c - h_f) \cdot q_p} \tag{2}$$

In which:

q_i = Conflicting flow rate of stream i.
q_p = Total conflicting platoon flow rate.

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

$$q_p = \sum \frac{(1 - p_{fi}) \cdot q_i}{1 - h_f \cdot q_i} \tag{3}$$

This formula for the platoon flow rate can then be used together with the extended Tanner (1967) formula to determine the capacity of priority-controlled intersections, including roundabouts.

2.4 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 are 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 written as:

$$c = \frac{q_p \cdot (1 - h_f \cdot q/n)^n}{1 - e^{-h_s \cdot q_p}} \cdot e^{-(t_c - h_f) \cdot q_p} \tag{4}$$

With:

$$q_p = \frac{(1 - p_f) \cdot q}{1 - h_f \cdot q/n} \tag{5}$$

In which:

q = Total conflicting flow rate (vehicles/second)
p_f = Proportion followers
n = Number of conflicting streams

2.5 Akçelik et al (1999) Formula

A capacity model was developed by Akçelik et al (1999) for use in the aaSIDRA software package (Akçelik & Besley, 2004).

The formula is as follows:

$$c = \frac{1}{h_s} \cdot \left(1 - h_{fn} \cdot q + \frac{h_s}{2} \cdot (1 - p_f) \cdot q\right) \cdot e^{-(t_c - h_{fn}) \cdot q_p} \quad (6)$$

The symbols and parameters are as defined for the Tanner formula while the formula for the platooned flow rate q_p is given in Equation 5. The following headway h_{fn} is 2.0 seconds for a single-lane and 1.2 seconds for a double-lane roundabout.

2.6 Wu (2001) Formula

The following formula was developed by Wu (2001) which is used in the German Highway Capacity Manual (FGSV, 2001):

$$c = \frac{1}{h_s} \cdot (1 - h_f \cdot q/n)^n \cdot e^{-(t_c - h_s/2 - h_f) \cdot q_p} \quad (7)$$

With symbols and parameters the same as those in the Tanner formula. the formula for the platooned flow rate q_p is given in Equation 5.

2.7 Comparison of Gap Acceptance Models

The different gap acceptance-based capacity models were compared and evaluated using microscopic simulation based on the same assumptions used by Tanner (1967).

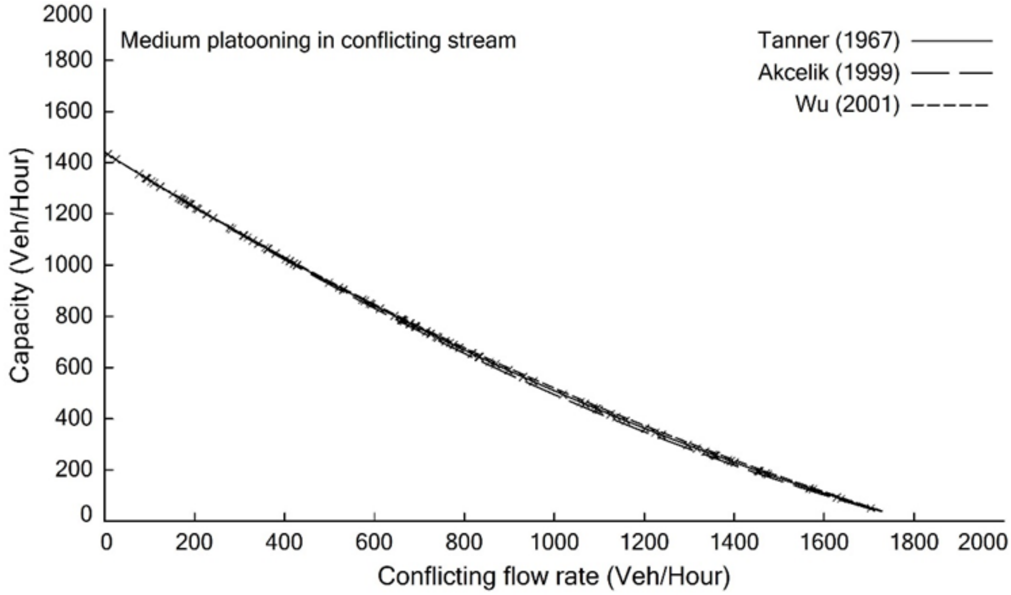
Simulations were undertaken for different levels of platooning in the conflicting stream. See Figure 1 for an example. The comparison shows a remarkable correlation between the simulation and the different capacity models, The Akçelik et al (1999) formula deviated slightly for high levels of platooning on double-lane roundabouts, but such levels of platooning are not typically found at roundabouts. It was concluded that any of the formulae can be used, with a preference for the well-known Tanner (1967) formula.

2.8 Saturation Follow-Up Headways

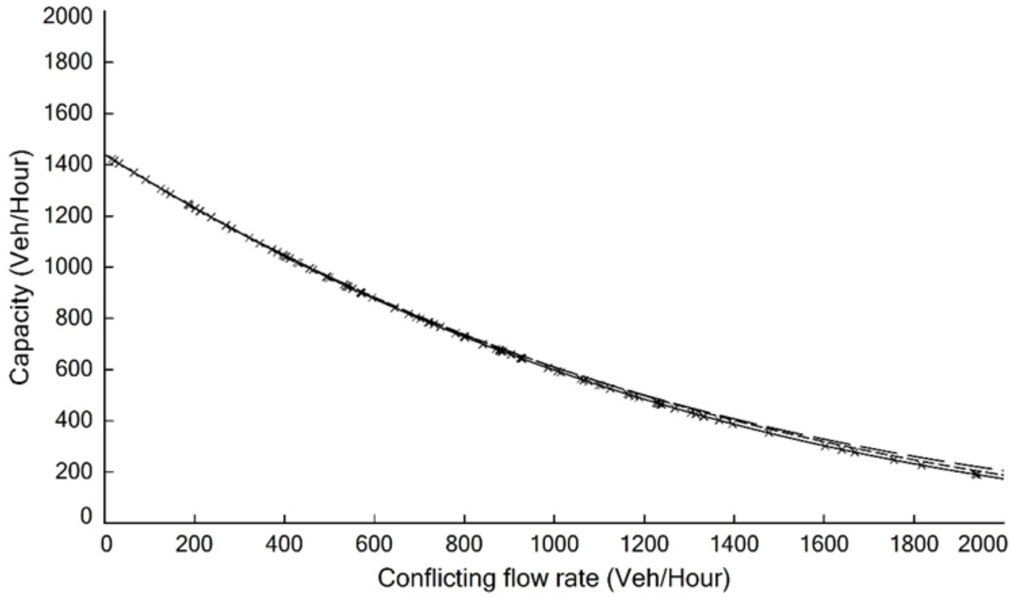
A key parameter is the saturation follow-up headway, i.e. the average headway for a continuous stream of entering vehicles with no conflicting traffic.

The video data were used to measure these and an average of 2.5 seconds was obtained. This headway is independent of the geometry or size of the roundabout and the type of vehicle. The latter could be due to drivers of heavy vehicles being more aggressive than those of light vehicles.

The average headway of 2.5 seconds implies that the maximum capacity of a single-entry lane to a roundabout is 1440 vehicles per hour per lane (3600/2.5).



Single conflicting traffic stream



Double conflicting traffic stream

Figure 1: Simulation evaluation of capacity models – Medium levels of platooning

2.9 Average Following Headways in Conflicting Stream

Following headways were measured on the circulating roadways and were determined as the average of the headways shorter than a threshold value of 3.0 seconds. An average of 2.0 seconds was obtained for all the roundabouts in the study.

The following headways are slightly shorter at larger roundabouts than at smaller roundabouts. However, including size to determine the following headway introduces unnecessary complexity. It is therefore proposed that an average headway of 2.0 seconds be used. This implies that the flow rate on the circulating roadway of a roundabout cannot exceed a maximum of 1800 vehicles per hour per lane.

2.10 Platooned Conflicting Streams

All three gap-acceptance models make provision for platooning in the conflicting stream. Such platooning can have a significant impact on the capacity of priority-controlled intersections (Van As & Joubert, 2002).

The platooning in the conflicting stream is considered using Equation 5 which effectively converts the conflicting traffic flow rate to an equivalent platoon rate. The conversion is based on the “travelling queue” headway distribution of inter-platoon headways (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 introduction of platooning as a consideration in capacity analysis introduces complications in the analysis of priority-controlled intersections. and the extent thereof at roundabouts was therefore investigated.

The proportion of followers in the conflicting 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 including a relationship determined by regression analysis using the following function:

$$p_f = (h_f \cdot q)^{f_p} \tag{8}$$

In which:

p_f = Proportion followers
q = Traffic flow rate (vehicles/second/lane)
h_f = Average follower headway (2.0 seconds)
f_p = Platooning factor obtained from regression

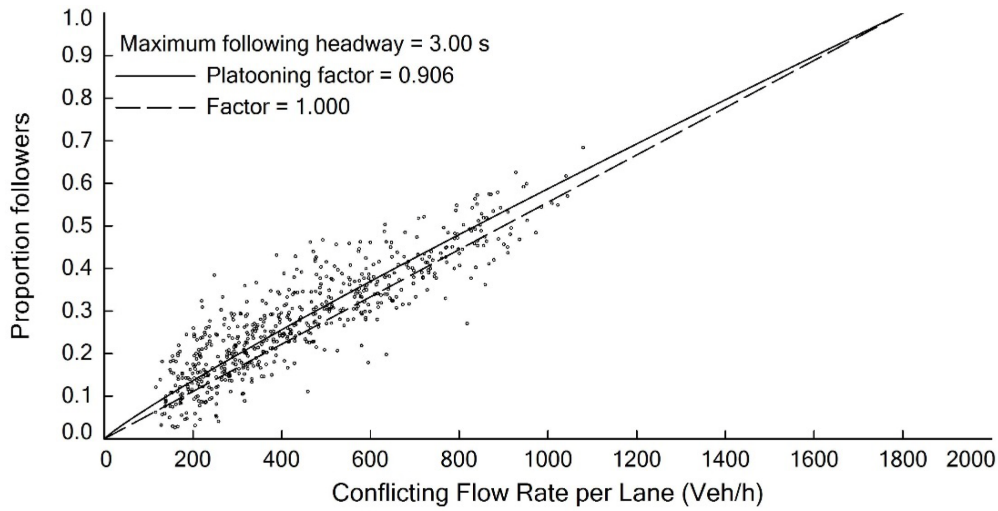
It was found that the proportion followers is nearly linearly related to the flow, as follows:

$$p_f \cong h_f \cdot q \tag{9}$$

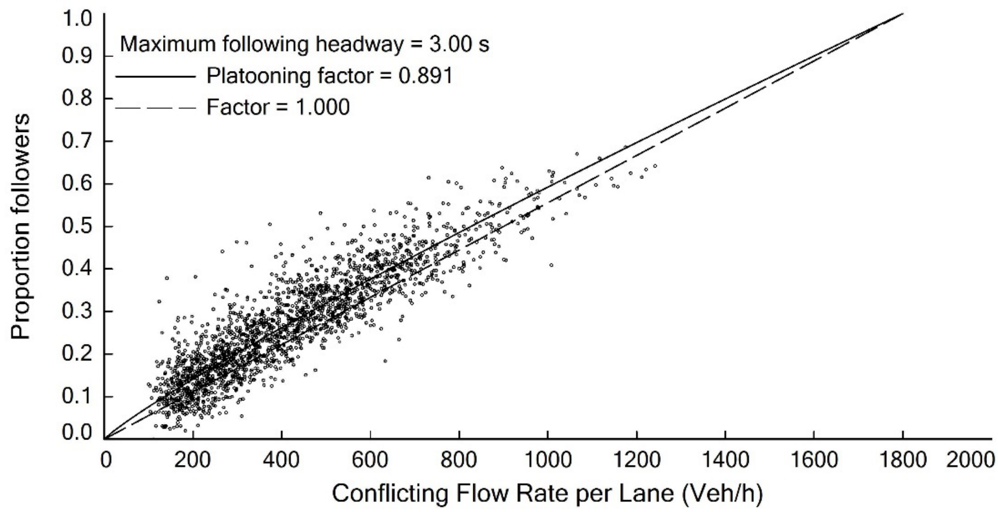
Replacing this term in Equation 5 for determining the platoon flow rate results in the following simplified relationship:

$$q_p \cong q \tag{10}$$

This implies that a stream of platooned conflicting traffic at a roundabout is nearly equivalent to a stream of traffic with no platooning. Hence, platooning can be ignored in the determination of the capacity of a roundabout.



Single circulating lane roundabouts



Double circulating lane roundabouts

Figure 2: Proportion followers (3.0 second follower threshold)

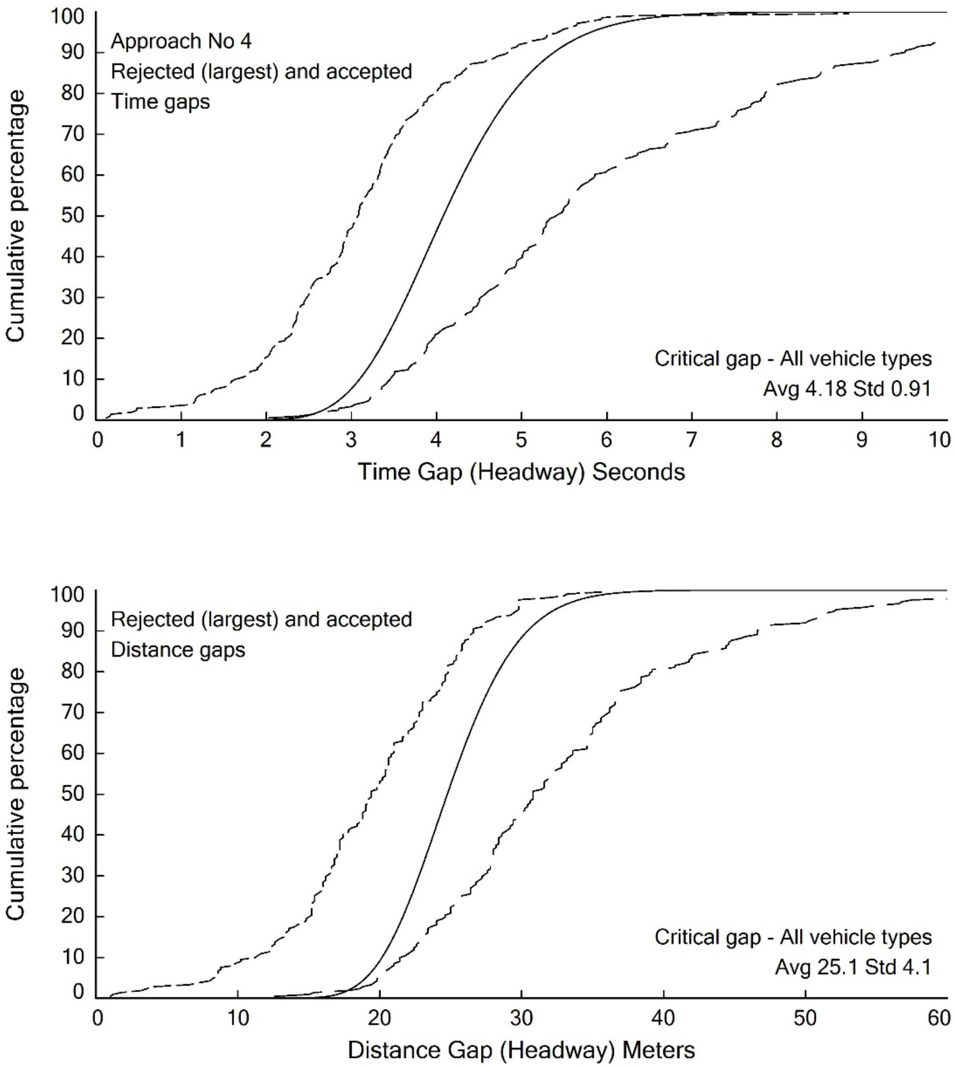
2.11 Critical Gap Observations

Critical gaps were derived from measured accepted and rejected gaps. These gaps were measured when the 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 vehicle.

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

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

Gap acceptances were measured for both time (seconds) and distance (meters) 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. The figure shows the fitted distributions together with the distributions of the largest rejected gaps and the accepted gaps (rejected gaps are typically always smaller than accepted gaps).



49 Umhlanga Rocks Dr x Centenary Blvd, Umhlanga, Durban, KZN

Figure 3: Example of fitted log-normal critical gap distributions

The maximum-likelihood method for determining critical gaps is that it is based on observations of gaps that are typically smaller and larger than the actual critical gaps. These two values are often relatively far apart for most observations which can have an impact on the accuracy of the method (as illustrated in Figure 3). The method also relies on the assumption that the critical gaps follow a lognormal distribution.

An alternative method for deriving the critical gaps was therefore also used. This involved regression analysis in which the Tanner (1967) capacity formula was fitted to observed capacities using the critical gap as the regression parameter. This alternative method is expected to predict capacities closer to the actual observed capacities (but not necessarily actual critical gaps).

It was found that at double-lane roundabouts, the critical gaps based on the gap acceptance analysis are close to those obtained from the regression analysis. At single-lane roundabouts, there was a slight difference but the difference is relatively small. Based on the analysis, the following critical gaps are proposed for use in South Africa.

Table 1: Proposed 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

3. 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 from a queue on an approach divided by the time that it takes for the queue to depart.

3.1 Exponential Regression Model

The Highway Capacity Manual (TRB, 2016) uses an exponential regression model for the estimation of the capacity of a roundabout:

$$c = \frac{3600}{h_s} \cdot e^{-f \cdot q/3600} \qquad (11)$$

In which:

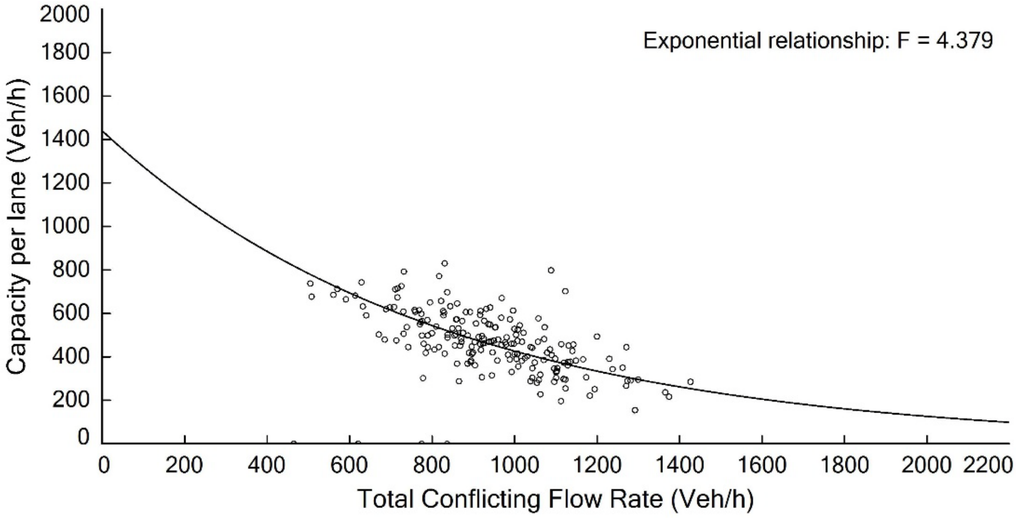
c = Capacity flow per lane (vehicles per hour)
q = Total conflicting flow rate (vehicles per hour)
h_s = Saturation follow-up headway (seconds)
f = Regression parameter

This model was fitted to the data as shown in Figure 4. The derived regression parameters are given in Table 2. These parameters are close to those of the Highway Capacity Manual (TRB, 2016) for double-lane roundabouts, but a higher parameter was found for single-lane roundabouts. This indicates that the capacity of local single-lane roundabouts is slightly lower than those in the USA.

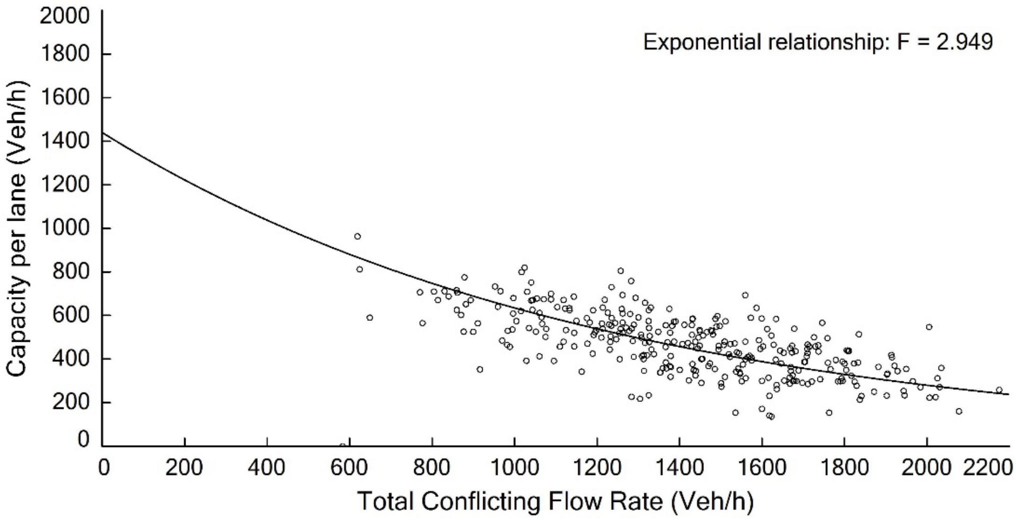
Table 2: Parameters of the fitted Exponential regression model

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

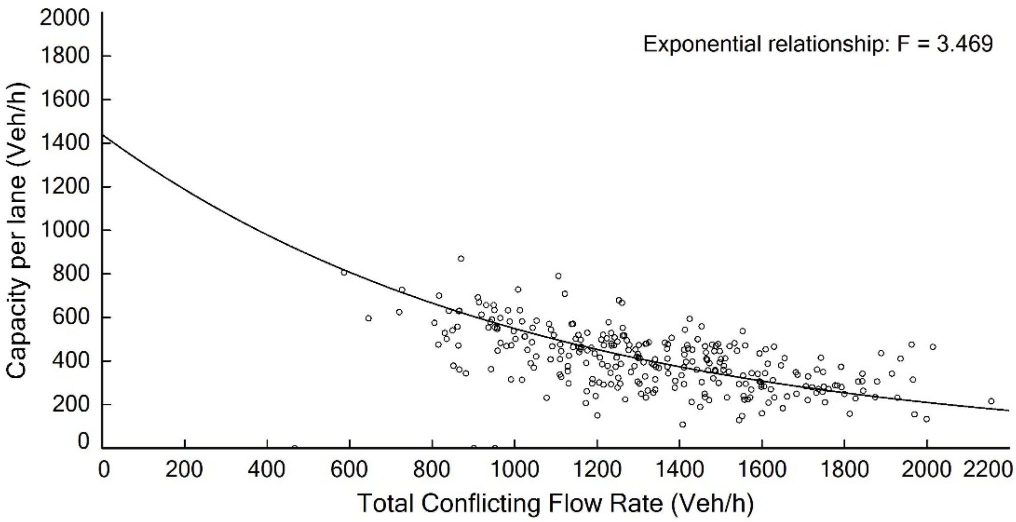
(*) Use parameters also for roundabouts with two approach lanes and one circulating lane



Single circulating lane roundabouts, Single approach lane



Double circulating lane roundabouts, Left/Single approach lanes



Double circulating lane roundabouts, Right approach lane

Figure 4: Capacity relationship – Exponential relationship

3.2 Linear-Exponential Regression Model

An alternative regression equation for the estimation of capacity was derived based on the Wu (2001) formula, expressed as follows:

$$c = \frac{3600}{h_s} \cdot \left(1 - \frac{h_f \cdot q}{3600 \cdot n}\right)^n \cdot e^{-f \cdot q/3600} \quad (12)$$

With symbols and parameters the same as for the exponential regression model but with the following additional parameters:

h_f = Following headway in the conflicting flow (seconds)
n = Number of conflicting streams

The regression model is shown in Figure 5 and the parameters are provided in Table 3.

Table 3: 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

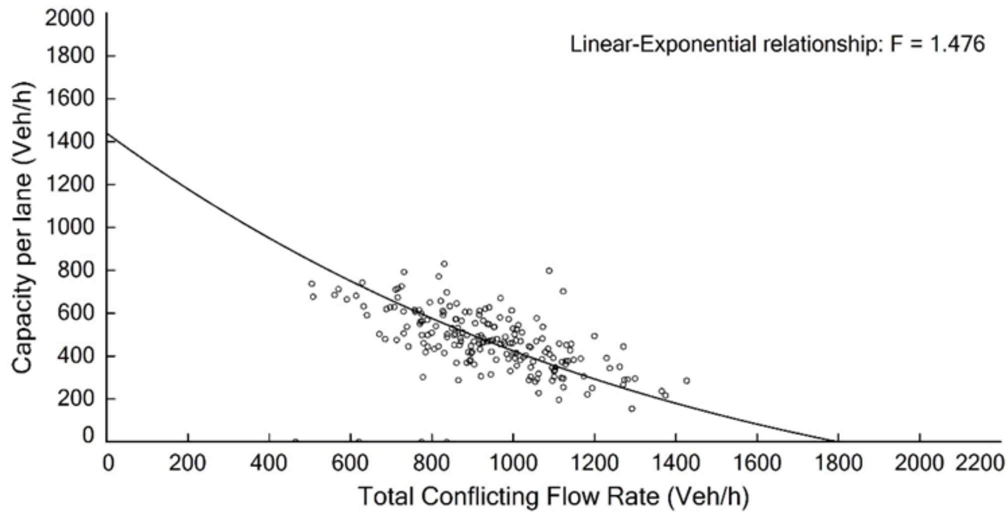
(*) Use parameters also for roundabouts with two approach lanes and one circulating lane

3.3 Comparison of Capacity Models

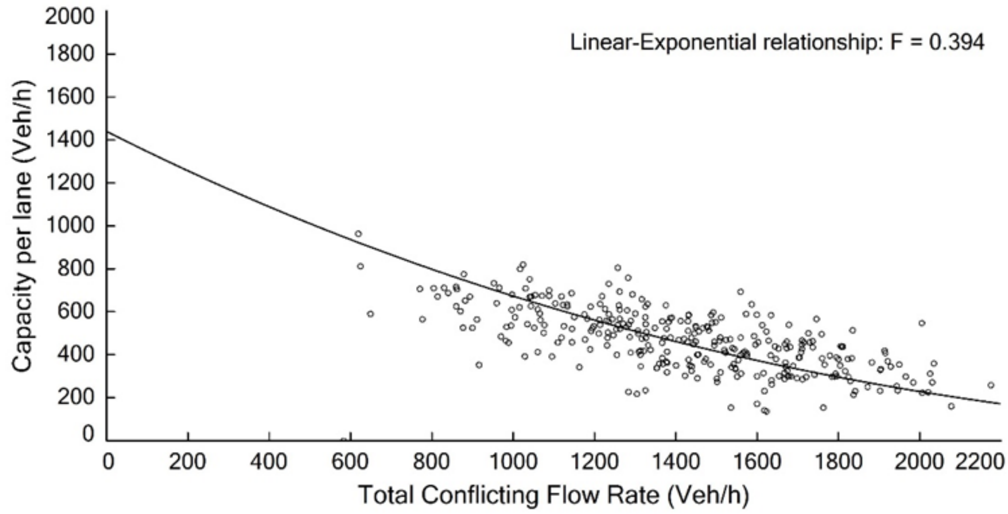
A comparison of the regression models is provided in Figure 6. There is a relatively close correlation between these models for lower conflicting flows. For higher conflicting flow rates, the exponential regression model predicts a higher capacity than the other models.

The exponential regression model probably provides a more accurate reflection of actual operations under high traffic volumes. The term “limited priority” has been used by Troutbeck & Kako (1997) to describe circulating stream vehicles forced to slow down to accommodate the entering vehicles. Kimber (1980) described it as “gap-forcing behaviour”. According to Troutbeck & Kako, this is 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 the roundabouts.

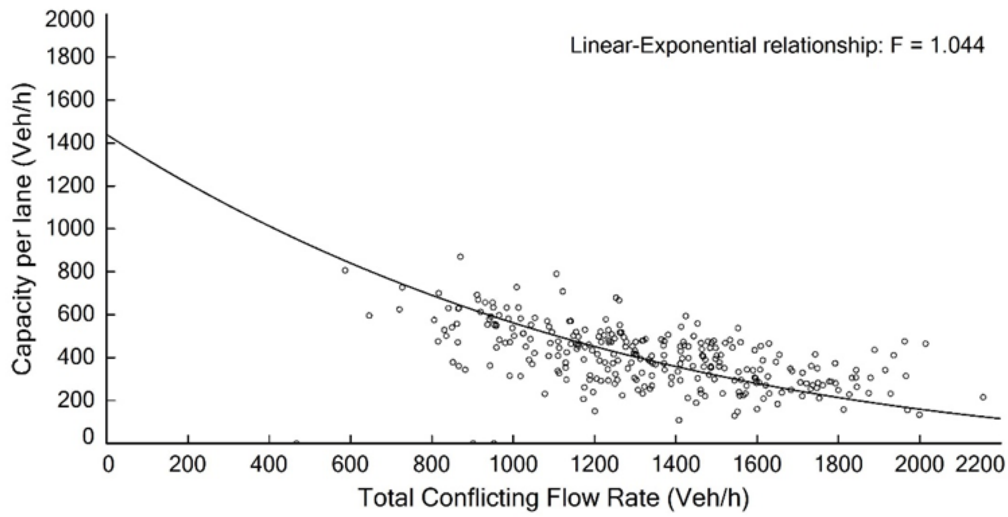
The gap-forcing behaviour may lead to higher capacities, but it increases the risk of accidents. It is therefore not advisable to rely on this added capacity in designs. It is more appropriate to use the linear-exponential relationship for the calculation of the lower capacities at the higher conflicting flows.



Single circulating lane roundabouts, Single approach lane

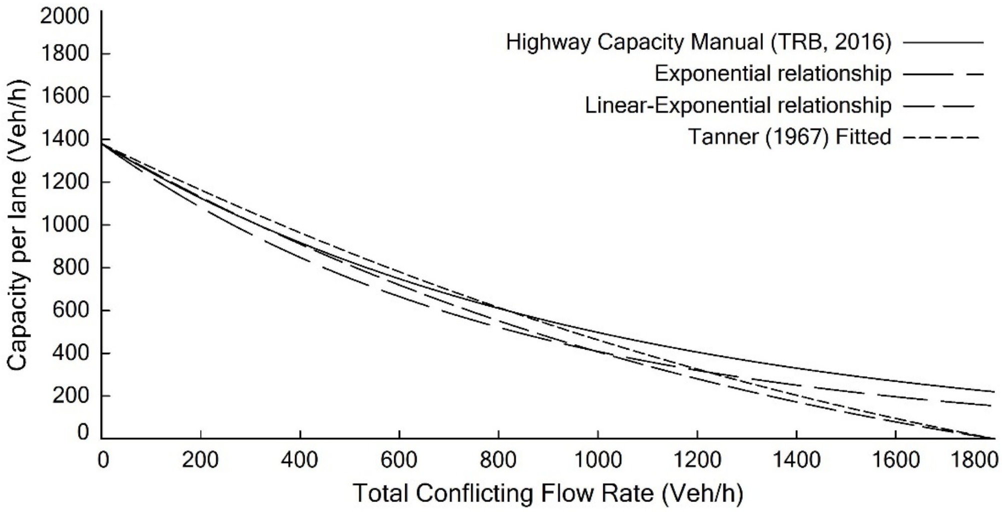


Double circulating lane roundabouts, Left/Single approach lanes

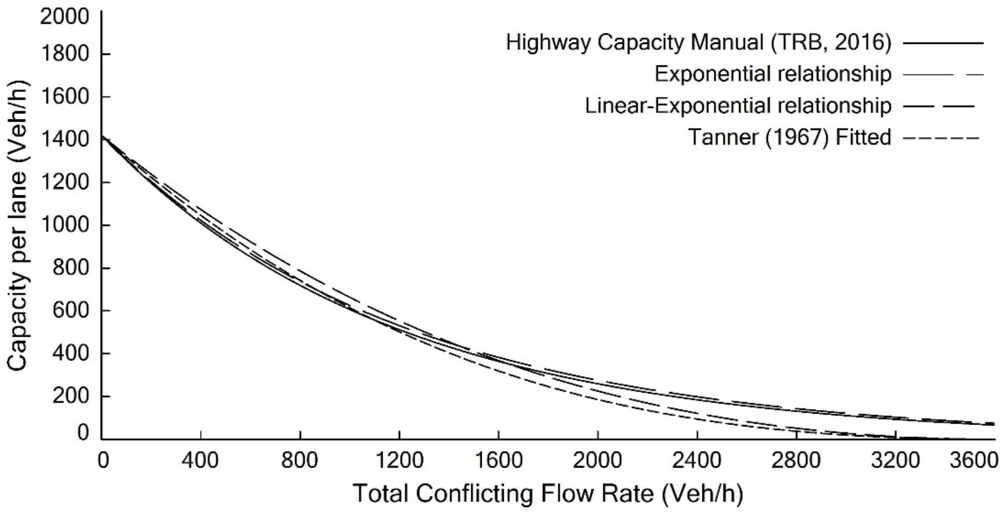


Double circulating lane roundabouts, Right approach lane

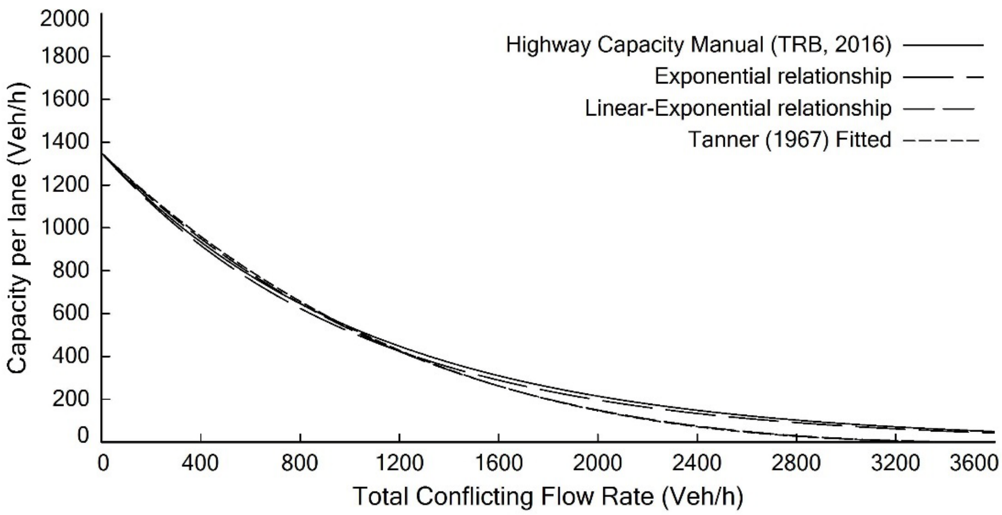
Figure 5: Capacity relationship – Linear exponential relationship



Single circulating lane roundabouts, Single approach lane



Double circulating lane roundabouts, Left/Single approach lanes



Double circulating lane roundabouts, Right approach lane

Figure 6: Comparison of regression relationships

4. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to develop models based on data from drone video recordings that can be used for the operational analysis of roundabouts in South Africa.

The main findings and recommendations of the study are as follows:

4.1 Critical Gap Acceptance

Critical gaps were obtained using both the maximum likelihood method and regression based on the Tanner (1967) formula.

4.2 Saturation Follow-Up Headways

An average follow-up headway of 2.5 seconds was obtained for all roundabouts for both light and heavy vehicles. This implies a capacity of 1440 vehicles per hour per lane.

4.3 Capacity of Roundabouts

Various gap acceptance models were tested with a remarkable correlation between the simulated capacities and the gap acceptance models. Any of the tested models can be used with a preference for the well-known Tanner (1967) 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. There is a close correlation between the different models under lower capacities. At higher capacities, 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 for high conflicting volumes for which relatively high capacities were observed. Operations under such conditions, however, are considered undesirable and could lead to conflicts and accidents. It is therefore proposed that the linear-exponential model be used for the capacity analysis of roundabouts in South Africa.

5. ACKNOWLEDGEMENT

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