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A Comparative Analysis of Exponential and Linear Roundabout Capacity Models Using HCM Research Data

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CONTENTS

Reference:

AKÇELIK, R., SHIRKE, C., BESLEY, M., ESPADA, I. and BILLINGHURST, D. (2022). *A Comparative Analysis of Exponential and Linear Roundabout Capacity Models Using HCM Research Data*. Technical Note. Akcelik & Associates Pty Ltd, Melbourne, Australia.

Accompanying report:

AKÇELIK, R. (2022). *Searching for a Gap Acceptance Theory Basis for Linear Capacity Models*. Technical Note. Akcelik & Associates Pty Ltd, Melbourne, Australia.

ABSTRACT

This report presents an investigation to assess basic exponential (non-linear) and linear model forms used in practice for roundabout capacity estimation. Best fit regression and anchored regression analyses were carried out using the HCM single-lane roundabout capacity research data. The full dataset as well as the Glens Falls and Carmel data subsets were analysed. These two data subsets for different roundabout geometry types represent a horizontal slicing of data with different capacity levels over the same range of circulating flows. To assess the applicability of basic exponential and linear models to low and high circulating flow ranges, additional data subsets were used by vertical slicing of the HCM capacity data. Using this method, two-segment linear and exponential models were analysed. Two-segment analyses were carried out using aggregate data as well. The models assessed also included the TRL-Kimber linear capacity model and the HCM exponential model with a new simplified version of the SIDRA geometry method added. The report includes discussions on frequency of data points in low, medium and high circulating flow ranges, the sum of entering flow (capacity) and circulating flow, the ratio of entering flow to circulating flow, issues related to anchored regression models, follow-up headways implied by best fit regression models being larger than measured values, and the quadratic model. As an issue related to underestimation of capacity at low circulating flows, a detailed single-lane roundabout example is given for unbalanced flow conditions under high demand levels. In conclusion, the assessments from various perspectives reported in this document demonstrate the non-linear characteristic of roundabout capacity data as a function of the circulating flow, and support the HCM exponential (non-linear) roundabout capacity model over the linear model form.

1 Introduction

This report presents the results of detailed comparative analyses of exponential and linear forms of capacity equations for roundabouts and sign-controlled (priority) intersections. Analyses were carried out using the US research data employed in developing the Highway Capacity Manual (HCM) roundabout capacity model (TRB 2016). Therefore, the results presented are specific to roundabout capacity models. The research data and the development of the HCM models are described in detail in FHWA (2015).

The purpose of the analyses reported in this document is to contribute to discussions about the empirical and theoretical aspects of roundabout capacity models for future research and development as well for the use of available models in practice. In particular, the aim is to help with choices between exponential and linear capacity model forms. The use of roundabout geometry parameters in the exponential and linear capacity models is discussed.

The comparisons presented in this report focus on the HCM (Siegloch M1) exponential capacity model and the TRL-Kimber (1980, 1985, 1989) linear capacity model. Different geometry parameters are used in these models. The TRL-Kimber model uses inscribed diameter, entry radius, entry angle, entry lane width, approach half width and effective flare length. The HCM model does not use these parameters.

The SIDRA roundabout capacity model (Akçelik 2011a, 2012, 2017a,b; 2018; Akçelik and Besley 2005; Akçelik, Chung, and Besley 1997; Akçelik and Troutbeck 1991) uses the inscribed diameter, entry radius, entry angle and entry lane width parameters to estimate the gap-acceptance parameters follow-up headway and critical gap. The SIDRA model uses short lane modelling rather than using flare length which is needed because of the approach-based modelling in the TRL-Kimber model.

The accompanying report (Akçelik 2022) describes applying a simplified version of the SIDRA geometry method (referred to as the Basic SIDRA Geometry Method) to the HCM exponential model using the inscribed diameter, entry radius and entry angle parameters. Detailed results for this method are given.

The analyses reported here are limited to single-lane roundabouts so that the multi-lane modelling issues are excluded. Thus, comparisons of lane-based models as they apply to the HCM and SIDRA exponential models and approach-based models as they apply to the TRL-Kimber linear model are not included.

The statistical error levels as measured by Root Mean Square Error (RMSE) are given for all models tested. Mean Absolute Error (MAE) values were also determined for all models but the results are not given since the MAE differences for different models were similar to the differences in the RMSE values.

While statistical error levels are important in research of this nature, model choices should not be based only on statistical error levels of field data available. The models should also be assessed in terms of dealing with specific situations, e.g. capacity estimates at low and high demand flows, and demand flow patterns causing unbalanced flow conditions at high demand flows (Akçelik, Chung and Besley 1996; Akçelik 2003, 2004, 2005, 2011b; Akçelik, Smit and Besley 2014). While the analyses of these conditions are relevant to existing roundabouts, they are also relevant to design life analyses of new and modified designs.

The investigation presented in this report stemmed from concerns about some aspects of a paper by Johnson and Lin (2018). The paper was useful in analysing subsets of HCM research data (the smaller Glens Falls roundabout which has a compact geometry compared with larger Carmel roundabouts which have "more curvilinear" geometry). This was used to emphasise the effect of distinct roundabout geometry types. This analysis represented *horizontal slicing* of the HCM research data indicating different capacity levels over the same range of circulating flows.

To assess the applicability of exponential and linear models to low and high circulating flow levels, the analyses reported in this document considered subsets of data based on *vertical slicing* of the HCM research data into lower and higher sets of circulating flow values in addition to the analyses based on subsets of data based on horizontal slicing of data. Using this method, two-segment linear models showed shortcomings in estimating capacity at low and high circulating flows (*Section 5*). The significance of this in relation to unbalanced flow conditions at high demand flow levels is discussed with a roundabout example in *Section 6*.

Capacity data, gap-acceptance parameters, geometry measurements and outlier characteristics of a subset of data are discussed in *Section 2*. The ratio of entry flow to circulating flow, the sum of entry and circulating flow, and capacity data frequency as a function of the circulating flow are discussed.

Analyses were done using data subsets for the Glens Falls roundabout and Carmel roundabouts as well as all HCM research data ("All Data"). Roundabout capacity models assessed were *Basic* linear and exponential capacity models as well as linear and exponential models that employ average *geometry parameters* representing these three data sets:

- basic exponential (Siegloch M1) model from best fit regressions,
- exponential (Siegloch M1) model with *Basic SIDRA Geometry Method* added (see Section 7 of Akçelik 2022),
- basic linear model from best fit regressions,
- TRL-Kimber linear model with parameters estimated using the TRL geometry method (Kimber 1980, 1985, 1989).

The specific HCM Edition 6 (TRB 2016) model for single lane roundabouts is represented by regressions with the y-intercept anchored.

The models are described in *Section 3*.

Model comparisons based on best fit regressions are presented in *Section 4*. Regressions with the y-intercept anchored for each model are also included.

Model calibration results for the HCM (Siegloch M1) exponential and TRL-Kimber linear model are given in *Section 5*. Calibration methods used are described in *Section 8* of the accompanying report (Akçelik 2022).

Refer to (Akçelik 2022) for a theoretical investigation to explore if a linear capacity model can be derived as a gap-acceptance capacity model assuming a uniform or linear arrival headway distribution of the opposing (conflicting / circulating) traffic stream. These headway distributions are not realistic given the random nature of arrival headways including bunching considerations. However, the purpose of this exercise was to see if a linear gap-acceptance model is possible. The investigation concluded that both uniform and linear headway distributions resulted in non-linear gap-acceptance capacity models. A form close to a linear model could be obtained by choosing low values of critical gap in these models. However, the chosen critical gap values were too low and not realistic when compared with observed values indicated by the HCM and Australian research data.

2 Capacity Data, Gap-Acceptance Parameters and Geometry Measurements

2.1 Capacity Data

Research data used in the development of the HCM roundabout capacity model data are discussed in detail in FHWA (2015).

In this report, analyses are given for single-lane roundabouts using all HCM research data (***All Data***) as well as two data subsets as used by Johnson and Lin (2018):

- all approaches of the Glens Falls roundabout (***Glens Falls NY07***), and
- all Carmel roundabouts (***Carmel IN All Data***).

The data are shown in shown in *Figure 2.1*. Regression analyses are reported in *Section 3* and calibrated models are discussed in *Section 4*.

There is a very small difference in the capacity dataset used in this report compared with the dataset reported in FHWA (2015) and used by Johnson and Lin (2018) as shown in *Table 2.1*. The dataset used for analyses reported in this document has 821 datapoints, two more than the number reported in FHWA (2015).

- Glens Falls roundabout (NY07): One data point reported in FHWA (2015) for the Northeast approach NY07-NE was not included in the dataset used in this report (total 241 data points used), and
- Port Orchard roundabout (WA04): Three extra data points for the Port Orchard roundabout are not included in the dataset reported in FHWA (2015).

These very small differences in data are not expected to have a significant effect on the results of the investigation given in this report.

The Eagle CO01 site indicates outlier characteristics which could be explained by the conditions of this site. Analyses excluding this site affected the results. However, the analyses using All Data were carried out including the Eagle Site data as in the HCM model development. This is discussed in *Section 2.1*.

Figure 2.1 shows the capacity data (Entering Flow), Q_e (pcu/h) as a function of the Circulating Flow, q_c (pcu/h).

Table 2.1 - HCM roundabout capacity research data used in this study: data subsets of interest indicated

Data subsets	Number of data points	Percent data points	Data points in FHWA (2015)	Average Entering Flow (Capacity)	Median Entering Flow	Notes
Glens Falls NY07	241	29.35%	242	611 pcu/h	606 pcu/h	Smaller roundabout with compact geometry used in detailed analyses. One data point reported in FHWA (2015) for the Northeast approach NY07-NE was not included in the dataset used in this report.
Carmel IN All Data	437	53.23%	437	783 pcu/h	763 pcu/h	Larger roundabouts with "more curvilinear" geometry used in detailed analyses.
Eagle CO01	39	4.75%	39	842 pcu/h	961 pcu/h	Included in "All Data" used for analyses. Outlier characteristics discussed in *Section 2.1*.
Other Data (NY08 and WA All Data)	104	12.67%	101	961 pcu/h	933 pcu/h	Included in "All Data" used for analyses. Three extra data points for the Port Orchard WA04 site are not included in the dataset reported in FHWA (2015).
All Data	**821**		**819**	**758 pcu/h**	**726 pcu/h**	

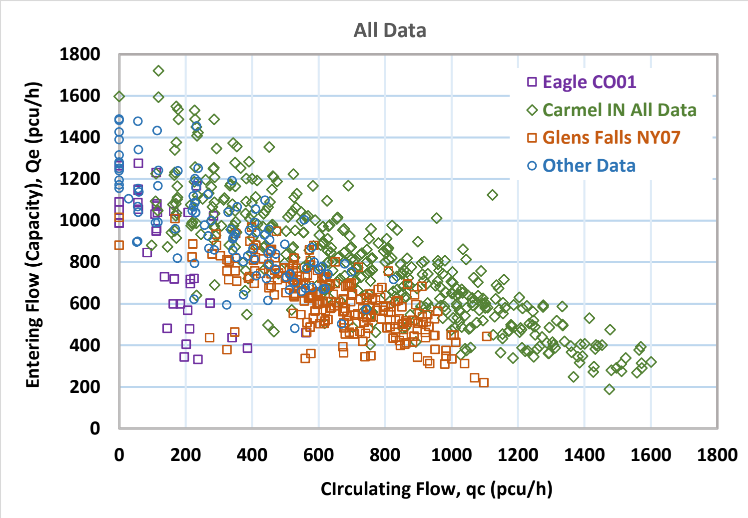


Figure 2.1 - HCM roundabout capacity research data used in this study: data subsets of interest indicated

It was noted that data included Heavy Vehicles in both entering traffic (2.0%) and circulating traffic (2.2%). Numbers of bicycles in entering and circulating traffic were negligible (less than 0.1%). Observed vehicle volumes were converted to flow rates in pcu/h using a Heavy Vehicle Factor of 2.0 pcu/veh and a Bicycle factor of 0.5 pcu/veh.

Ratio of Entering Flow to Circulating Flow

The *Ratio of Entering Flow to Circulating Flow* is of interest in relation to the modelling of unbalanced flow conditions. *Figure 2.2* shows the values of these ratios for All Data and the two subsets of data. As expected, it is seen that the Ratio of Entering Flow to Circulating Flow values are high at low circulating flows and low at high circulating flows. Average values are 3.2 for circulating flows below 700 pcu/ and 0.6 for circulating flows above 700 pcu/h.

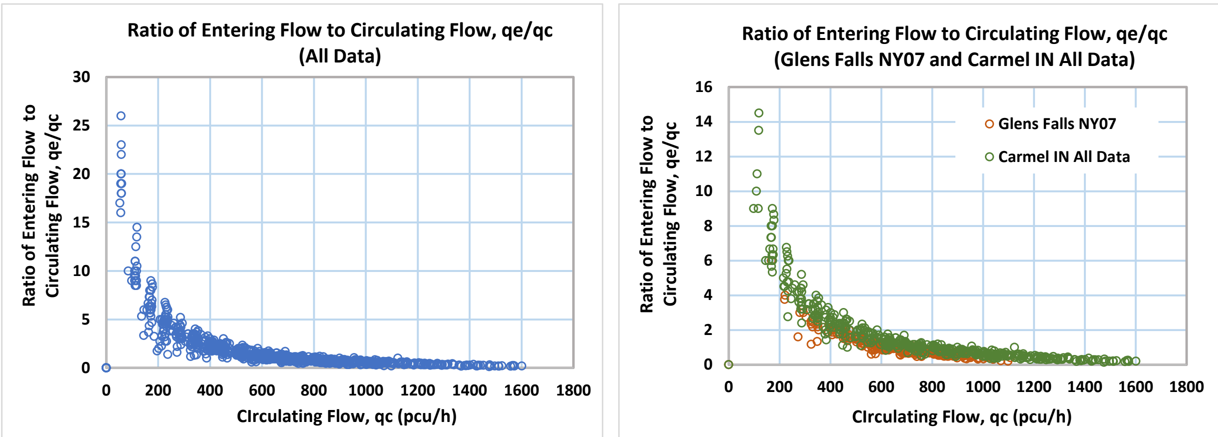


Figure 2.2 - The Ratio of Entering Flow to Circulating Flow for All Data and two subsets of data

Sum of Entering Flow (Capacity) and Circulating Flow

The *sum of entering flow (capacity) and circulating flow* is often discussed by practitioners. *Figure 2.3* shows the values of this parameter for the Glen Falls NY07 and Carmel IN All Data subsets including linear trendlines.

It is seen that high values of the *sum of entering flow (capacity) and circulating flow* are achieved at high circulating flows. This may indicate a potential for higher entry flow values at low circulating flows. This comment relates to the modelling of unbalanced flow conditions.

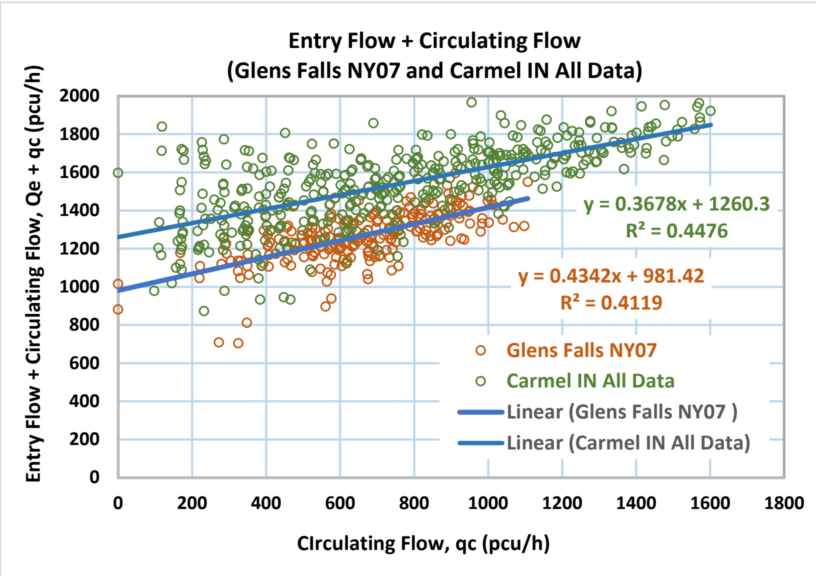


Figure 2.3 - The Sum of Entering Flow (Capacity) and Circulating Flow for two subsets of data

Frequency of Capacity Data Points as a Function of the Circulating Flow

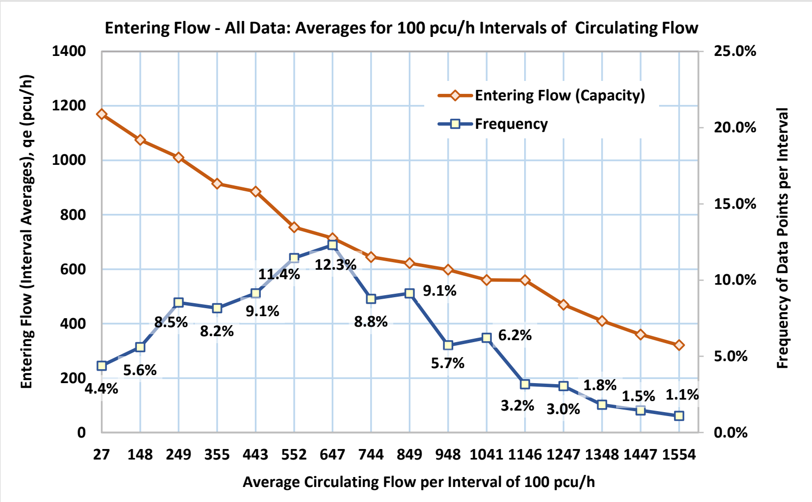
Model developers should pay attention to the effect of the frequency of data points by circulating flow on best fit regression results for the linear and nonlinear models as this is likely to cause a bias towards hiding non-linearity of the capacity curve. *Figure 2.4* shows the frequency of capacity data points for All Data, Glens Falls NY07 and Carmel IN All Data as a function of the circulating flow in 100 pcu/h intervals (x axis shows the average value of circulating flow for each interval). Average values of entering flow (capacity) per 100 pcu/h interval are also shown in *Figure 2.4*.

It is seen that, for All Data and Glens Falls NY07, the frequencies are small for ranges of high entering flow at low circulating flows and for low entering flows at high circulating flows, peaking in the range 500 to 700 pcu/h.

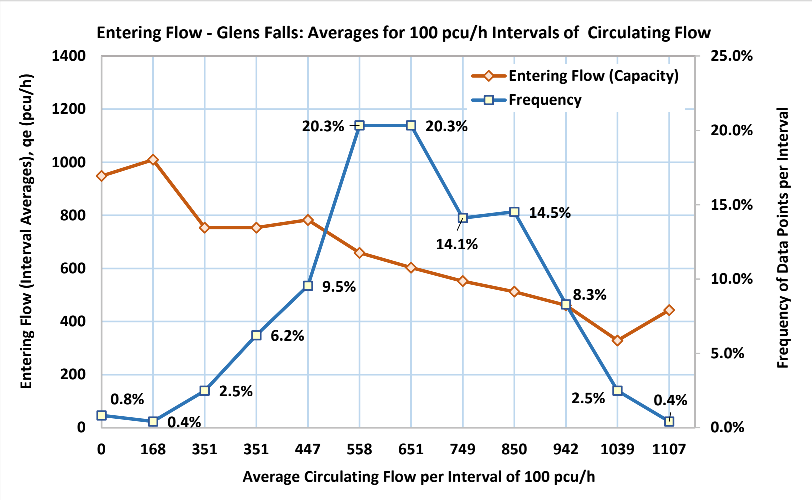
Figure 2.4 shows significant differences between the two subsets, i.e. Glens Falls NY07 and Carmel IN All Data, the latter showing a more equal distribution of frequencies with higher capacity values. All Data frequencies have a combined effect of these two subsets which form 83% of All Data.

Figure 2.5 in relation to this issue is taken from Akçelik (2003) in a discussion on the TRL-Kimber linear capacity model. It shows two examples from UK roundabout research reports indicating that relative frequencies of data at circulating flows below 600 pcu/h were very small (Semmens 1982; Semmens, et al 1980). The circulating flows in this figure are approach values.

All Data



Glens Falls INY07



Carmel IN All Data

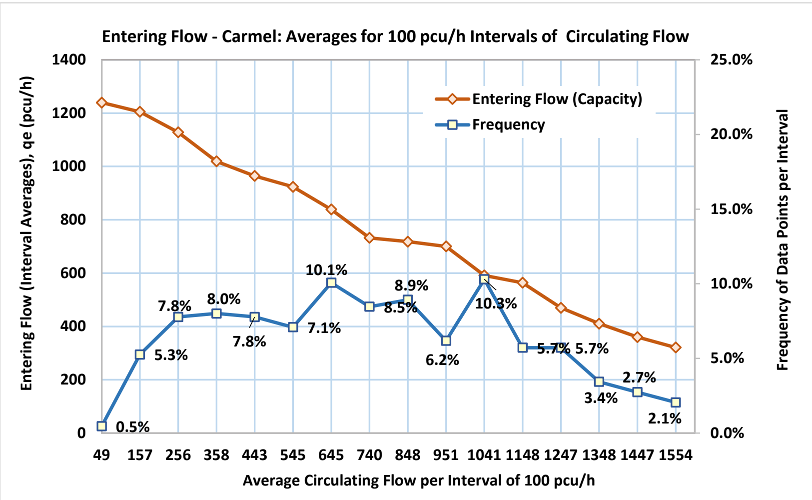
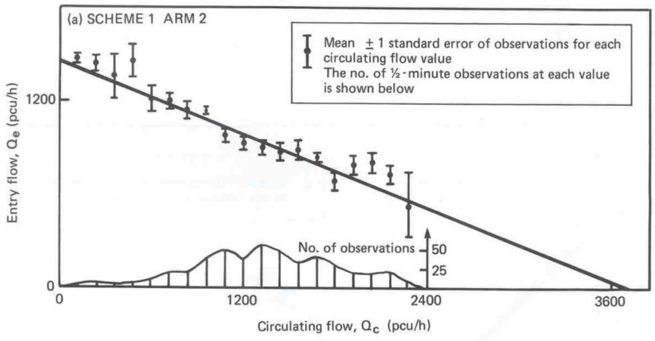


Figure 2.4 - Frequency of capacity data points as a function of the circulating flow and average entering flow (capacity) data in 100 pcu/h intervals

At-grade roundabout in Wincheap, Canterbury, UK (Semmens, et al 1980)



Grade-separated roundabout in Bradford, UK (Semmens 1982)

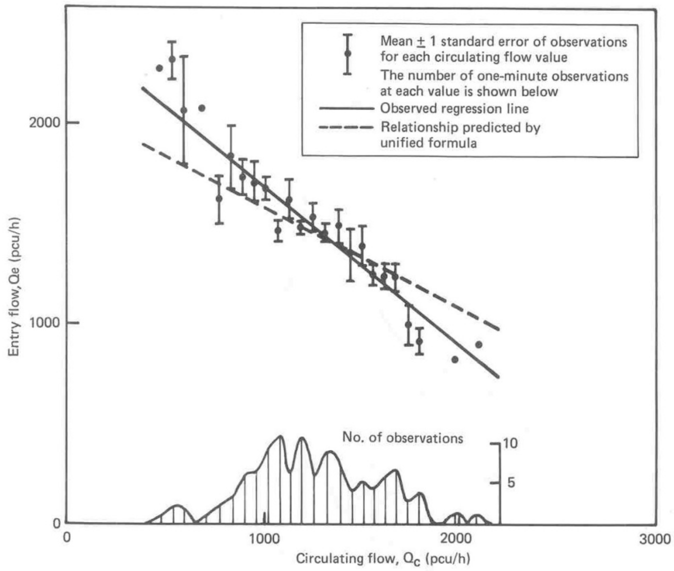


Figure 2.5 - Data from roundabout capacity surveys at UK roundabouts

Outlier Characteristics of Eagle CO01 Data

Eagle CO01 site data (4.8% of All Data) showed outlier characteristics as its capacity drops very quickly for low circulating flows in the 200 to 300 pcu/h range. This can be seen in *Figure 2.1* as well as *Figure 2.6* where capacity curves based on best fit exponential regression models are shown.

An inspection of the geometry of this roundabout indicated an issue with the North approach which is the main contributor to the circulating flow for the West approach. As seen in *Figure 2.7*, the North approach has double right turns with unusual geometry and lane disciplines. This is expected to create uncertainties for drivers entering from the West approach which may explain the quick drop in capacity.

Although elimination of data for the Eagle CO01 site affects the results significantly, "All Data" analyses reported in this document included the data for the Eagle CO01 site as used in the development of the HCM roundabout capacity model (FHWA 2015). Some results for analyses without the Eagle CO01 site are given in *Section 4.5*.

Exponential and linear capacity models based on best fit regressions with and without the Eagle CO01 data are summarised in *Table 2.2*. The exponential and linear models are described in *Section 3*.

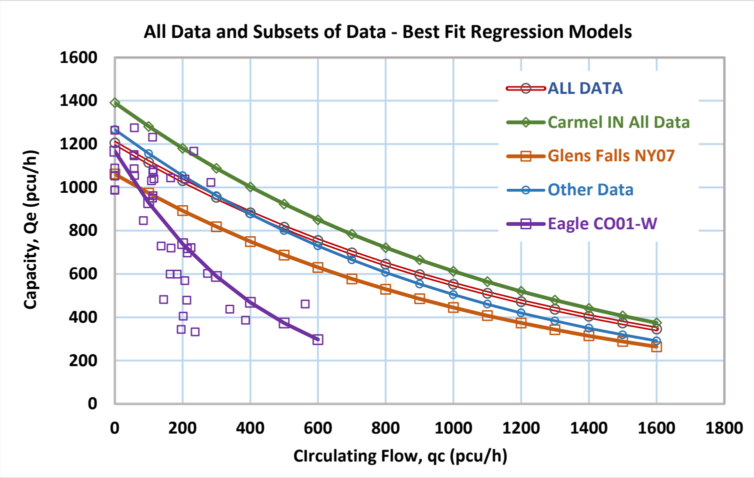


Figure 2.6 - Best fit regression models for the exponential capacity model

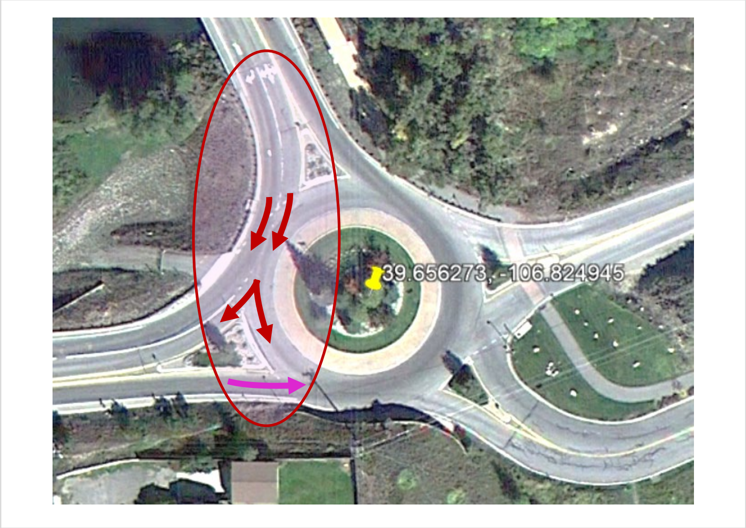


Figure 2.7 - Entering and circulating movement details for the Eagle CO01 site

Table 2.2 - Capacity Models based on best fit regressions for All Data with and without Eagle CO01 data

Regression type	A	B	t_f	t_c	RMSE
All Data with Eagle CO01					
Exponential (Siegloch M1)	1205	0.00078	3.00	4.30	180.2
Linear	1115	- 0.5570	3.23	-	183.5
All Data without Eagle CO01					
Exponential (Siegloch M1)	1271	0.00085	2.83	4.48	168.2
Linear	1148	- 0.5916	3.14	-	174.1

2.2 Gap-Acceptance Parameters

The gap acceptance parameters *follow-up headway*, t_f and *critical gap (headway)*, t_c were measured in surveys for the development of HCM roundabout capacity model. These are reported in Chapter 4 of FHWA (2015).

Table 2.3 summarises the average values of follow-up headway and critical gap calculated for the purposes of analyses described in this report. The average values are weighted by the number of observations.

Some lack of correspondence was observed between the gap acceptance parameter data and the capacity data in relation to the sites included in the two groups of data (FHWA 2015).

It also appears that, as indicated by the different number of data points in *Table 2.3*, the follow-up headway and critical gap data were not collected at the same time.

Table 2.3 - Average values of follow-up headway and critical gap calculated for All Data and data subsets of interest

Data	Follow-up Headway, t_f (seconds)		A = 3600 / t_f	Critical Gap (Headway), t_c (seconds)	
	Number of observations	Weighted Average		Number of observations	Weighted Average
All Data with Eagle CO01	3622	**2.601**	**1384**	2742	**4.687**
All Data without Eagle CO01	3539	**2.596**	**1387**	2727	**4.677**
Glen Falls	1097	**2.838**	**1268**	1576	**4.788**
Carmel All Data	1217	**2.405**	**1497**	616	**3.769**
Other Data	1221	**2.568**	**1402**	535	**5.396**

2.3 Geometry Measurements

In addition to the best fit regression analyses, roundabout geometry parameters were used to estimate model parameters and apply calibration methods to assess these models.

Geometry parameters of interest are:

(i) inscribed diameter, entry radius and entry angle for both the TRL-Kimber linear model and the HCM exponential model with the Basic SIDRA Geometry Method added, and

(ii) the entry width, approach half width and effective flare length for the TRL-Kimber linear model.

Inscribed diameter and entry width values are included in the HCM roundabout capacity research dataset provided. Geometry measurements for Glens Falls NY07 and Carmel IN All Data subsets are given by Johnson and Lin (2018).

Entry width parameter values required for the TRL-Kimber model were used as given in Johnson and Lin (2018). These are "effective entry width" values that are significantly smaller than the entry width values given in the database (and confirmed via Google Earth measurements). For example, the simple average entry width for the Glens Falls roundabout is 16.3 ft (average weighted by the number of data points is 16.6 ft) but a value of 12 ft was used in the TRL-Kimber model. Similarly, simple average entry width for Carmel sites is 18.0 ft (average weighted by the number of data points is 17.6 ft) but a value of 14 ft was used in the TRL-Kimber model. These are reasonable values as "entry lane width" values.

If actual entry width values were used for the TRL-Kimber model, they would overestimate capacity substantially because, being approach based, the model would not understand this is a single lane case. An "effective entry width" concept is used to avoid this problem with the model (Johnson and Hale 2015).

The inscribed diameter, entry radius and entry angle measurements were conducted for Glens Falls NY07 and Carmel IN10 roundabouts roundabout using Google Earth. A good amount of judgement is needed in measuring the entry radius and entry angle values in particular. There are likely to be differences in values from measurements by different people. Differences due to definitional issues are also a possibility.

Our measurements of geometry data are shown in *Figures 2.8 to 2.11*. The measurements for the Glens Falls roundabout indicated differences from those given in Johnson and Lin (2018) as shown *Table 2.4*. The inscribed diameter value of 116 ft matches the HCM capacity research data. The entry angle values are practically the same. A larger difference is observed in entry radius values.

For the analyses reported in this document for the Glens Falls and Carmel data subsets, the values given by Johnson and Lin (2018) were used to facilitate comparison. For All Data, geometry parameters were calculated as the weighted average values of the parameters for the Glens Falls and Carmel data subsets. Data are given in *Table 2.5*. Therefore, these results should be interpreted as rough indicators of the roundabout geometry effect on roundabout capacity.

Table 2.4 - Roundabout geometry parameters for Glens Falls NY07 roundabout (weighted average values for South, East, Northwest and West approaches)

Glens Falls NY07Dataset		D_i	r_e	ϕ_e	w_L	w_a	L_f
Johnson and Lin (2018)	(ft)	105	21	26°	12	11	20
	(m)	32.0	6.4		3.66	3.35	6.1
This report	(ft)	116	34	25°	12	11	20
	(m)	35.4	10.4		3.66	3.35	6.1

D_i = inscribed diameter, **r_e** = entry radius, **ϕ_e** = entry angle, **w_L** = effective entry lane width (smaller than full entry width), **w_a** = approach half width, **L_f** = effective flare length

Table 2.5 - Roundabout geometry parameters used for analyses in this report

Dataset		D_i	r_e	ϕ_e	w_L	w_a	L_f
All Data	(ft)	125	47	20°	13	11.6	22
	(m)	38.1	14.3		3.96	3.54	6.7
Glens Falls NY07	(ft)	105	21	26°	12	11	20
	(m)	32.0	6.4		3.66	3.35	6.1
Carmel IN All Data	(ft)	138	65	16°	14	12	23
	(m)	42.1	19.8		4.27	3.66	7.0

D_i = inscribed diameter, **r_e** = entry radius, **ϕ_e** = entry angle, **w_L** = effective entry lane width (smaller than full entry width), **w_a** = approach half width, **L_f** = effective flare length

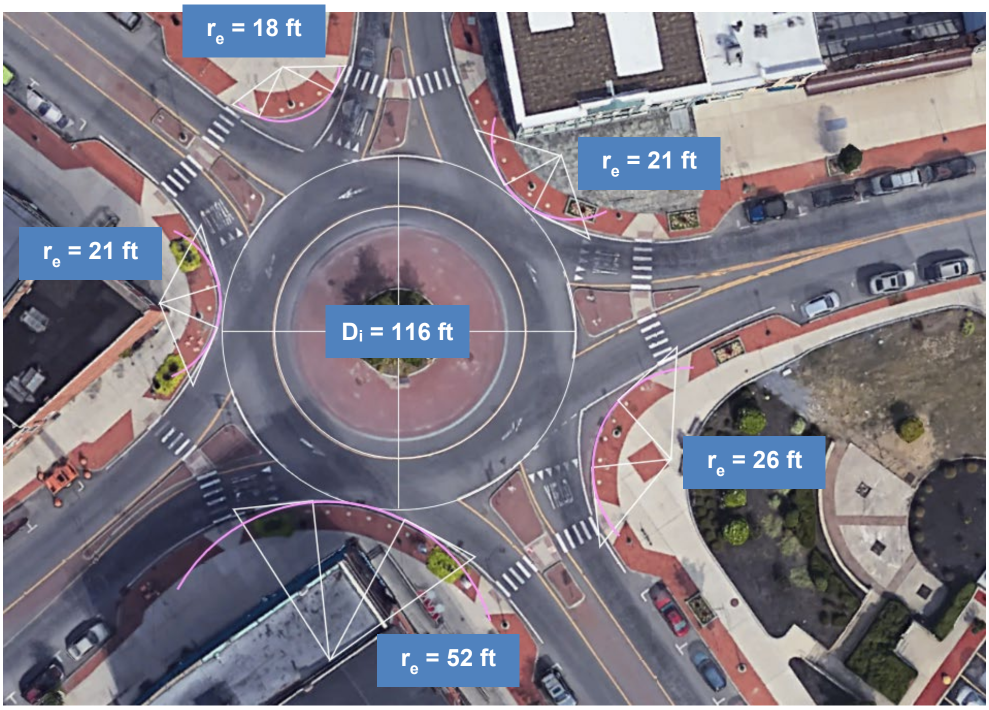


Figure 2.8 - Measuring entry radius values for the Glens Falls NY07 roundabout

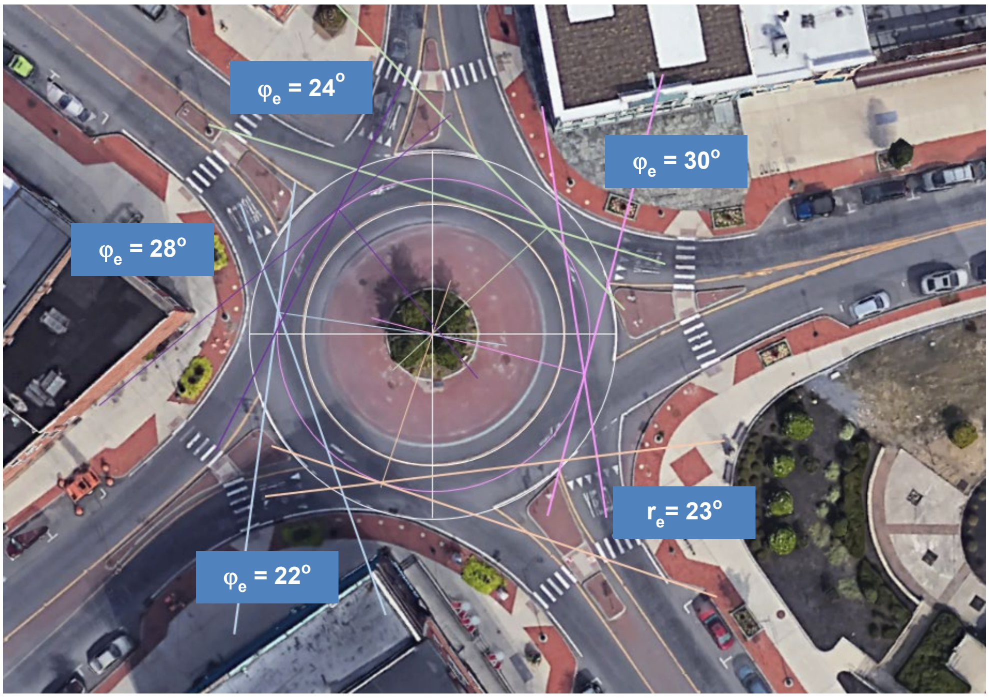


Figure 2.9 - Measuring entry angle values for the Glens Falls NY07 roundabout

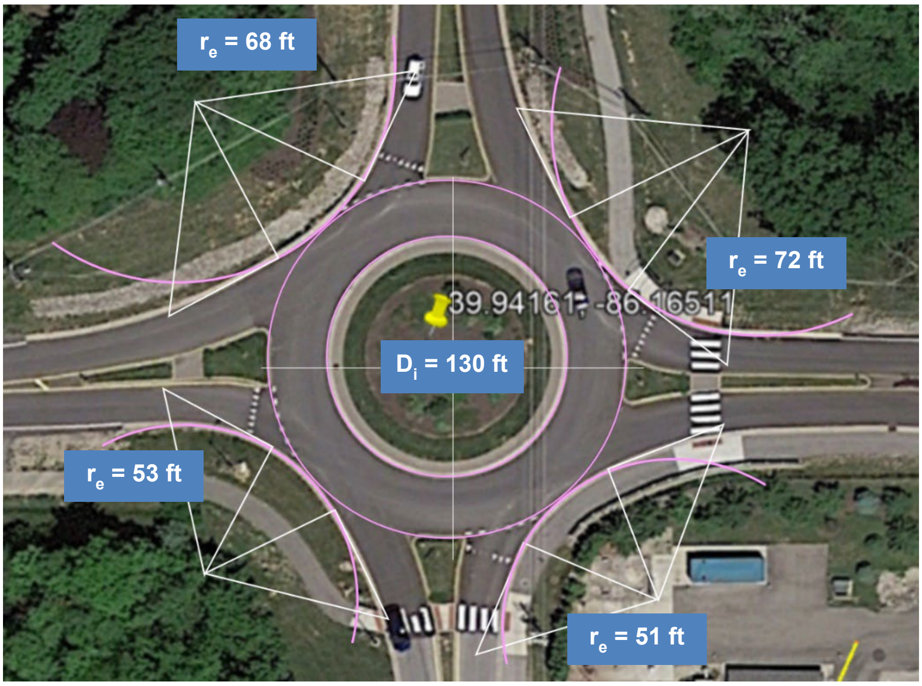


Figure 2.10 - Measuring entry radius values for the Carmel IN10 roundabout

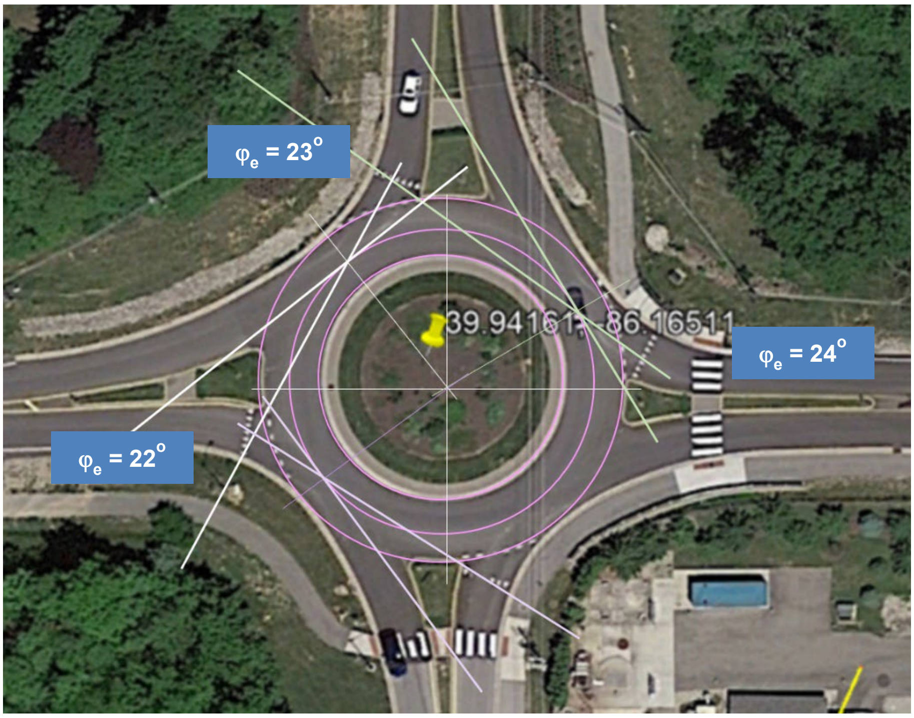


Figure 2.11 - Measuring entry angle values for the he Carmel IN10 roundabout

3 Exponential (Siegloch M1) and Linear Capacity Models

The roundabout capacity models discussed in this report are:

- basic exponential (Siegloch M1) model from best fit regressions,
- HCM exponential (Siegloch M1) model with Basic SIDRA Geometry Method added,
- basic linear model from direct regressions,
- TRL-Kimber linear model with parameters estimated using TRL geometry method (Kimber 1980, 1985, 1989), and
- basic quadratic model for a limited test.

These models are described below. For more detailed discussions on these models, see Akçelik (2022). Results of comparisons of these models for the HCM roundabout research data are given in *Sections 4 and 5*.

3.1 Basic Exponential (Siegloch M1) Capacity Model

The Siegloch (1973) capacity model, which is used in the German guidelines (Brilon 1988, Brilon and Grossman 1991), and forms the basis of the HCM roundabout capacity model (TRB 2016), assumes a negative exponential model of arrival headways (M1), and is given as:

$$Q_e = (3600 / t_f)\, exp\, (-t_o\, q_s) \tag{3.1}$$

$$t_o = t_c - 0.5\, t_f. \tag{3.2}$$

where t_o is the unused part of average accepted headway, t_f is the follow-up headway, t_c is the critical gap (headway) and q_s is the circulating (conflicting / opposing) flow in passenger car units per second (pcu/s).

The HCM roundabout capacity model uses parameters $A = 3600 / t_f$ and $B = t_o / 3600$:

$$Q_e = A\, exp\, (-B\, q_c) \tag{3.3}$$

where $q_c = 3600\, q_s$ is the circulating flow rate in passenger car units per hour (pcu/h).

From *Equations (3.1) to (3.3)*, it can be seen that the critical gap can be estimated from parameter B using:

$$t_c = 3600\, B + 0.5\, t_f \tag{3.4}$$

The slope of the exponential capacity curve given by *Equation (3.1)* is:

$$dQ_e/dq_c = -A\, B\, exp\, (-B\, q_c) = -B\, Q_e \tag{3.5}$$

For single-lane roundabouts, the HCM model parameters are $A = 1380$ ($t_f = 2.61$) and $B = 0.00102$ ($t_c = 4.98$).

3.2 HCM Exponential (Siegloch M1) Capacity Model with Basic SIDRA Geometry Method

A simplified application of the SIDRA model for estimating the gap acceptance parameters as a function of roundabout geometry in the HCM Exponential (Siegloch M1) Capacity Model is introduced in the accompanying report by Akçelik (2022). The method is referred to as the *Basic SIDRA Geometry Method*.

This method estimates the gap acceptance parameters follow-up headway, t_f and critical gap (headway), t_c as a function of inscribed diameter, entry radius and entry angle. Parameters A and B are then calculated from $A = 3600 / t_f$ and $B = t_o / 3600$ where $t_o = t_c - 0.5\, t_f$ as given for the basic model above.

Refer to Section 7 of Akçelik (2022) for a detailed description of the model.

3.3 Basic Linear Capacity Model

The basic ***Linear roundabout capacity model*** form is:

$$Q_e = A + B\, q_c \tag{3.6}$$

where q_c is the circulating flow rate in pcu/h.

Parameters A (y-intercept) and B (slope) in *Equation (3.6)* for the basic model have constant values. As in the exponential model, parameter A can be expressed as:

$$A = 3600 / t_f \tag{3.7}$$

where t_f is treated as an implied follow-up headway (seconds).

3.4 TRL-Kimber Linear Capacity Model with Geometry Parameters

The TRL-Kimber linear model for roundabout capacity applies the basic linear model as an *approach-based* model using parameters describing the roundabout geometry, namely inscribed diameter, entry radius, entry angle, entry lane width, approach half width and effective flare length. Refer to Kimber (1980) or Johnson and Lin (2018) for a detailed description of the model.

3.5 Quadratic Capacity Model

The following quadratic (second degree polynomial) model was tested by Kimber (1980) for estimating capacity as a function of circulating flow:

$$Q_e = A + B\, q_c + C\, q_c^2 \tag{3.8}$$

where q_c is the circulating flow rate in pcu/h and parameter $A = 3600 / t_f$ where t_f is the implied follow-up headway as in the linear model.

Limited testing of this model is discussed in *Section 4.5*.

4 Regression Analyses

4.1 Best Fit and Anchored Regression Results

This section presents results of best fit regressions and anchored regressions (y-intercept specified according to the measured follow-up headway) for the Basic Exponential (Siegloch M1) capacity model (*Section 3.1*) and Basic Linear capacity model (*Section 3.3*). The results are given for All Data, Glens Falls NY07 and Carmel IN All Data (*Section 2.1*).

Regressions were carried out using the R statistical computing software package.

The statistical error levels as measured by Root Mean Square Error (RMSE) are given for models tested. Mean Absolute Error (MAE) values were also determined for all models but the results are not given since the MAE differences for different models were similar to the differences in the RMSE values.

The results for All Data for best fit and anchored regressions are given in *Tables 4.1 to 4.3*. *Figures 4.1 to 4.3* show the corresponding data and regression lines.

Table 4.1 - All Data: Best fit and anchored regressions for
Basic Exponential (Siegloch M1) and Basic Linear capacity models

	A	B	t_f	t_c	t_f / t_c	RMSE	
Exponential (Siegloch M1)	1205	0.00078	2.988	4.302	0.695	180.2	
Basic Linear	1115	-0.5570	3.229	-	-	183.5	
A (t_f) parameter anchored	A	B	t_f	t_c	t_f / t_c	RMSE	Increase in RMSE
Exponential (Siegloch M1)	1384	0.00099	2.601	4.865	0.535	190.5	5.7%
Basic Linear	1384	-0.8795	2.601	-	-	224.0	22.1%

Table 4.2 - Glen Falls NY07: Best fit and anchored regressions for
Basic Exponential (Siegloch M1) and Basic Linear capacity models

	A	B	t_f	t_c	t_f / t_c	RMSE	
Exponential (Siegloch M1)	1062	0.00087	3.389	4.827	0.702	104.2	
Basic Linear	981	-0.5658	3.669	-	-	102.6	
A (t_f) parameter anchored	A	B	t_f	t_c	t_f / t_c	RMSE	Increase in RMSE
Exponential (Siegloch M1)	1268	0.00114	2.838	5.524	0.514	111.2	6.7%
Basic Linear	1268	-0.9674	2.838	-	-	132.0	28.7%

Table 4.3 - Carmel IN All Data: Best fit and anchored regressions for
Basic Exponential (Siegloch M1) and Basic Linear capacity models

	A	B	t_f	t_c	t_f / t_c	RMSE	
Exponential (Siegloch M1)	1391	0.00082	2.588	4.246	0.610	152.4	
Basic Linear	1260	-0.6322	2.857	-	-	152.0	
A (t_f) parameter anchored	A	B	t_f	t_c	t_f / t_c	RMSE	Increase in RMSE
Exponential (Siegloch M1)	1497	0.00092	2.405	4.515	0.533	155.5	2.0%
Basic Linear	1497	-0.8845	2.405	-	-	184.6	21.4%

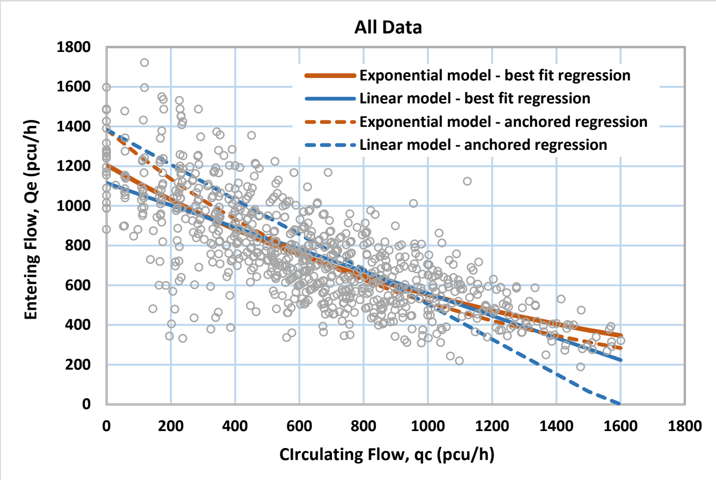


Figure 4.1 - All Data: best fit and anchored regression models

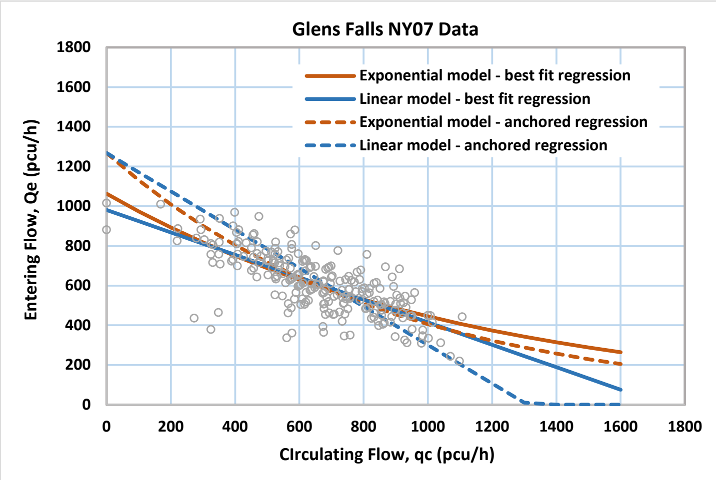


Figure 4.2 - Glens Falls NY07: best fit and anchored regression models

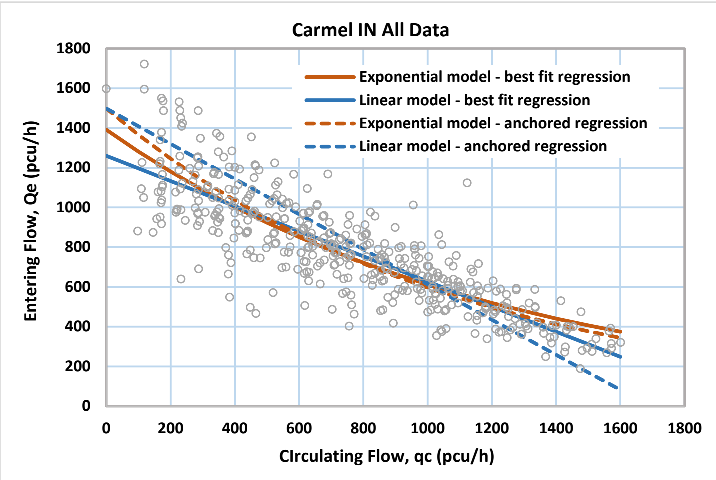


Figure 4.3 - Carmel IN All Data: best fit and anchored regression models

4.2 About the Anchored Regression Results

The best fit regression results in *Tables 4.1 to 4.3 and Figures 4.1 to 4.3* indicate that both exponential and linear models perform well with close values of RMSE, and they give close estimates of capacity for the medium range of circulating flow but the linear model estimates lower values of capacity for low and high circulating flows.

On the other hand, the anchored regressions indicate different results for the exponential and linear models. Anchored regressions were conducted by specifying the y-intercept (A) values based on the measured follow-up headways, t_f ($A = 3600 / t_f$) given in *Table 2.3*.

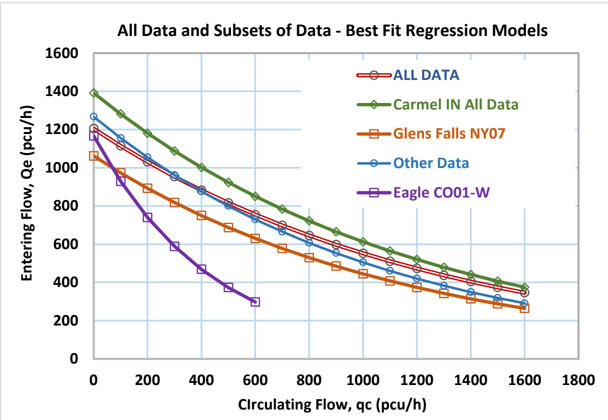
The capacity estimates from anchored regressions indicate that the exponential model estimates can stay close to the best fit regression estimates for medium to high circulating flows whereas the linear model capacity estimates become significantly lower at high circulating flows. This is due to the constant slope of the linear model. The reducing slope of the exponential model helps it to adopt to the changes in the observed data. In *Tables 4.1 to 4.3*, this is indicated by small increases in RMSE values for the anchored regressions for the exponential model (2.0% to 6.7%) but large increases for the linear model (21.4% to 28.7%).

Therefore, the calibration of the linear model by measuring the follow-up headway is not recommended whereas this method is considered to be suitable for the exponential model. This is further discussed in *Section 5*.

Higher capacity estimates at low circulating flows given by anchored regressions are useful in modelling the specific condition of unbalanced flows. The exponential model achieves this with small increases in the overall error levels with good accuracy of capacity estimates at high circulating flows. On the other hand, capacity estimates from the linear model indicate significantly increased overall error levels and unsatisfactory results for high circulating flows.

The importance of estimating high levels of capacity for low circulating flows in modelling unbalanced flow conditions is discussed further in *Section 6*.

Best fit regression results for All Data, Glen Falls NY07, Carmel IN All Data as well as Other Data (NY08 and WA All Data) and Eagle CO01 data shown in *Figure 4.4* indicates the consistency of the exponential model best fit regressions unlike the linear model which shows wider variability. The outlier characteristic of the Eagle CO01 data is also seen (discussion in *Section 2.1*).



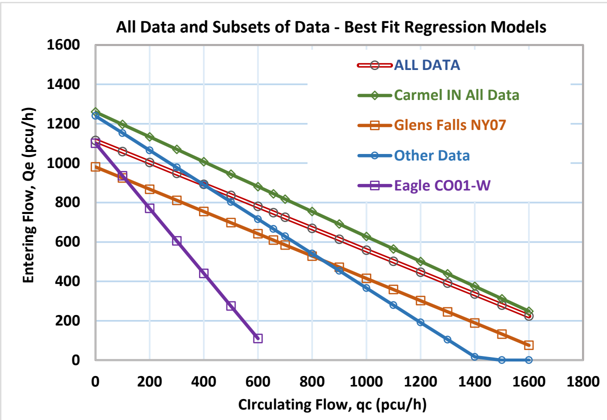


Figure 4.4 - Best fit regressions for All Data and subsets of data: model consistency differences between results for exponential and linear models

4.3 Follow-up Headway and Critical Gap Values Implied by Best Fit Regressions

The gap acceptance parameters *follow-up headway*, t_f and *critical gap (headway)*, t_c measured in surveys for the development of the HCM roundabout capacity model FHWA (2015) were discussed in *Section 2.2*. The average values of measured follow-up headway and critical gap are summarised in *Table 2.3*.

As seen in *Table 4.4*, the best fit regression models are found to imply larger values of follow-up headways compared with the measured follow-up headways. The ratios of implied follow-up headway to measured follow-up headway are larger for the linear model since the estimated y-intercept values ($A = 3600 / t_f$) and capacities at low circulating flows found by best fit regression are lower.

There are also differences between the implied values of critical gap from best fit regressions for the exponential model compared with the measured values of critical gap.

While the larger implied follow-up headway values are expected for the linear model, the differences between implied and measured values of gap acceptance parameters need to be investigated for the exponential model. In particular, the survey methods used for these gap acceptance parameters should be paid more attention. The Siegloch survey method attributed to Siegloch (Brilon and Grossman 1991; Brilon, Koenig and Troutbeck 1997; TRB 1997; Akçelik 2007) is recommended by the authors for this purpose since this method measures critical gaps and follow-up headways at the same time. The method has been recommended for calibration and validation of the SIDRA gap acceptance model over alternative methods including the maximum likelihood method.

Ideally, the follow-up headway and critical gap surveys should be carried out at the same time as the capacity surveys. As discussed in *Section 2.2*, the HCM roundabout research data FHWA (2015) indicate various mismatches between the gap acceptance parameter data and capacity data in relation to the sites included in the datasets. It also appears that, as indicated by the different number of data points in *Table 2.3*, the follow-up headway and critical gap data were not collected at the same time.

Table 4.4 - Comparing follow-up headway values implied by Best fit regression against measured follow-up headway values

	Exponential (Siegloch M1) Model			Linear Model		
Capacity Data >>	ALL DATA	Glens Falls NY07	Carmel IN All Data	ALL DATA	Glens Falls NY07	Carmel IN All Data
Regression A =	1205	1062	1391	1115	981	1260
Regression B =	0.00078	0.00087	0.00082	-0.5570	-0.5658	-0.6322
RMSE	180.2	104.2	152.4	183.5	102.6	152.0
Regression $t_f = 3600 / A$	2.988	3.390	2.588	3.229	3.670	2.857
Regression t_c =	4.302	4.827	4.246	-	-	-
Regression t_f / t_c =	0.694	0.702	0.610	-	-	-
Measured t_f =	2.601	2.838	2.405	2.601	2.838	2.405
Measured t_c =	4.687	4.788	3.769	4.687	4.788	3.769
Measured t_f / t_c =	0.555	0.593	0.638	0.555	0.593	0.638
$A = 3600 / t_f$ =	1384	1268	1497	1384	1268	1497
Ratio of implied t_f to measured t_f	1.15	1.19	1.08	1.24	1.29	1.19
Ratio of implied t_c to measured t_c	0.92	1.01	1.13	-	-	-

t_f = follow-up headway, t_c =critical gap (headway)

It is also likely that the *small frequencies of capacity data for low circulating flows* will affect the differences between follow-up headways implied by best fit regressions and the measured follow-up headways. The capacity data frequencies by circulating flow are discussed in *Section 2.1* with *Figure 2.4* showing significant differences between Glens Falls NY07 data and Carmel IN All Data.

4.4 Two-Segment Regression Models

Discussions in *Sections 4.1 and 4.2* indicate that the linear model has a structural issue in estimating low capacities for low and high circulating flows. Data analyses so far focused on differences in data subsets for the Glens Falls NY07 roundabout and all sites in Carmel IN. This was suggested by Johnson and Lin (2018) as a way of distinguishing between different types of roundabout geometry. While this is a useful suggestion, it is also necessary to understand the exponential characteristic of roundabout capacity generally. This is indicated by a visual inspection of HCM roundabout research data as seen in *Figure 2.1*.

The exponential characteristic of the HCM roundabout data is clearer when the Eagle CO01 data is excluded as indicated in *Figure 4.5* (the outlier characteristic of this site is discussed in *Section 2.1*). This characteristic of roundabout capacity data is a result of the circulating flow headway distributions (Akçelik 2007, 2022).

FHWA (2015), Chapter 5 discusses the case of Carmel IN10-N and IN10-W datasets at the same roundabout where the North and West approaches have very close geometry parameter values (see *Figures 2.10 and 2.11* in *Section 2.3*) but the North approach has low circulating flows and the West approach has high circulating flows (Figure 37 of FHWA 2015). The report stated "*... it is clear when plotting the two (datasets) together on the same graph that the two linear regression models have different slopes, despite having the same geometric configuration. An exponential model visibly provides the best overall fit (RMSE of 99) by capturing the higher slope under low circulating flows and the lower slope under high circulating flows. By contrast, a linear regression model across both sites yields an RMSE of 117.*".

While the Glens Falls NY07 and Carmel IN All Data subsets considered by Johnson and Lin (2018) represent a *horizontal slicing of data*, the discussion in FHWA (2015) represents a *vertical slicing of data* into lower and higher sets of circulating flow values.

With this in mind, two-segment linear and exponential models were explored via best fit regressions applied to two separate subsets of data created by vertical slicing of data. This was carried out for All Data and Carmel IN All Data. The Glens Falls dataset was not used for this analysis due to a very low number of data points in the low circulating flow range.

The two segments were defined with entering flow (capacity) data in the circulating flow range of 0-700 pcu/h for Segment 1 and above 700 pcu/h for Segment 2. The separation at 700 pcu/h was selected considering the average value of circulating flow at 642 pcu/h for All Data and 754 pcu/h for Carmel IN All data. Accordingly, the numbers of entering flow data points are 489 (60%) in Segment 1 and 332 (40%) in Segment 2 for All Data, and 203 (46%) in Segment 1 and 234 (54%) in Segment 2 for Carmel IN All Data.

The regression analyses were specified with continuity of the two segments so that the same capacity was estimated at the circulating flow of 700 pcu/h.

The results of these regressions are summarised in *Tables 4.5 and 4.6* and shown in *Figures 4.6 and 4.7*. Comparisons of these results show (more clearly for All Data in *Table 4.5* and *Figure 4.6*) that the slopes of the linear model vary for the two segments significantly with some improvement in the RMSE values. This is because a two-segment linear model has the ability to adapt to differences between low and high circulating flow conditions indicating the exponential characteristic of the capacity data. It is important to note that these results are obtained with no change in the roundabout geometry characteristics in datasets.

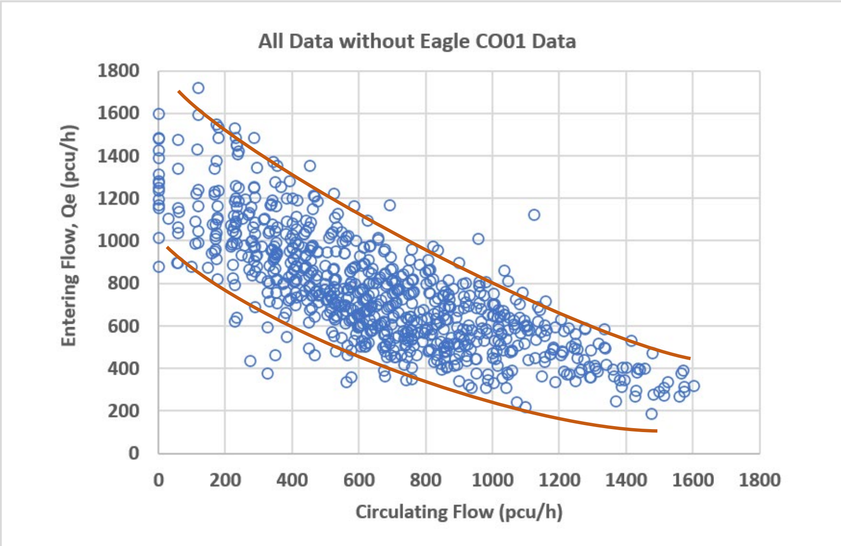


Figure 4.5 - Exponential characteristic of the HCM roundabout capacity research data (Eagle COI01 site excluded) indicated by visual inspection

Table 4.5 - All Data: Two-segment best fit regressions for Basic Exponential (Siegloch M1) and Basic Linear capacity models

Exponential (Siegloch M1)	Aver. q_c	Aver. Q_e	A	B	t_f	t_c	t_f / t_c	RMSE
Segment 1 ($q_c \leq 700$ pcu/h)	408	885	1219	0.00082	2.953	4.429	0.67	180.0
Segment 2 ($q_c > 700$ pcu/h)	986	571	1118	0.00069	3.220	4.094	0.79	
Single segment regression	642	758	1205	0.00078	2.988	4.302	0.70	180.2
Basic Linear	Aver. q_c	Aver. Q_e	A	B	t_f	t_c	t_f / t_c	RMSE
Segment 1 ($q_c \leq 700$ pcu/h)	408	885	1191	-0.7500	3.023	-	-	179.6
Segment 2 ($q_c > 700$ pcu/h)	986	571	916	-0.3561	3.930	-	-	
Single segment regression	642	758	1115	-0.5570	3.229	-	-	183.5

q_c: Circulating flow (pcu/h), Q_e = Entering flow (pcu/h), t_f = Follow-up headway (s), t_c = Critical gap (s)

Table 4.6 - Carmel IN All Data: Two-segment best fit regressions for Basic Exponential (Siegloch M1) and Basic Linear capacity models

Exponential (Siegloch M1)	Aver. q_c	Aver. Q_e	A	B	t_f	t_c	t_f / t_c	RMSE
Segment 1 ($q_c \leq 700$ pcu/h)	420	998	1349	0.00074	2.669	3.999	0.67	151.7
Segment 2 ($q_c > 700$ pcu/h)	1045	597	1545	0.00093	2.330	4.513	0.52	
Single segment regression	754	783	1391	0.00082	2.588	4.246	0.610	152.4
Basic Linear	Aver. q_c	Aver. Q_e	A	B	t_f	t_c	t_f / t_c	RMSE
Segment 1 ($q_c \leq 700$ pcu/h)	420	998	1304	-0.7309	2.761			151.0
Segment 2 ($q_c > 700$ pcu/h)	1045	597	1187	-0.5635	3.033	-	-	
Single segment regression	754	783	1260	-0.6322	2.857	-	-	152.0

q_c: Circulating flow (pcu/h), Q_e = Entering flow (pcu/h), t_f = Follow-up headway (s), t_c = Critical gap (s)

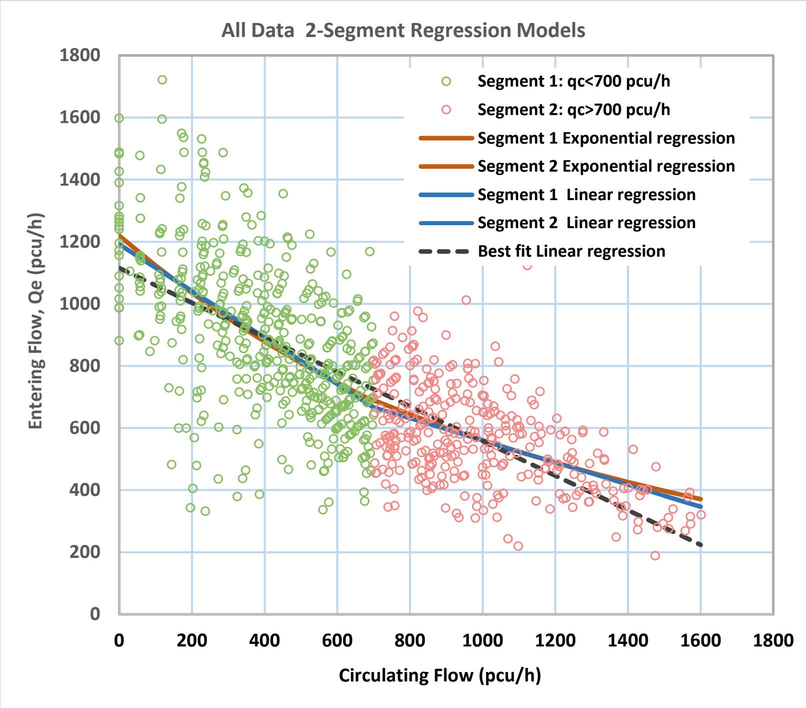


Figure 4.6 - All Data: two-segment exponential and linear regression models (single-segment best fit linear model also shown)

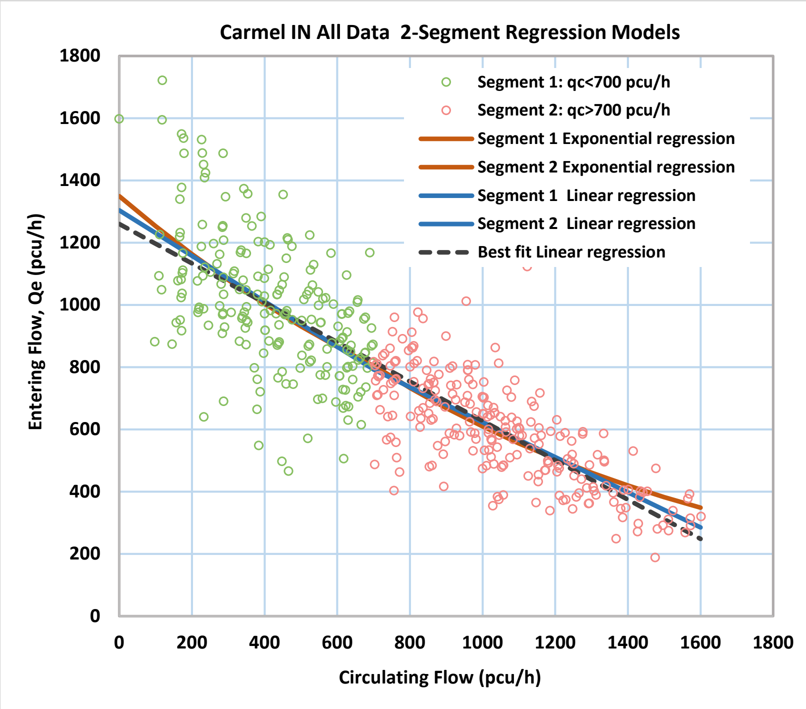


Figure 4.7 - Carmel IN All Data: two-segment exponential and linear regression models (single-segment best fit linear model also shown)

4.5 Aggregate Data Analysis

FHWA (2015) Chapter 5 described tests of models using data clustered into groups of 10 observations of entering flows with mean values after data were sorted by conflicting (circulating) flow. The results of regression of group means were given in Figure 32 of the report with the conclusion that the exponential model did better than then linear model in terms of RMSE values.

To test whether the data became too coarse due to aggregation by 10 data points in the original study, mean values of entering flow and conflicting flow were calculated for groups of 2 and 3 data points for testing the basic exponential and linear models. Single-segment and two-segment best fit and anchored regression tests were applied. Two-segment regressions used a vertical slicing of data at circulating flow rate of 700 pcu/h. For a variation, analyses reported in this section were done using All Data but excluding the Eagle CO01 site, therefore referred to as the ***All Data without Eagle CO01*** dataset (the outlier characteristic of the Eagle CO001 site is discussed in *Section 2.1*).

As the original data were qualified as ***one-minute*** observations, the aggregate data were referred to as ***two-minute*** and ***three-minute*** datasets (these are approximate descriptors of the durations of data points). One-minute, two-minute and three-minute datasets had 782, 391 and 261 data points, respectively.

The results of these regression tests are summarised in *Tables 4.7 to 4.10*. As the results for two-minute and three-minute datasets were very close, only the results for the three-minute dataset are given.

The results for the two-segment best fit regression models as well as the linear single-segment best fit model obtained with the three-minute dataset are shown in *Figure 4.8*.

From *Figure 4.8* and *Tables 4.7 to 4.10*, it is seen that the results for the three-minute aggregated dataset are much the same as the original one-minute dataset. While the RMSE values are close for the two-segment exponential and linear models, the latter has higher RMSE values for single-segment analysis.

These datasets also show that the form of capacity - circulating flow functions is essentially an exponential (non-linear) one as indicated clearly by the two different slopes of the two-segment model. As in the analyses reported in other sections, the estimates of y-intercept values by the linear model are consistently lower than those estimated by the exponential model, and the linear model does not perform well with anchored regressions.

Table 4.7 - All Data without Eagle CO01: Best fit regressions using One-Minute dataset for Basic Exponential (Siegloch M1) and Basic Linear capacity models

Basic Exponential (Siegloch M1) Model	Aver. q_c	Aver. Q_e	A	B	t_f	t_c	t_f / t_c	RMSE
Single-segment analysis - One-Minute dataset - Best fit regression								
	666	754	1271	0.00085	2.832	4.476	0.633	168.2
Two-Segment analysis - One-Minute dataset - Best fit regression								
Segment 1 ($q_c \le 700$ pcu/h)	430	889	1310	0.00094	2.748	4.758	0.578	167.3
Segment 2 ($q_c > 700$ pcu/h)	986	571	1081	0.00066	3.330	4.041	0.824	
Basic Linear Model	**Aver. q_c**	**Aver. Q_e**	**A**	**B**	**t_f**	**t_c**	**t_f / t_c**	**RMSE**
Single-segment analysis - One-Minute dataset - Best fit regression								
	666	754	1148	-0.5916	3.136	-	-	174.1
Two-Segment analysis - One-Minute dataset - Best fit regression								
Segment 1 ($q_c \le 700$ pcu/h)	430	889	1267	-0.8807	2.841	-	-	167.0
Segment 2 ($q_c > 700$ pcu/h)	986	571	882	-0.3259	4.082	-	-	

q_c: Circulating flow (pcu/h), Q_e = Entering flow (pcu/h), t_f = Follow-up headway (s), t_c = Critical gap (s)

Table 4.8 - All Data without Eagle CO01: Best fit regressions using Three-Minute dataset for Basic Exponential (Siegloch M1) and Basic Linear capacity models

Basic Exponential (Siegloch M1) Model	Aver. q_c	Aver. Q_e	A	B	t_f	t_c	t_f / t_c	RMSE
Single-segment analysis - Three-Minute dataset - Best fit regression								
	667	753	1271	0.00084	2.832	4.440	0.638	99.1
Two-segment analysis - Three-Minute dataset - Best fit regression								
Segment 1 ($q_c \le 700$ pcu/h)	430	889	1309	0.00094	2.750	4.759	0.578	97.6
Segment 2 ($q_c > 700$ pcu/h)	988	570	1081	0.00066	3.330	4.041	0.824	
Basic Linear Model	**Aver. q_c**	**Aver. Q_e**	**A**	**B**	**t_f**	**t_c**	**t_f / t_c**	**RMSE**
Single-segment analysis - Three-Minute dataset - Best fit regression								
	667	753	1147	-0.5914	3.139	-	-	108.9
Two-segment analysis - Three-Minute dataset - Best fit regression								
Segment 1 ($q_c \le 700$ pcu/h)	430	889	1267	-0.8799	2.841	-	-	97.3
Segment 2 ($q_c > 700$ pcu/h)	988	570	876	-0.3213	4.110	-	-	

q_c: Circulating flow (pcu/h), Q_e = Entering flow (pcu/h), t_f = Follow-up headway (s), t_c = Critical gap (s)

Table 4.9 - All Data without Eagle CO01: Anchored regressions using One-Minute dataset for Basic Exponential (Siegloch M1) and Basic Linear capacity models

Basic Exponential (Siegloch M1) Model	Aver. q_c	Aver. Q_e	A	B	t_f	t_c	t_f / t_c	RMSE
Single-segment analysis - One-Minute dataset - Anchored regression								
	666	754	1387	0.00098	2.596	4.826	0.538	172.0
Two-Segment analysis - One-Minute dataset - Anchored regression								
Segment 1 ($q_c \le 700$ pcu/h)	430	889	1387	0.00106	2.596	5.114	0.508	168.6
Segment 2 ($q_c > 700$ pcu/h)	986	571	1006	0.00059	3.579	3.913	0.914	
Basic Linear Model	**Aver. q_c**	**Aver. Q_e**	**A**	**B**	**t_f**	**t_c**	**t_f / t_c**	**RMSE**
Single-segment analysis - One-Minute dataset - Anchored regression								
	666	754	1387	-0.8765	2.596	-	-	205.3
Two-Segment analysis - One-Minute dataset - Anchored regression								
Segment 1 ($q_c \le 700$ pcu/h)	430	889	1387	-1.1156	2.596	-	-	172.5
Segment 2 ($q_c > 700$ pcu/h)	986	571	780	-0.2376	4.615	-	-	

q_c: Circulating flow (pcu/h), Q_e = Entering flow (pcu/h), t_f = Follow-up headway (s), t_c = Critical gap (s)

Table 4.10 - All Data without Eagle CO01: Anchored regressions using Three-Minute dataset for Basic Exponential (Siegloch M1) and Basic Linear capacity models

Basic Exponential (Siegloch M1) Model	Aver. q_c	Aver. Q_e	A	B	t_f	t_c	t_f / t_c	RMSE
Single-segment analysis - Three-Minute dataset - Anchored regression								
	667	753	1387	0.00098	2.596	4.826	0.538	105.5
Two-segment analysis - Three-Minute dataset - Anchored regression								
Segment 1 ($q_c \le 700$ pcu/h)	430	889	1387	0.00106	2.596	5.114	0.508	100.0
Segment 2 ($q_c > 700$ pcu/h)	988	570	1000	0.00059	3.600	3.924	0.917	
Basic Linear Model	**Aver. q_c**	**Aver. Q_e**	**A**	**B**	**t_f**	**t_c**	**t_f / t_c**	**RMSE**
Single-segment analysis - Three-Minute dataset - Anchored regression								
	667	753	1387	-0.8754	2.596	-	-	154.2
Two-segment analysis - Three-Minute dataset - Anchored regression								
Segment 1 ($q_c \le 700$ pcu/h)	430	889	1387	-1.1154	2.596	-	-	107.1
Segment 2 ($q_c > 700$ pcu/h)	988	570	765	-0.2255	4.706	-	-	

q_c: Circulating flow (pcu/h), Q_e = Entering flow (pcu/h), t_f = Follow-up headway (s), t_c = Critical gap (s)

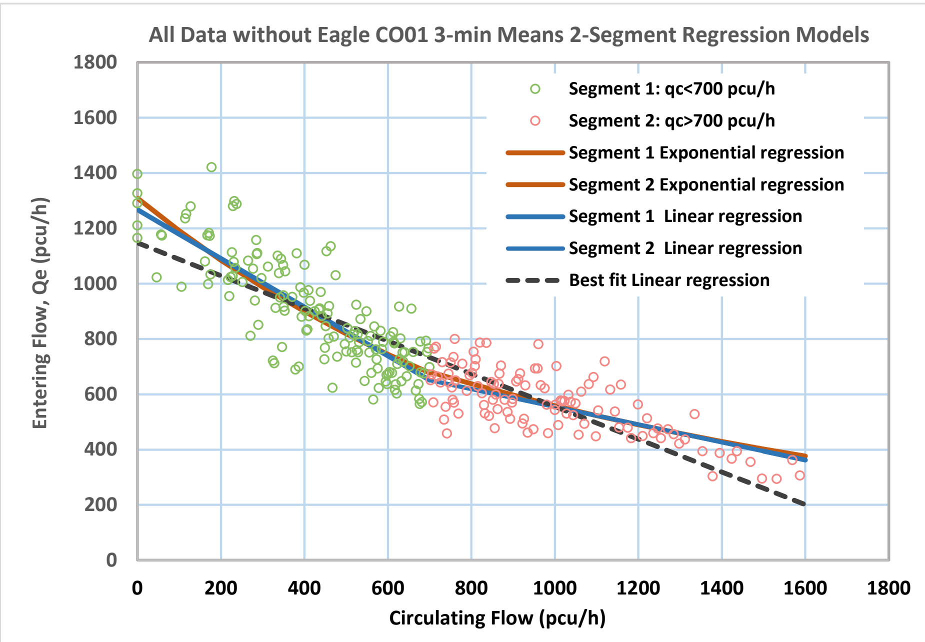


Figure 4.8 - All Data without Eagle CO01: two-segment exponential and linear regression models (single-segment best fit linear model also shown)

4.6 Quadratic Model Regressions

In the report for the TRL-Kimber linear model, Kimber (1980) tested the quadratic ("second order empirical") model and concluded that "it has not been possible to detect any (statistically) significant non-linearity with respect to (circulating flow)". It appears that Kimber did not test a non-linear model of the exponential form. The quadratic model is described in *Section 3.5*.

The best fit regression results for All Data given in *Table 4.11* and shown in *Figure 4.9* indicate that the basic quadratic model somehow gave a better model than the basic linear model indicating non-linear characteristic of the dataset. However, a poor characteristic of this model is that capacity estimates start increasing at high circulating flows as seen clearly for the anchored regression model. Therefore, the quadratic model is not recommended for use.

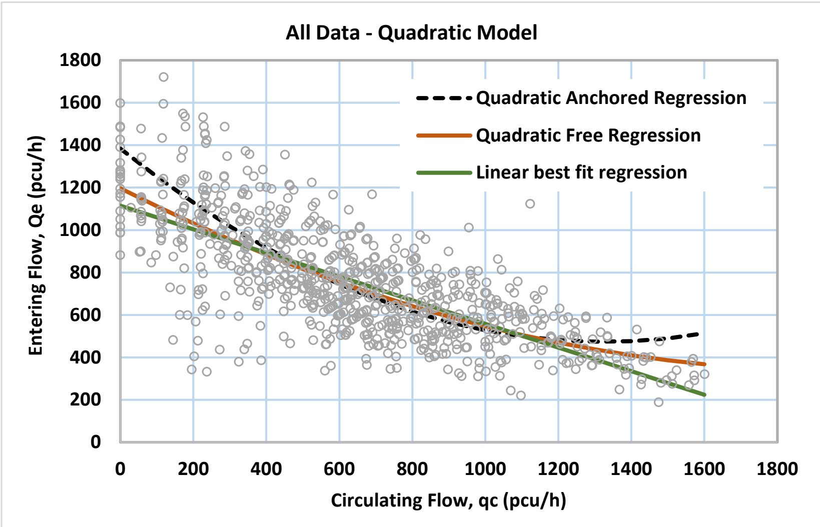


Figure 4.9 - All Data: best fit and anchored regression models for the quadratic model

Table 4.11 - All Data: best fit and anchored regressions for the Quadratic model

	A	B	C	t_f	t_c	t_f / t_c	RMSE
Basic Quadratic	**1197**	**-0.8700**	**0.00022**	**3.008**	**-**	**-**	**180.4**
Basic Linear	**1115**	**-0.5570**	**-**	**3.229**	**-**	**-**	**183.5**
A (t_f) parameter anchored	**A**	**B**		**t_f**	**t_c**	**t_f / t_c**	**RMSE**
Basic Quadratic	**1384**	**-1.376**	**0.00052**	**2.601**	**-**	**-**	**189.5**
Basic Linear	**1384**	**-0.8795**	**-**	**2.601**	**-**	**-**	**224.0**

5 Calibrated Capacity Models

Model calibration results for the HCM (Siegloch M1) Exponential with the *Basic SIDRA Geometry Method* added (*Section 3.2*) and the TRL-Kimber Linear model with geometry parameters (*Section 3.4*) are given in this section. The original estimates from these models are referred to as *default models*. These models are subjected to alternative calibration methods.

Average roundabout geometry parameters used in the analyses are given in *Table 2.5* in *Section 2.3*.

Adding the Basic SIDRA Geometry Method to the HCM (Siegloch M1) roundabout capacity model is discussed in detail in Section 7 of the accompanying report (Akçelik 2022).

The calibration methods investigated are described in detail in Section 8 of the accompanying report (Akçelik 2022). In summary, the following methods are tested (in the equations given, Q_{ea} = average entry flow (capacity) in pcu/h and q_{ca} = average circulating flow in pcu/h.

- ***HCM Exponential (Siegloch M1) model with the Basic SIDRA Geometry Method***:
  - Calibration Method 1: adjust the Environment Factor (f_e) in the Basic SIDRA Geometry Method,
  - Calibration Method 2: use the y-intercept (A) of the default model as specified and calculate the slope (B):

    $$B = -ln\,(Q_{ea} / A) / q_{ca} \qquad (5.1)$$

    This equation was used for the results given in this section. It is also possible to use the average value of *ln* (Q_e / A) instead of using the average Q_{ea} in the equation.
  - Calibration Method 3: use the y-intercept determined from measured follow-up headway, t_f (A = 3600 / t_f) and calculate the slope (B) from *Equation (5.1)*.

- ***TRL-Kimber Linear capacity model***:
  - Calibration Method 1: use the slope (B) of the default model as specified and calculate the y-intercept (A) as recommended in Kimber (1980):

    $$A = Q_{ea} + B\,q_{ca} \qquad (5.2)$$
  - Calibration Method 2: use the y-intercept (A) of the default model as specified and calculate the slope (B):

    $$B = (Q_{ea} - A) / q_{ca} \qquad (5.3)$$
  - Calibration Method 3: use the y-intercept determined from measured follow-up headway, t_f (A = 3600 / t_f) and calculate the slope (B) from *Equation (5.3)*.

The results for alternative calibration methods for the linear and exponential models are summarised in *Tables 5.1 to 5.3* and shown in *Figures 5.1 to 5.3*. Best fit regression models are included in these tables and figures for comparisons of RMSE values.

It is seen that the default HCM exponential model estimates with the Basic SIDRA Geometry Method have lower RMSE values (1.6% to 4.6%) than the default the TRL-Kimber model estimates (10.5% to 19.5%).

RMSE values of Calibration Methods 1 and 2 are seen to be close to RMSE values of best fit regression models (0.9% to 5.3% for the HCM model with the Basic SIDRA Geometry Method and 0.2% to 2.9% for the TRL-Kimber model).

The RMSE values for Calibration Method 3 (using the measured follow-up headway) are reasonably close to best fit regression values for the HCM model with the Basic SIDRA Geometry Method (4.3% to 7.1%). Differences are large for the TRL-Kimber model (26.0% to 31.0%). This is similar to the results of anchored regressions for the basic linear model (21.4% to 28.7%) as discussed in *Section 4.2*.

Figures 5.1 to 5.3 show that, as for anchored regressions, the exponential model calibrated using the measured follow-up headway can stay close to the best fit regression estimates for medium to high circulating flows whereas estimates from the linear model calibrated using the measured follow-up headway become significantly lower at high circulating flows. As discussed in *Section 4.2*, this is due to the constant slope of the linear model.

As shown by Johnson and Lin (2018), it is reasonable to expect that roundabout geometry parameters may have a combined (aggregate) effect applicable to different roundabout geometry types. Analyses of calibration methods for subsets of data using both the HCM (Siegloch) exponential capacity model with the Basic SIDRA Geometry Method added (Akçelik 2022) and the TRL-Kimber model support the suggestion by Johnson and Lin (2018).

Table 5.1 - All Data: Alternative calibration methods for HCM Exponential model with the Basic SIDRA Geometry Method added and the TRL-Kimber Linear model

Exponential model with SIDRA Geometry	A	B	t_f	t_c	t_f / t_c	RMSE	Increase in RMSE
Basic Exponential - Best fit regression	1205	0.000780	2.988	4.302	0.695	180.2	-
SIDRA Geometry default (f_e = 1.05)	1363	0.000954	2.641	4.755	0.556	188.4	4.6%
Calibration 1: SIDRA Geometry (f_e = 1.07)	1337	0.000972	2.693	4.845	0.556	186.6	3.6%
Calibration 2: B from *Equation (5.1)*	1363	0.000914	2.641	4.612	0.573	189.8	5.3%
Calibration 3: B from *Equation (5.1)* with A from measured t_f	1384	0.000938	2.601	4.678	0.556	192.0	6.5%
TRL-Kimber Linear model	**A**	**B**	**t_f**	**t_c**	**t_f / t_c**	**RMSE**	**Increase in RMSE**
Basic Linear - Best fit regression	1115	-0.5570	3.229	-	-	183.5	-
TRL-Kimber default model	1197	-0.5495	3.008	-	-	202.8	10.5%
Calibration 1: A from *Equation (5.2)*	1090	-0.5495	3.304	-	-	184.7	0.7%
Calibration 2: B from *Equation (5.3)*	1197	-0.6840	3.008	-	-	188.8	2.9%
Calibration 3: B from *Equation (5.3)* with A from measured t_f	1384	-0.9755	2.601	-	-	234.8	28.0%

Average entering flow (capacity), Q_{ea} = 758 pcu/h, Average circulating flow, q_c = 642 (pcu/h)

Table 5.2 - Glens Falls NY07: Alternative calibration methods for HCM Exponential model with the Basic SIDRA Geometry Method added and the TRL-Kimber Linear model

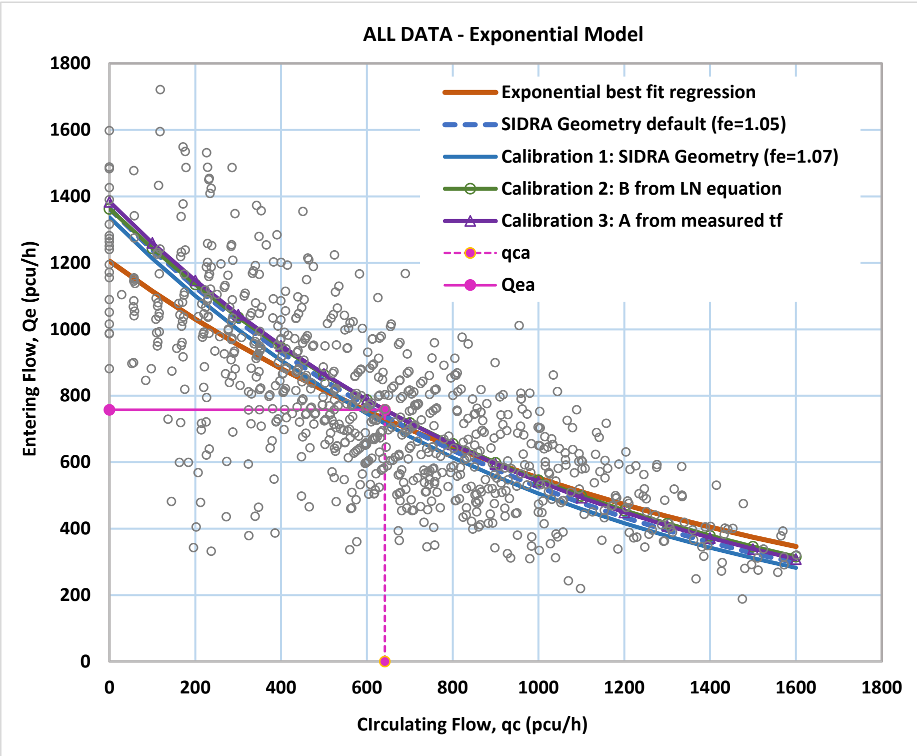
Exponential model with SIDRA Geometry	A	B	t_f	t_c	t_f / t_c	RMSE	Increase in RMSE
Basic Exponential - Best fit regression	1062	0.00087	3.389	4.827	0.702	104.2	-
SIDRA Geometry default (f_e = 1.05)	1195	0.00109	3.013	5.423	0.556	108.3	3.9%
Calibration 1: SIDRA Geometry (f_e = 1.04)	1206	0.00108	2.985	5.373	0.556	107.9	3.6%
Calibration 2: B from *Equation (5.1)*	1195	0.00102	3.013	5.195	0.580	107.6	3.3%
Calibration 3: B from *Equation (5.1)* with A from measured t_f	1268	0.00112	2.838	5.435	0.522	111.6	7.1%
TRL-Kimber Linear model	**A**	**B**	**t_f**	**t_c**	**t_f / t_c**	**RMSE**	**Increase in RMSE**
Basic Linear - Best fit regression	981	-0.5658	3.669	-	-	102.6	-
TRL-Kimber default model	997	-0.4845	3.611	-	-	124.7	21.5%
Calibration 1: A from *Equation (5.2)*	928	-0.4845	3.879	-	-	103.9	1.3%
Calibration 2: B from *Equation (5.3)*	997	-0.5900	3.611	-	-	102.8	0.2%
Calibration 3: B from *Equation (5.3)* with A from measured t_f	1268	-1.0040	2.838	-	-	134.4	31.0%

Average entering flow (capacity), Q_{ea} = 611 pcu/h, Average circulating flow, q_c = 655 (pcu/h)

Table 5.2 - Carmel IN All Data: Alternative calibration methods for HCM Exponential model with the Basic SIDRA Geometry Method added and the TRL-Kimber Linear model

Exponential model with SIDRA Geometry	A	B	t_f	t_c	t_f / t_c	RMSE	Increase in RMSE
Basic Exponential - Best fit regression	1391	0.00082	2.588	4.246	0.610	152.4	-
SIDRA Geometry default (f_e = 1.05)	1432	0.00091	2.514	4.524	0.556	154.8	1.6%
Calibration 1: SIDRA Geometry (f_e = 1.03)	1460	0.00089	2.466	4.438	0.556	153.7	0.9%
Calibration 2: B from *Equation (5.1)*	1432	0.00080	2.514	4.136	0.608	156.1	2.4%
Calibration 3: B from *Equation (5.1)* with A from measured t_f	1497	0.00086	2.405	4.292	0.560	158.9	4.3%
TRL-Kimber Linear model	**A**	**B**	**t_f**	**t_c**	**t_f / t_c**	**RMSE**	**Increase in RMSE**
Basic Linear - Best fit regression	1260	-0.6322	2.857	-	-	152.0	-
TRL-Kimber default model	1314	-0.5745	2.740	-	-	181.7	19.5%
Calibration 1: A from *Equation (5.2)*	1217	-0.5745	2.959	-	-	153.5	1.0%
Calibration 2: B from *Equation (5.3)*	1314	-0.7031	2.740	-	-	154.3	1.5%
Calibration 3: B from *Equation (5.3)* with A from measured t_f	1497	-0.9454	2.405	-	-	191.5	26.0%

Average entering flow (capacity), Q_{ea} = 783 pcu/h, Average circulating flow, q_c = 754 (pcu/h)



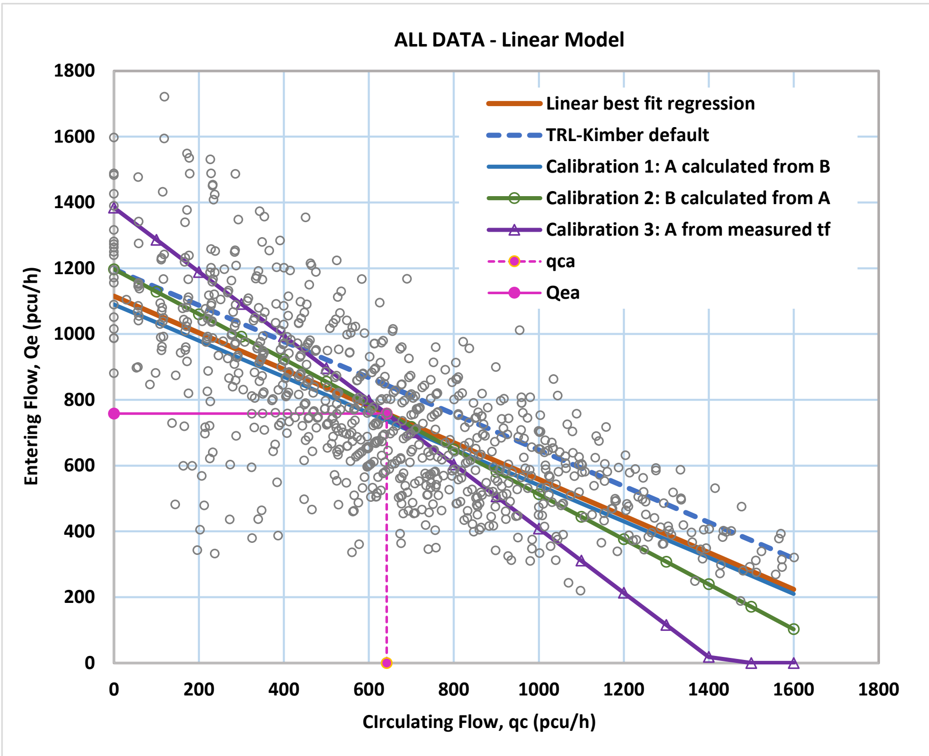


Figure 5.1 - All Data: Alternative calibration methods for HCM Exponential model with the Basic SIDRA Geometry Method added and the TRL-Kimber Linear model

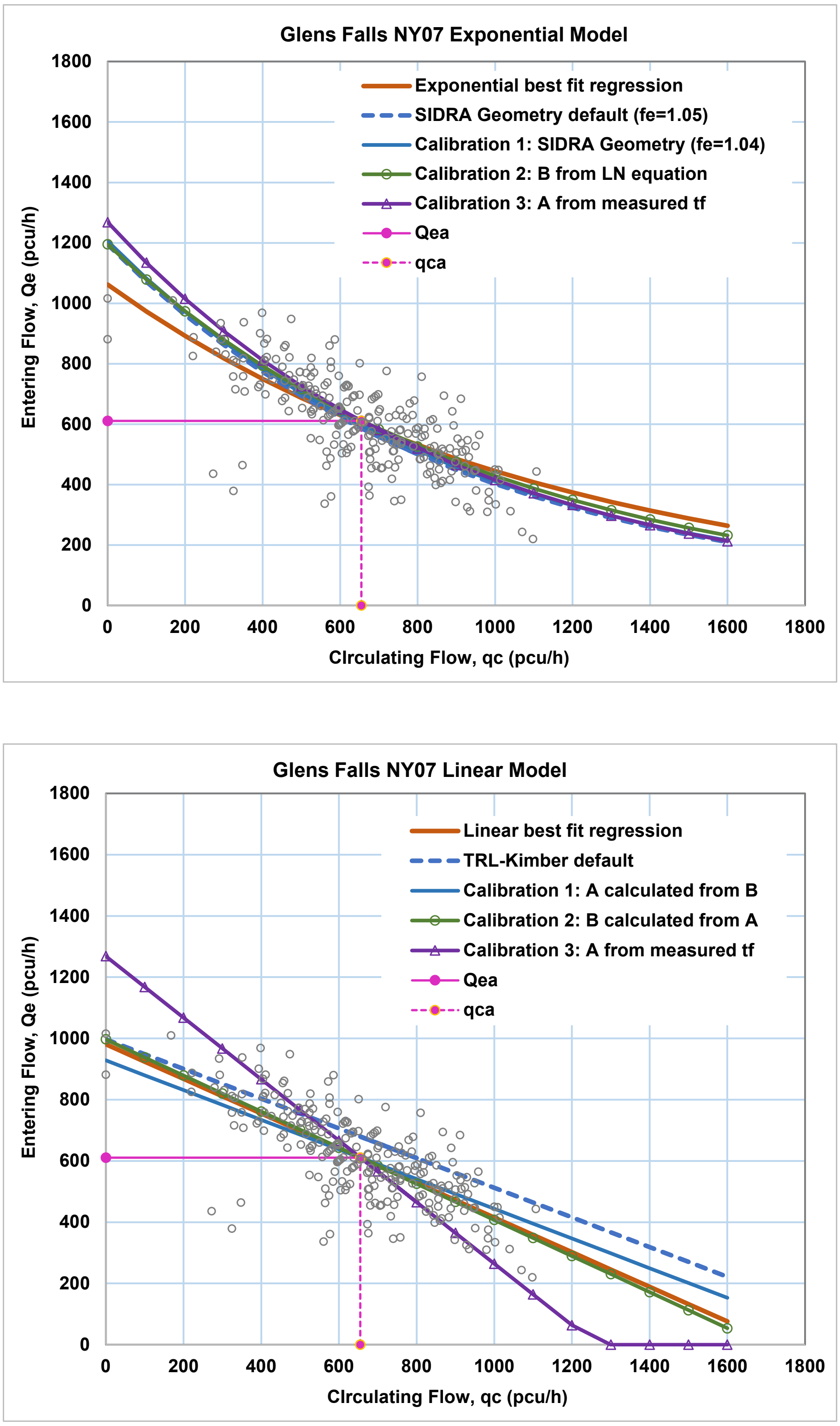
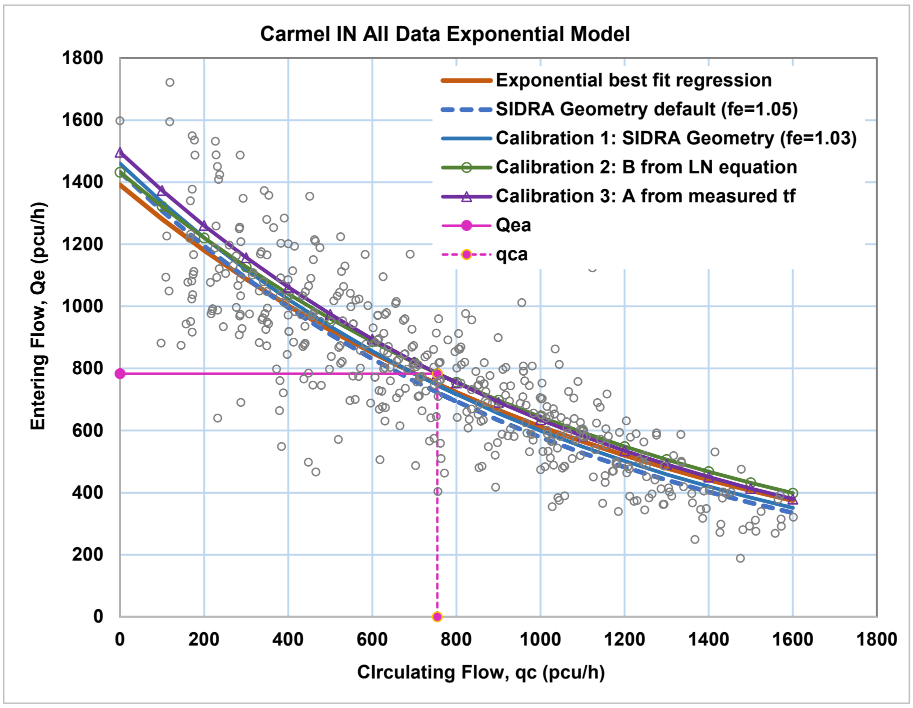


Figure 5.2 - Glens Falls NY 07: Alternative calibration methods for HCM Exponential model with the Basic SIDRA Geometry Method added and the TRL-Kimber Linear model



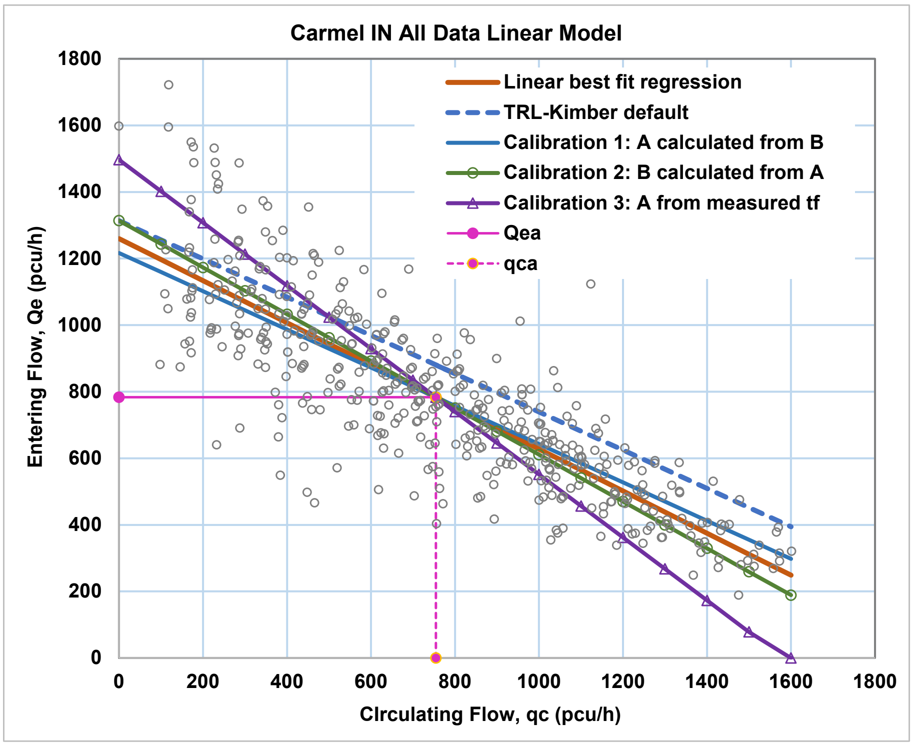


Figure 5.3 - Carmel IN All Data: Alternative calibration methods for HCM Exponential model with the Basic SIDRA Geometry Method added and the TRL-Kimber Linear model

6 Example for Modelling Unbalanced Flow Conditions

In this section, a single-lane roundabout example is given for unbalanced flow conditions in order to explain the interactions among roundabout entry flows from different approaches causing these conditions.

In previous sections, concern was expressed about linear roundabout capacity models underestimating capacity for low circulating flows, especially considering specific cases of unbalanced flow conditions under high demand levels (Akçelik 2003, 2004). The anchored regression models have been supported for this reason as they are based on measured follow-up headways that correspond to y-intercept (capacity) values larger than those estimated by the best fit regression models (for both linear and exponential models). As the HCM Edition 6 roundabout capacity model is based on the use of an anchored mode, it is useful to explain the reason for this support.

The best fit regression models are set up to minimise error levels between estimated and measured data points. While statistical error levels are important in research of this nature, model choices should not be based only on statistical error levels of field data available. The models should also be assessed in terms of ability to deal with specific situations, e.g. capacity estimates at low and high demand flows, and demand flow patterns causing unbalanced flow conditions at high demand flows. While the analyses of these conditions are relevant to existing roundabouts, they are also relevant to design life analyses of new and modified designs.

The SIDRA INTERSECTION software has a function for calibrating the capacity model for high approach demand flows interrupted by low circulating flows. This function increases capacity estimates according to the ratio of entering (demand) flow to circulating flow. The HCM Edition 6 capacity model does not have this functionality but the software option "Apply the SIDRA Model for Unbalanced Flow Conditions for HCM 6" is available.

The ratio of entry flow to circulating flow for the HCM roundabout research data is discussed in *Section 2.1*.

The capacity constraint function is also relevant to this discussion. Again, the HCM Edition 6 capacity model does not have this functionality but the SIDRA INTERSECTION software applies this to oversaturated approach lanes generally, including the HCM models. This is important in the case of unbalanced flow conditions since capacity constraint reduces the circulating flow downstream of the oversaturated approach. This prevents the modelling of unbalanced flow conditions as shown in this example.

The example given in this section is a modified version of the example given in (Akçelik 2003). The example is described in *Figure 6.1*. Roundabout geometry parameters shown are the average values for the All Data (*Table 2.5* in *Section 2.3*).

As shown in *Table 6.1*, HCM 6 roundabout capacity is tested for two cases for the Exponential (Siegloch M1) model:

(i) anchored regression model, and
(ii) best fit regression model.

The volumes in this example (shown in *Figure 6.1*) are selected to demonstrate the issues in modelling the unbalanced flow cases:

- East (WB) and South (NB) approaches have low demand volumes resulting in low degrees of saturation. The resulting circulating flow in front of the North approach is a very low value of 120 pcu/h.
- North (SB) approach has high demand flow (1210 pcu/h). Thus this is a case of high ratio of entry (demand) flow to circulating flow.
- West (EB) approach has low demand flow (460 pcu/h) but a high circulating flow which is 1100 pcu/h if the North approach is not oversaturated.

There are no heavy vehicles in this example, therefore all volumes are stated in pcu/h.

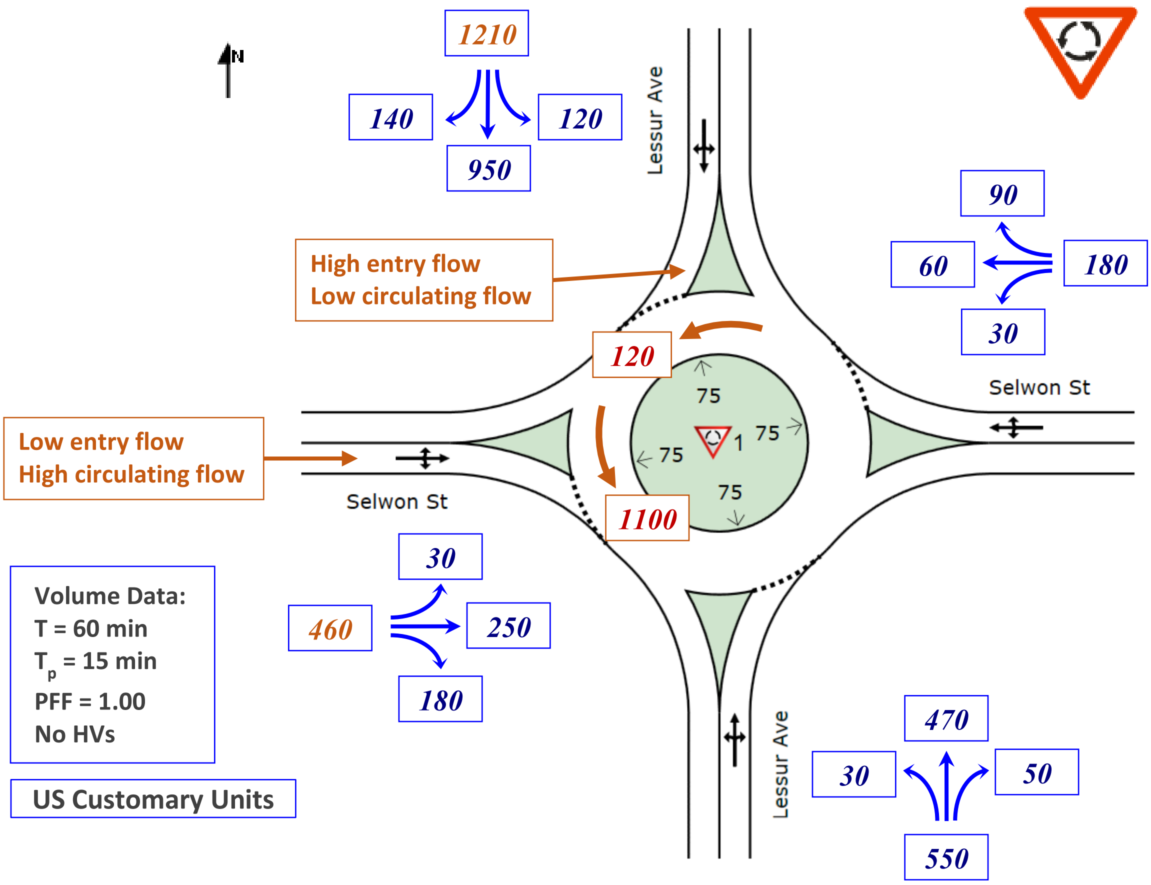
The results in *Figure 6.2* and *Table 6.2* showing the estimates of capacity, degree of saturation (v/c ratio), delay, level of service and back of queue values indicate that the HCM 6 roundabout capacity model with the y-intercept anchored gives more correct estimates for the unbalanced flow conditions that occur in this example as explained below.

- The HCM 6 model with ***best fit regression*** parameters estimates oversaturated conditions for the North approach (v/c ratio = 1.103), therefore capacity constraint applies. While the demand flow is 1210 pcu/h, only the capacity flow of 1210 / 1.103 = 1097 pcu/h can enter the roundabout from the North approach. This results in a reduced circulating flow of 1000 pcu/h in front of the West approach. This consists of (950 + 120) / 1.103 = 970 pcu/h from the North approach and 30 pcu/h from the East approach.
- With the reduced circulating flow, the West approach capacity results in a degree of saturation of 0.833 (capacity = 552 pcu/h) with reasonably low delay and queue values, and LOS D.
- On the other hand the HCM 6 model with the ***anchored regression*** parameters estimates higher capacity, and therefore undersaturated conditions for the North approach although the degree of saturation is still high (0.985). This is a more reasonable solution than the above since the low circulating flow of 120 pcu/h means long acceptable headways and an unblocked time ratio of 89%. Being in a long queue and experiencing long delays otherwise, it is expected that drivers would behave more aggressively in entering the roundabout. This means the average follow-up headway would decrease under these circumstances. In this example, the follow-up headway is 3.00 s for ***best fit regression***, reduced to 2.60 s for the ***anchored regression***.
- With the higher circulating flow, the capacity decreases for the West approach. In addition to the increased circulating flows, there is the negative effect of what the SIDRA model calls the "O-D Factor". A low value of the O-D factor indicates unbalanced flow conditions. This occurs when most of the circulating traffic enters from a dominant approach, North in this case, and the dominant approach traffic is highly queued (proportion queued is 100% on the North approach). Although the North approach has enough capacity to be undersaturated, the interruption by the low circulating flow causes a long moving queue to develop due to the high entry demand flow rate. This is a case where the delay is acceptable (LOS D) but the back of queue distance is large for the North approach. Delay is not very high because the blocked time for the entry is low (11% of the time).
- For the West approach, low O-D Factor (0.59) for the West approach (when modelled using the anchored regression parameters) coupled with higher circulating flow results in a high degree of saturation (degree of saturation = 0.988) associated with high delay (LOS F) and longer queues.

Thus it is seen that the best regression model has lower RMSE values considering *general data*, but it fails to estimate the effect of unbalanced flow conditions on the West approach and overestimates the delay and LOS on the North approach as demonstrated by this example.

Table 6.1 - All Data: Basic Exponential (Siegloch M1) best fit and anchored regressions, Basic Linear best fit regression and TRL-Kimber Linear default models

	A	B	t_f	t_c	t_f / t_c	RMSE	Increase in RMSE
Basic exponential (Siegloch M1) model best fit regression	1205	0.00078	2.988	4.302	0.695	180.2	
A (t_f) parameter anchored	1384	0.00099	2.601	4.865	0.535	190.5	5.7%
Basic linear model best fit regression	1115	-0.5570	3.229	-	-	183.5	
TRL-Kimber Linear default model	1197	-0.5495	3.008	-	-	202.8	10.5%
TRL-Kimber Linear calibrated model	1090	-0.5495	3.304	-	-	184.7	0.7%



Circulating flows - Anchored Regression:
Capacity constraint did not apply
West: 1100 pcu/h
South: 400 pcu/h
East: 530 pcu/h
North: 120 pcu/h

Circulating flows - Best Fit Regression:
Capacity constraint applied to North approach
West: 1000 pcu/h (reduced)
South: 389 pcu/h (reduced)
East: 530 pcu/h
North: 120 pcu/h

Roundabout geometry parameters

	D_i	r_e	ϕ_e	w_L	w_a	L_f
(ft)	125	47	20°	13	11.6	22
(m)	38.1	14.3		3.96	3.54	6.7

D_i = inscribed diameter, r_e = entry radius, ϕ_e = entry angle,
w_L = effective entry lane width (smaller than full entry width),
w_a = approach half width, L_f = effective flare length

Figure 6.1 - Single-lane roundabout example with unbalanced flow conditions using average geometry parameters for All Data

HCM 6 model parameters based on Best Fit Exponential Regression

LANE SUMMARY

Site: 1 [All Data Best Fit Exponential Regrn (Site Folder: All Data - HCM 6 Model)]
Output produced by SIDRA INTERSECTION Version: 9.1.0.160

Single-lane roundabout with HCM All Data Average Geometry
HCM 6 model parameters from All Data Best Fit Exponential Regression Model

Lane Use and Performance

	DEMAND FLOWS [Total	HV]	ARRIVAL FLOWS [Total	HV]	Cap.	Deg. Satn	Lane Util.	Aver. Delay	Level of Service	95% BACK OF QUEUE [Veh	Dist]
	veh/h	%	veh/h	%	veh/h	v/c	%	sec			ft
South: Lessur Ave											
Lane 1[d]	550	0.0	550	0.0	890	0.618	100	13.3	LOS B	5.5	137.9
Approach	550	0.0	550	0.0		0.618		13.3	LOS B	5.5	137.9
East: Selwon St											
Lane 1[d]	180	0.0	180	0.0	797	0.226	100	6.9	LOS A	0.7	18.6
Approach	180	0.0	180	0.0		0.226		6.9	LOS A	0.7	18.6
North: Lessur Ave											
Lane 1[d]	1210	0.0	1210	0.0	1097	1.103	100	67.9	LOS F	93.2	2329.3
Approach	1210	0.0	1210	0.0		1.103		67.9	LOS F	93.2	2329.3
West: Selwon St											
Lane 1[d]	460	0.0	460	0.0	552	0.833	100	34.7	LOS D	6.5	162.6
Approach	460	0.0	460	0.0		0.833		34.7	LOS D	6.5	162.6
Intersection	2400	0.0	2400	0.0		1.103		44.5	LOS E	93.2	2329.3

HCM 6 model parameters based on Exponential Anchored Regression

LANE SUMMARY

Site: 1 [All Data Anchored Exponential Regrn (Site Folder: All Data - HCM 6 Model)]
Output produced by SIDRA INTERSECTION Version: 9.1.0.160

Single-lane roundabout with HCM All Data Average Geometry
HCM 6 model parameters from All Data Anchored Exponential Regression Model

Lane Use and Performance

	DEMAND FLOWS [Total	HV]	ARRIVAL FLOWS [Total	HV]	Cap.	Deg. Satn	Lane Util.	Aver. Delay	Level of Service	95% BACK OF QUEUE [Veh	Dist]
	veh/h	%	veh/h	%	veh/h	v/c	%	sec			ft
South: Lessur Ave											
Lane 1[d]	550	0.0	550	0.0	931	0.590	100	12.1	LOS B	5.6	140.2
Approach	550	0.0	550	0.0		0.590		12.1	LOS B	5.6	140.2
East: Selwon St											
Lane 1[d]	180	0.0	180	0.0	819	0.220	100	6.7	LOS A	1.0	23.9
Approach	180	0.0	180	0.0		0.220		6.7	LOS A	1.0	23.9
North: Lessur Ave											
Lane 1[d]	1210	0.0	1210	0.0	1229	0.985	100	34.4	LOS D	62.9	1572.1
Approach	1210	0.0	1210	0.0		0.985		34.4	LOS D	62.9	1572.1
West: Selwon St											
Lane 1[d]	460	0.0	460	0.0	466	0.988	100	67.2	LOS F	13.3	333.0
Approach	460	0.0	460	0.0		0.988		67.2	LOS F	13.3	333.0
Intersection	2400	0.0	2400	0.0		0.988		33.5	LOS D	62.9	1572.1

Figure 6.2 - Capacity and performance estimates for the single-lane roundabout example with unbalanced flow conditions (shown in Figure 6.1)

Table 6.2 - Results from HCM 6 roundabout capacity model with exponential model parameters based on BEST FIT and ANCHORED regressions

Approach	Demand Flow	Circulating Flow	Capacity	v/c Ratio (Deg. of Satn)	Delay	Level of Service	95% Back of Queue
	veh/h	pcu/h	veh/h		sec		vehicles
HCM 6 model parameters based on BEST FIT Exponential Regression (A = 1205, B = 0.00078) * Capacity Constraint applied to North approach							
North (SB)	1210	120	1097	1.103	67.9	LOS F	93.2
West (EB)	460	1000 *	552	0.833	34.7	LOS D	6.5
South (NB)	550	389 *	890	0.618	13.3	LOS B	5.5
East (WB)	180	530	797	0.226	6.9	LOS A	0.7
HCM 6 model parameters based on ANCHORED Exponential Regression (A = 1384, B = 0.00099) Capacity Constraint did not apply to North approach							
North (SB)	1210	120	1229	0.985	34.4	LOS D	62.9
West (EB)	460	1100	466	0.988	67.2	LOS F	13.3
South (NB)	550	400	931	0.590	12.1	LOS B	5.6
East (WB)	180	530	819	0.220	6.7	LOS A	1.0

Roundabout LOS Method: Same as Sign Control

Analyses for this example using the *TRL-Kimber Linear default* model (*Table 6.1*) gave the same pattern of results as the analysis using the exponential best fit regression parameters described above because of low capacity estimated for the North approach (capacity = 1131 pcu/h, v/c ratio (degree of saturation) = 1.070) resulting in acceptable conditions for the West approach (capacity = 631 pcu/h, v/c ratio (degree of saturation) = 0.729).

With the *TRL-Kimber calibrated* model (Calibration Method 1 in *Section 5*) which has a better RMSE value than the default model (closer to the linear model best fit regression), underestimation of capacity is increased for the North approach (capacity = 1024 pcu/h, v/c ratio (degree of saturation) = 1.182) also resulting in acceptable conditions for the West approach capacity (capacity = 571 pcu/h, v/c ratio (degree of saturation) = 0.806).

It should be noted that this example has been set up with volumes to demonstrate that the HCM 6 model with the anchored y-intercept value has a better chance of modelling unbalanced flow conditions. This does not mean that the HCM 6 capacity model would always model the unbalanced flow conditions satisfactorily. However, the implementation of the HCM 6 model in the SIDRA INTERSECTION software provides calibration options for this purpose.

7 Conclusions

Analyses were carried out using the HCM roundabout capacity research data to contribute to discussions about the empirical and theoretical aspects of roundabout capacity models for future research and development. In particular, the aim is to help with choices between exponential (non-linear) and linear capacity model forms used in practice. The analyses reported are limited to single-lane roundabouts. The following is a brief summary of the method used and conclusions.

Analysis Method

The comparisons presented in this report focused on the HCM (Siegloch M1) exponential capacity model and the TRL-Kimber (1980, 1985, 1989) linear capacity model. The models were assessed using the full HCM capacity dataset (All Data) as well as the data subsets for the Glens Falls roundabout and Carmel roundabouts. These data subsets were identified by Johnson and Lin (2018) as having two different roundabout geometry types. They represented *horizontal slicing of* the HCM capacity data indicating different capacity levels over the same range of circulating flows.

The full dataset and the two data subsets were used to analyse the exponential and linear models for the full circulating flow range. To assess the applicability of exponential and linear models to low and high circulating flow levels, additional data subsets were also considered by *vertical slicing* of the HCM capacity data into lower and higher sets of circulating flow values. Using this method, *two-segment* linear and exponential models were analysed.

Roundabout capacity models assessed were (i) *basic* linear and exponential capacity models derived from best fit regressions and regressions with the y-intercept anchored, and (ii) linear and exponential models that employ *average geometry parameters* representing the full dataset and the two data subsets. For the latter, the TRL-Kimber linear capacity model and the HCM exponential model with a simplified version of the SIDRA geometry method added (referred to as the *Basic SIDRA Geometry Method*) were assessed.

The statistical error levels as measured by Root Mean Square Error (RMSE) are given for all models tested. While statistical error levels are important, model choices should not be based only on statistical error levels of available data. It is emphasised that models should also be assessed in terms of dealing with specific situations, e.g. capacity estimates at low and high demand flows, and demand flow patterns causing unbalanced flow conditions at high demand flows. While the analyses of these conditions are relevant to existing roundabouts, they are also relevant to design life analyses of new and modified designs.

Features of Data

It was noted that a good amount of judgement is needed in measuring the entry radius and entry angle values in particular leading to differences in values from measurements by different people. Differences due to definitional issues are also a possibility.

Attention was drawn to the effect of the *frequency of data points* in low, medium and high circulating flow ranges on best fit regression results for the linear and nonlinear models as this is likely to cause a bias towards hiding non-linearity of the capacity curve. While the full data set and the Glens Falls data subset had low frequencies at low and high circulating flows, the Carmel data subset showed a more even distribution of frequencies.

The *sums of entering flow (capacity) and circulating flow* were observed to increase from low to high circulating flows. This may indicate a potential for higher entry flow (capacity) values at low circulating flows which could be realised in specific unbalanced flow conditions under high demand levels. The *ratio of entering flow to circulating flow* is of interest in relation to these cases.

Best Fit and Anchored Regression Results

The best fit regression results indicated that both exponential and linear models perform well in terms of close values of RMSE, and they give close estimates of capacity for the medium range of circulating flow. However, the linear model estimated lower values of capacity for low and high circulating flows, and the regressions with the y-intercept values anchored indicated significantly different results for the exponential and linear models.

The capacity estimates from anchored regressions indicate that the exponential model estimates can stay close to the best fit regression estimates for medium to high circulating flows (indicated by small increases of 2.0% to 6.7% in RMSE values). The reducing slope of the exponential model helps it to adopt to the changes in the observed data. On the other hand, the anchored regressions cause the linear model to estimate significantly lower capacities at high circulating flows (resulting in RMSE increases of 21.4% to 28.7%). Therefore, the calibration of the linear model by measuring the follow-up headway is not recommended whereas this method is considered to be suitable for the exponential model.

Higher capacity estimates at low circulating flows given by anchored regressions are useful in modelling the specific condition of unbalanced flows. The exponential model achieves this with small increases in the overall error levels and good accuracy of capacity estimates at high circulating flows. On the other hand, capacity estimates from the linear model indicate significantly increased overall error levels and unsatisfactory results for high circulating flows.

Follow-up Headway and Critical Gap

The best fit regression models were found to imply larger values of follow-up headways compared with the measured follow-up headways. The difference was larger for the linear model regressions which is as expected due to the estimation of lower capacities at low circulating flows by the linear model. There were also differences between the implied values of critical gap (headway) from best fit regressions for the exponential model compared with the measured values of critical gap.

In relation to this issue, the survey methods used for follow-up headway and critical gap parameters should be paid more attention. The Siegloch survey method attributed to Siegloch (Brilon and Grossman 1991; Brilon, Koenig and Troutbeck 1997; TRB 1997; Akçelik 2007) is recommended by the authors for this purpose since this method measures critical gaps and follow-up headways at the same time. HCM capacity data indicated some lack of correspondence with the follow-up headway and critical gap data, and it appeared that the follow-up headway and critical gap data were not collected at the same time. It is also likely that the *small frequencies of capacity data for low circulating flows* will affect the differences between follow-up headways implied by best fit regressions and the measured follow-up headways.

Two-Segment Regression Models

Separate analyses of the Glens Falls and Carmel data subsets conducted by Johnson and Lin (2018) showed the effect of different types of overall roundabout geometry (compact vs larger curvilinear) on capacity. This approach represents a *horizontal slicing* of data indicating different capacity levels over the same range of circulating flows. To demonstrate the fundamental exponential (non-linear) characteristic of roundabout capacity generally, *two-segment* linear and exponential models were explored via best fit regressions applied to two separate segments (subsets) of data created by *vertical slicing of data*. This was considered in view of the persistent estimation of low capacities for low and high circulating flows by the linear model.

The analyses were carried out for the full dataset and the Carmel data subset. The Glens Falls data subset was not used for this analysis due to a very low number of data points in the low circulating flow range. The two segments were defined with entering flow (capacity) data in the circulating flow range 0-700 pcu/h for Segment 1 and above 700 pcu/h for Segment 2. The separation at 700 pcu/h was selected considering the average values of circulating flow at 642 pcu/h for All Data and 754 pcu/h for Carmel IN All data. The regression analyses were specified with continuity of the two segments so that the same capacity was estimated at the circulating flow of 700 pcu/h.

The results of these regressions showed that the slopes of the linear model vary for the two segments significantly with some improvement in the RMSE values. This is because a two-segment linear model has the ability to adapt to differences between low and high circulating flow conditions indicating the exponential characteristic of the capacity data. It is important to note that these results were obtained with no change in the roundabout geometry characteristics in datasets. Similar results were obtained from additional analyses using aggregate data.

Quadratic Model

Kimber (1980) tested the quadratic ("second order empirical") model and concluded that "it has not been possible to detect any (statistically) significant non-linearity with respect to (circulating flow)". The best fit regression results for the full HCM capacity research data showed that the basic quadratic model somehow gave a better model than the basic linear model indicating the non-linear characteristic of the dataset. However, a poor characteristic of this model is that capacity estimates start increasing at high circulating flows. Therefore, the quadratic model is not recommended for use.

Calibrated Capacity Models

Alternative model calibration methods were applied to the HCM (Siegloch M1) Exponential model with a new *Basic SIDRA Geometry Method* added (*Akçelik 2022*) and the TRL-Kimber Linear model with geometry parameters. The original estimates from these models are referred to as *default models*. Average roundabout geometry parameters were used in the analyses.

The default HCM exponential model estimates with the Basic SIDRA Geometry Method were found to have lower RMSE values (1.6% to 4.6%) than the default the TRL-Kimber model estimates (10.5% to 19.5%).

Calibration Method 3 using the measured follow-up headway had a reasonably close RMSE value for the HCM model with the Basic SIDRA Geometry Method (4.3% to 7.1%) compared with high values for the TRL-Kimber model (26.0% to 31.0%). This is similar to the results of anchored regressions for the basic linear model (21.4% to 28.7%).

The exponential model calibrated using the measured follow-up headway stayed close to the best fit regression estimates for medium to high circulating flows whereas estimates from the linear model calibrated using the measured follow-up headway became significantly lower at high circulating flows due to the constant slope of the model.

Analyses of calibration methods for subsets of data using both the HCM (Siegloch) exponential capacity model with the Basic SIDRA Geometry Method added and the TRL-Kimber model supported the finding by Johnson and Lin (2018) that roundabout geometry parameters may have a combined (aggregate) effect on capacity of different roundabout geometry types.

Example Unbalanced Flow Conditions

A detailed single-lane roundabout example is included in this report for unbalanced flow conditions under high demand levels in order to explain the interactions among roundabout entry flows from different approaches causing these conditions. The concern about linear roundabout capacity models underestimating capacity for low circulating flows is relevant to these specific conditions.

The anchored regression model used for the HCM Edition 6 roundabout capacity model is supported for this reason as it is based on measured follow-up headways that correspond to y-intercept (capacity) values larger than those estimated by the best fit regression models (for both linear and exponential models). The example is set to explain how the best regression model (that has lower RMSE values based on *general data*) fails to estimate the effect of unbalanced flow conditions and overestimates the delay and LOS on the North approach.

Can a Linear Gap-Acceptance Capacity Model be Derived?

A theoretical investigation was carried out to explore if a linear capacity model can be derived as a gap-acceptance capacity model assuming a uniform or linear arrival headway distribution of the opposing (conflicting / circulating) traffic stream although these headway distributions are not realistic given the random nature of arrival headways including bunching considerations (Akçelik 2022). The investigation concluded that both uniform and linear headway distributions resulted in non-linear gap-acceptance capacity models with unrealistic features.

Preferred Model

In conclusion, the assessments from various perspectives conducted using the HCM single-lane roundabout capacity research data reported in this document demonstrate the non-linear characteristic of roundabout capacity data as a function of the circulating flow. They are found to support the HCM exponential (non-linear) roundabout capacity model over the linear model form which has shortcomings in estimating capacity at low and high circulating flows.

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