ROUNDABOUT CAPACITY AND COMPARATIVE SOFTWARE ANALYSIS

by

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Abstract

Interest continues to increase in how roundabouts can most effectively be used in the United States (U.S.) transportation system to achieve goals of safety, efficiency, along with other benefits. Using the right software can enhance accuracy and productivity in designing for these goals. However, a growing number of software choices and evolving features provide the motivation for this research because many questions exist about which software is the best option.

This research explores the popular models and software available for analyzing roundabout capacity in order to increase understanding of the similarities and differences. Specifically, two roundabouts, one single-lane and one multi-lane, that experienced congestion were compared using capacity models and results from seven software packages: RODEL 1.9.7, ARCADY 7.1, RCAT 1.4, Kreisel 7.0, Girabase 4.0, HCS 2010 6.1, and SIDRA 5.1.

Analysis showed that in calibrated scenarios, all models performed acceptably well in terms of root-mean-square error in comparison to the field data. However, achieving a properly calibrated model is difficult because of data collection and availability needs. Further, calibration can only be performed on existing roundabouts, leaving analysis of future roundabouts to rely on projections or uncalibrated models. From the sites analyzed, the uncalibrated U.S. based model (NCHRP 572/HCM 2010) and German models fit the observed data better than all other models. Certainly there are many considerations when choosing a software package, but in terms of technical accuracy, a package that has the capability of performing capacity analysis using U.S. based models is desirable based upon the findings of this research.

In terms of software modeling, lane-by-lane methods were shown to be

more accurate for capacity analysis. Because significant lane imbalance can occur, variability in performance measures on the same approach is a concern for detailed analysis. However, the analyst still has a responsibility for understanding how drivers will utilize the available lanes because default assumptions in the software packages were not always appropriate.

Ultimately, software is constantly evolving along with roundabout operations, and this research has come at the beginning of understanding roundabouts in the U.S. Therefore, a definitive software recommendation is open-ended due to the unique requirements of an agency and future research. The purpose, potential growth, evolution, and flexibility of any software and parent company must be carefully considered in order to make a smart investment for the future. Further research needs include investigating secondary, advanced features (such as integration with CAD software, corridor analysis, etc) as well as developing design guidance and calibrated model parameters.

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For my loving wife Amanda, who probably counts vehicles circulating through roundabouts in her sleep, thank you for sustaining my eternal happiness.

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1 Introduction

Roundabouts have been used worldwide due to their contribution to safety and operational efficiency, as well as other side benefits such as speed control and reduced operational costs. Some European countries such as the United Kingdom (U.K.), Germany, and France, as well as Australia, have a long history of roundabout research while experience in the United States is varied and relatively recent. How well worldwide experience translates to U.S. roundabout implementations is still a topic of active research because driver populations, expectations, and roadway geometry vary significantly from country to country. This research provides insight and comparisons of various models and software developed around the world for operational analysis of roundabouts.

Successful design and implementation of roundabouts largely depends on communication and quality engineering, but is also influenced by public opinion and driver education. Recommending roundabouts for the correct reasons and communicating to the user with good geometry, signs, and markings are all responsibilities of the engineer in the design phase to achieve smooth traffic operations and safety. Equally important for success in the design and planning phases, are accurate estimations of intersection demand and capacity, which critically provide the basis for all performance measures used in comparing intersection control alternatives. Worldwide studies on roundabout capacity have led to the development of many mathematical models, based on traffic flow theory, empirical observations, or a combination of theory and observation, to predict performance under congested conditions. Software development has grown in parallel with capacity research to provide an interface to the models for analysts. With a multitude of options available, understanding the underlying models and principles of each software aids informed decision making in order to provide the most value for a successful, safe, and efficient transportation system.

1.1 Problem Statement

Traffic volumes continue to grow while the available lane-miles remain relatively steady, creating a need for ways to allow more vehicles in an already congested transportation system. Fairly evaluating intersection alternatives hinges on appropriate analysis methods. As roundabouts continue to be recommended as an intersection alternative for safety and operational reasons, engineers need to have confidence that they are analyzing roundabouts appropriately. Operationally, engineers in the U.S. and particularly Wisconsin, have been using the roundabout capacity model based on Kimber's research from the 1970s and '80s done in the U.K for design and analysis. Here, referred simply as the U.K. capacity model, Kimber showed that capacity can be predicted as a function of roundabout geometry. Some concern has been expressed about the validity of applying the U.K. model in the U.S. where driver behaviors, expectancies, and geometries may differ. Such concerns have led many agencies to undergo evaluations of the multitude of software packages to identify which best fit their needs.

In design, a desirable solution needs to balance constraints and should not be over or under designed. Choosing unsuitable software, or misusing appropriate software, could lead to poor estimations of capacity. Further, inaccurate estimations of capacity could lead to undesirable consequences of decreased safety or increased delay and queuing. As traffic volumes continue to increase system-wide, research can provide insight about how to make the best use of roundabouts as part of a diverse toolbox for transportation engineers.

1.2 Objective, Contributions, and Scope of Work

The objective of this thesis was to:

- Compare underlying capacity models within several roundabout analysis software packages which included:
  - RODEL version 1.9.7
  - ARCADY version 7.1
  - RCAT version 1.4
  - Kreisel version 7.0
  - Girabase version 4.0
  - HCS 2010 version 6.1
  - SIDRA version 5.1
- Compare the capacity prediction from each of the above software models to field data as a means of rating technical accuracy;
- Compare the software in terms of usability and features; and
- Provide a summary of findings in an evaluation matrix consisting of major categories that rate technical accuracy, usability, licensing type, and cost.

Upon completion of these objectives, the findings expanded the understanding of capacity operations in the U.S. where few roundabouts have experienced congestion. Concerns addressed within touched on topics of universal and broad interest. Evaluating and comparing software packages helps researchers, practitioners, and software developers around the world understand the current state-of-the-art in analysis tools and better understand future needs.

The scope of this research was constrained to where congestion was sufficient to cause direct measurements of capacity, which resulted in analyzing two Wisconsin roundabouts. One multilane and one single lane roundabout were used, and the focus was strictly on capacity measurements. Software comparison and analysis was performed for only these two cases in order to make direct comparisons. Because of the rapidly changing environment of software development, only the most widely-used versions identified at the onset of this thesis were used.

1.3 Document Organization

This thesis is organized into seven chapters that follow a progression from identifying a purpose and need to findings and conclusions. Chapter 1 introduces the topic and purpose of this research. Chapter 2 presents relevant definitions and literature required to understand the analysis performed. Chapter 3 explains the study design and process followed for achieving results. Chapter 4 describes the field data collection procedures and introduces the study locations. Chapter 5 presents the analysis of the field data, which formed the basis for the majority of the findings. Chapter 6 investigates the software analysis that was completed for the studied locations, as well as a comparison of software usability and features. Chapter 7 highlights the conclusions and considerations resulting from this research. References and appendices are provided thereafter.

2 Literature Review

Discussion of capacity models as well as background for each software used is presented in the following literature. A few definitions are presented first to aid understanding and clarify commonly used terminology.

2.1 Capacity

Capacity, in general, has been defined as the maximum sustainable number of vehicles to traverse a location within a given time period under prevailing conditions [1]. For roundabouts, this means that each approach has a capacity for entering vehicles traversing the yield line. Capacity is dynamic in nature due to continually varying traffic composition (heavy vehicles, motorcycles, and bicycles), proportions of turning vehicles, driver population characteristics, and weather conditions. For example, a roundabout that services nearly all heavy vehicles at one time of the day could be expected to have a different capacity during a time when only passenger cars are serviced. Varying conditions are the reason that capacity must be thought of in terms of what flow rates can be repeatedly observed during peak periods and not the maximum flow ever observed [1]. Generally capacity data is based on minute-by-minute counts of entering vehicles and conflicting (circulating) vehicles for a specific approach or lane as shown in Figure 2.1. The general trend is that fewer vehicles can enter the roundabout as the number of circulating vehicles increases.

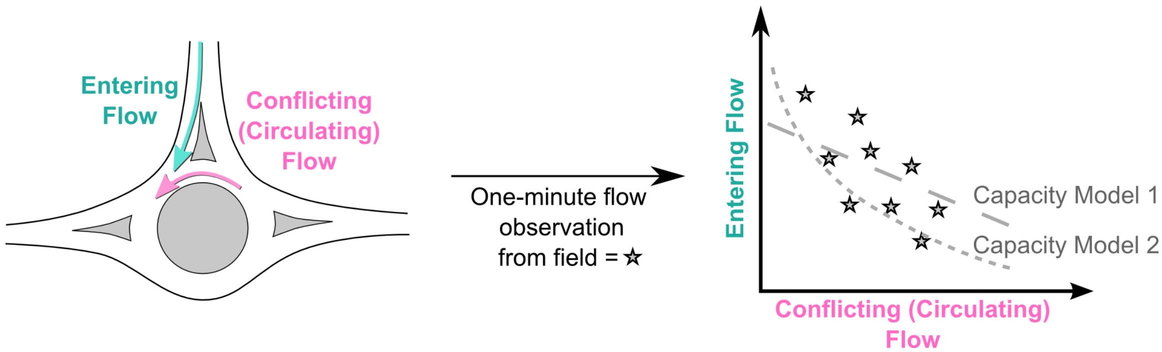


Figure 2.1. Example Entering-Circulating Capacity Graph Development

2.2 Congestion

Capacity models generally require making minute-by-minute observations during *congestion*. These are time periods where the demand volume meets or exceeds the currently available capacity, resulting in sustained queuing and delay. The need for observing operations at congestion can be understood by making an analogy to gathering saturation flow data, which relates to capacity, at a signal. A signal has a predictable cycle that alternates green intervals which are analogous to continuous gaps in the circulating traffic in a roundabout, and red intervals which are analogous to an extended time without gaps in the circulating stream of a roundabout. Collecting saturation flow data at a signal is relatively straight forward because one only needs to wait for a queue to develop during a red interval. At a roundabout, there is no signal to make the alternation of right-of-way or queuing predictable, and therefore having queuing present throughout the study period is critical. Such time periods of congestion allow direct observation of at- or near-capacity data and also driver behavior.

2.3 Gap Acceptance

Some capacity models use traffic flow theory related to gap acceptance, of which two main parameters are critical gap (t_c) and follow-up headway (t_f). Some research has also used the terms critical headway and follow-up time to represent the same parameters, but definitions are consistent throughout the literature. Gap acceptance models have been used for determining capacity at other unsignalized intersections, such as two-way stop controlled or yield controlled intersections [1]. Roundabouts and these other unsignalized intersection types share a common traffic flow theory concept of a priority, or major, traffic stream conflicting a minor, or entering, traffic stream. Capacity of the entering stream is then a function of how time gaps between major stream vehicles are distributed and how well the minor stream utilizes these gaps. The following definitions of critical gap and follow-up headway further clarify the idea.

If major stream traffic was flowing bumper-to-bumper, with little time between vehicles, the entering stream would not find any acceptable gaps to enter the roundabout. Thus there must be some minimum acceptable gap in order to provide any capacity to the minor stream. Critical gap is the minimum amount of time between circulating vehicles that a driver would find acceptable in order to safely enter the roundabout [1]. Figure 2.2 illustrates the concept of an entering vehicle accepting a gap. Only the gaps accepted and rejected by a driver can be observed; the smallest gap that a driver would accept cannot be directly seen but can be estimated.

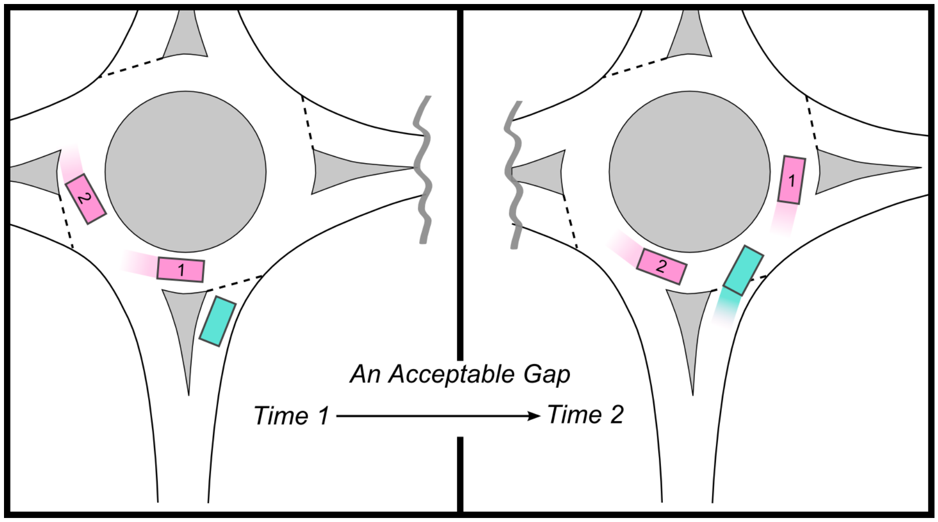


Figure 2.2. Critical Gap Depiction

Several methods exist to estimate critical gap, including use of logit procedures, the Raff method, and the Hewitt method [2]; however, the statistical procedure of the maximum likelihood method was focused on for this research and has been shown to be accurate and practical [3]. In the field of statistics, the maximum likelihood procedure is used for estimating parameters of distributions, which can be applied to finding the mean and variance of a critical gap distribution. For each driver, two values need to be obtained to apply the procedure: first, the largest rejected gap, and second, the actual gap accepted. Critical gap is estimated to have a value between these two observations. Mean and variance for a sample of critical gap estimates, assuming a log-normal distribution, is determined by numerically solving the following equations [4]:

$$\sum_{i=1}^{n} \frac{f(x_i) - f(y_i)}{F(y_i) - F(x_i)} = 0$$

$$\sum_{i=1}^{n} \frac{(x_i - \hat{\mu})f(x_i) - (y_i - \hat{\mu})f(y_i)}{F(y_i) - F(x_i)} = 0$$

where

n	=	Total drivers observed
x_i	=	Log of the gap accepted by ith driver
y_i	=	Log of the largest gap rejected by ith driver
$f(\,)$	=	Probability density function assumed, with $\mu$and σ^2
$F(\,)$	=	Cumulative density function assumed, with $\mu$and σ^2
$\hat{\mu}$	=	Estimated mean of the critical gap distribution
μ	=	Mean of the critical gap distribution
σ^2	=	Variance of the critical gap distribution

Follow-up headway is the amount of time between entering vehicles that are utilizing the same gap in circulating traffic [1]. Unlike critical gap, follow-up headway can be directly measured in the field by taking a sample average and standard deviation [5]. Figure 2.3 shows the concept where multiple entering vehicles use the same gap. Each vehicle must have been queued in order to qualify for a true follow-up headway measurement. The follow-up headway process at a roundabout is analogous to the discharge of a queue of vehicles at a signal and measuring saturation headway. If there were no conflicting vehicles in the roundabout, capacity would only be a function of the maximum theoretical frequently that vehicles could enter the roundabout.

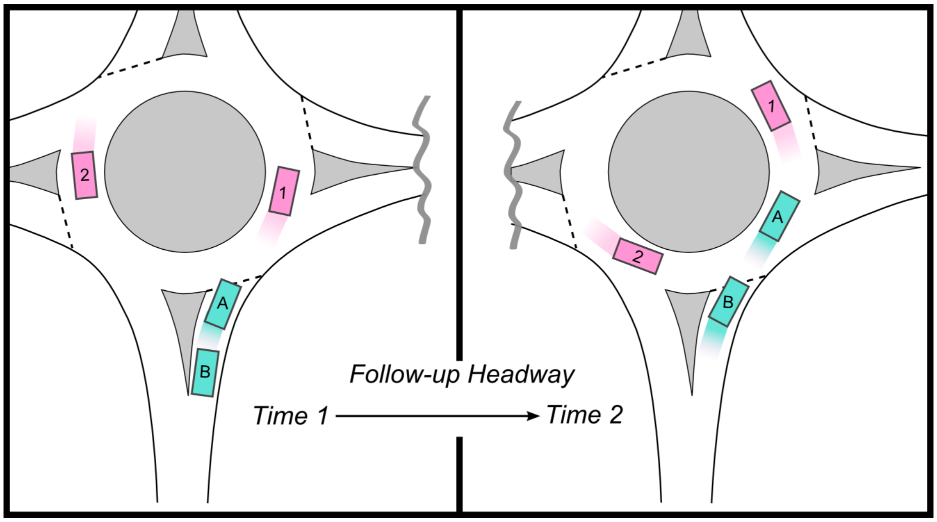


Figure 2.3. Follow-up Headway Depection

In general, as critical gap decreases, capacity increases because drivers are hesitating less by rejecting fewer gaps, or accepting more risk, to enter the roundabout. The same is true for follow-up headway because more than one driver could use the same gap, which also increases capacity. These generalizations hold true assuming that drivers are consistent in rejecting and accepting gaps of the same length, and that all drivers behave the same in comparison to each other, which may not always hold, but provide reasonable estimates [1].

2.4 Capacity Models

Understanding and modeling roundabout capacity has been researched worldwide because capacity measurements form the basis for operationally comparing intersection alternatives. Three categories of models have emerged in regards to what parameters are included in a capacity model: gap acceptance, geometry, or a hybrid of gap acceptance and geometry. Gap acceptance models predict capacity as a function of critical gap and follow-up headway driver behavior parameters. Geometric capacity models show that capacity is correlated to roundabout geometry such as entry with and inscribed circle diameter. Hybrid models combine elements of both methods to predict capacity. Another major division between models is whether or not the model predicts capacity lane-by-lane or if the prediction is aggregated for the entire approach.

Extensive research has gone into developing all model types, and a summary of each is presented in Table 2.1, along with the associated software package used in this study. A brief discussion of the models follows after the table. Noticeably, three software packages were selected to analyze the U.K. model due to the fact that this model is the basis for the current standard required in Wisconsin as described in the Wisconsin Facilities Development Manual (FDM) [6]. What has been termed the 'WisDOT Adjusted' U.K. model uses the U.K. model except that the entry width parameter is restricted to a discrete range of values prescribed in the FDM [6]. Essentially, this restriction is in the spirit of calibrating the model to what Wisconsin drivers are expected to use as effective entry width.

Table 2.1. Summary of Capacity Models

<table>
<tr><th>Name</th><th>Software Used</th><th>Capacity Aggregation</th><th>Model Parameters</th><th>Calibration Needs</th></tr>
<tr><td>U.K. Model [7]</td><td rowspan="2">RODEL 1.9.7, ARCADY 7.1, RCAT 1.4</td><td>Approach</td><td>Geometry</td><td>Observe entering and circulating flows during saturated periods, then adjust only the intercept of the linear model</td></tr>
<tr><td>WisDOT Adjusted' U.K. Model [6]</td><td colspan="3">Same as U.K. Model, except entry width is limited to a discrete range of values</td></tr>
<tr><td>German Model [8, 9]</td><td>Kreisel 7.0</td><td>Approach</td><td>Gap Acceptance</td><td rowspan="3">Observe critical gap and follow-up headway and substitute default parameters with the observed values</td></tr>
<tr><td>French Model [10]</td><td>Girabase 4.0</td><td>Approach</td><td>Hybrid Gap Acceptance and Geometry</td></tr>
<tr><td>NCHRP 572 / HCM 2010 [1, 5]</td><td>HCS 2010 6.1</td><td>Lane-by-lane</td><td>Gap Acceptance</td></tr>
<tr><td>SIDRA Standard Model* [11, 26]</td><td>SIDRA 5.1</td><td>Lane-by-lane</td><td>Hybrid Gap Acceptance and Geometry</td><td>Observe critical gap and follow-up headway and substitute default parameters with the observed values, or establish calibrated environment factors</td></tr>
</table>

* For capacity graphing, ARR 321 was used to approximate the SIDRA Standard Model with an environment factor of 1.0

Capacity models for roundabouts have historically started with gap acceptance theory of unsignalized intersections, and countries worldwide have undergone various changes of their recommended model. Specifically, the research of Tanner in the 1960's, Harders in the 1960's and 1970's, and Siegloch in the 1970's, as well as many others, has been used for the capacity of unsignalized intersections [12] which has been applied to roundabout capacity models worldwide [1, 5-11]. Much debate has occurred about the two primary techniques for developing capacity models: gap acceptance or empirical regression [13-19], each with advantages and disadvantages, similarities and differences, but more importantly the focus should be on how to best learn from, and use the various capacity models. Recently, Troutbeck has been mentioned regarding that "there are no strong reasons for adopting either technique" [13]. Countries from around the world have used various capacity modeling techniques at different times; just as capacity is dynamic, so is the best modeling technique. Germany has used linear and gap acceptance modeling techniques [8, 13, 20], as well as France [13], and the U.K. has changed through estimates based on weaving, gap acceptance, and linear regression [15]. Certainly roundabout capacity modeling has changed in the U.S. as well, from linear form [21], to early gap acceptance techniques [22] which continue to be refined as more is learned in the U.S. [5].

2.4.1 U.K. Model

R. L. Kimber with the Transport Research Laboratory in the mid 1970's worked on an extensive research project that led to the development of a capacity model for roundabouts in the U.K. Observations from a multitude of sites provided the data for developing a capacity model using linear regression. Prediction of entering flow was found to correlate to circulating flow and six geometric parameters [7]:

- Entry width (e),
- Flare length (l'),

- Approach width (v),
- Entry radius (r),
- Entry angle (PHI, ϕ), and
- Inscribed circle diameter (D).

Depictions of the six geometric parameters can be seen in Figure 2.4 [6].

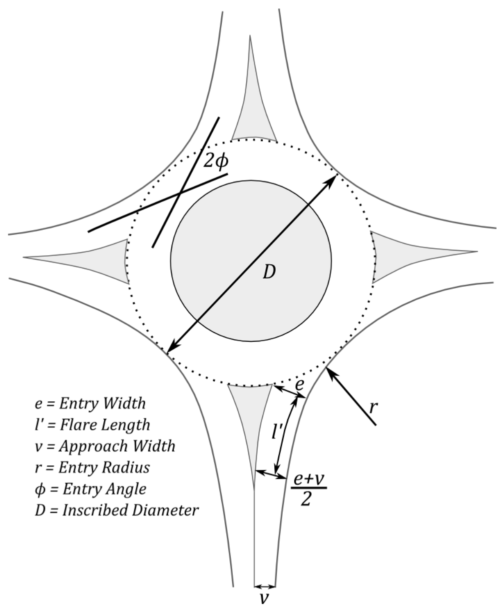


Figure 2.4. U.K. Model Geometric Parameters

(Based on WisDOT FDM 11-26-20 Attachment 20.1)

No parameters related to critical gap, follow-up headway, or other driver behavior parameters are used in the model. This is because the U.K. model linear regression approach does not explicitly try to recreate a model of driver behavior, but rather capture the end result of all of the complex factors that affect capacity. Capacity prediction from the U.K. model is aggregated for the entire approach and uses the six geometric parameters listed above. The resulting capacity equation, with geometry parameters as previously described, is:

$$c = \begin{cases} k(F - f_c Q_c) & \text{if } f_c Q_c \leq F \\ 0 & \text{if } f_c Q_c > F \end{cases}$$

where

$$\begin{aligned}
c &= \text{Approach capacity (pcu/h)} \\
k &= 1 - 0.00347(\phi - 30) - 0.978\left(\frac{1}{r} - 0.05\right) \\
F &= 303x_2 \\
f_c &= 0.210t_D(1 + 0.2x_2) \\
t_D &= 1 + \frac{0.5}{1 + e^{\frac{D-60}{10}}} \\
x_2 &= v + \frac{e - v}{1 + 2S} \\
S &= \frac{1.6(e - v)}{l'}
\end{aligned}$$

The model is very sensitive to the entry width parameter, which like all other variables is a continuous variable [7]. What has been termed the 'WisDOT adjusted' U.K. model limits the entry width parameter to discrete values to better predict the actual amount of capacity expected. For software modeling purposes, single lane roundabout entries are limited to using widths of 4.0 to 4.3 m, two-lane entries 6.7 to 8.0, and three-lane entries 9.75 to 12.0 m when using the U.K. model with WisDOT adjustments [6]. Making such adjustments is what is referred to as using effective geometry that drivers actually use, regardless of the exact field measured dimensions. Recommended calibration procedures require at least three periods of 20 minutes each with sustained queues of at least five vehicles on the approach being calibrated, the details to calibrate the capacity equation are summarized as follows [7]:

- During the study period, the amount of entering and circulating flow is gathered on a minute-by-minute basis;
- From the gathered data, average entering flow, $\bar{Q}_e$, and average circulating flow, $\bar{Q}_c$, are computed;
- Slope computation remains the same from the uncalibrated equation, with variables as defined previously:

$$slope = kf_c$$

- A calibrated, local, intercept for the capacity equation is calculated by:

$$F^l = Q_e + kf_c\bar{Q}_c$$

- The calibrated local capacity, $\bar{Q}_e^l$,equation becomes:

$$Q_e^l = F^l + kf_cQ_c$$

Notably, following this capacity calibration procedure results in a linear capacity prediction that is forced through the average entering flow of the field data, which can be seen in the Q_e^l equation by setting $Q_c = \bar{Q}_c$.

2.4.2 German Model

The model presented in the German Highway Capacity Manual (HBS 2001) was used for this research [8, 9]. This model uses gap acceptance theory with critical gap and follow-up headway as the main parameters. Capacity prediction is aggregated at the approach level; however, the number of lanes is an input in the model to allow for the higher capacities seen at multilane roundabouts. The resulting capacity equation is:

$$c = 3600\left(1 - \frac{t_{min} q_c}{3600 n_c}\right)^{n_c} \frac{n_e}{t_f} e^{-\frac{q_c}{3600}\left(t_c - \frac{t_f}{2} - t_{min}\right)}$$

where

c	=	Entry capacity for approach (pcu/h)
q_c	=	Circulating flow (pcu/h)
n_c	=	Number of circulating lanes
n_e	=	Number of entry lanes
t_f	=	Follow-up headway, 2.9 s
t_c	=	Critical gap, 4.1 s
t_{min}	=	Minimum gap between succeeding circulating vehicles, 2.1 s

No calibration procedure for the capacity equation has been specifically identified. Instead, on the basis of how gap models in general are calibrated, this research used the critical gap and follow-up headway values observed from the field study to represent a calibrated German model. Just as the U.S. Highway Capacity Manual has been updated to the year 2010 edition, an update for the German HBS 2001 will be available soon [23].

2.4.3 French Model

Original research from France obtained for this study was only published in the French language [10], which presented some difficulties. Other literature [14, 24] has presented French capacity equations; however, these appeared to be based on Girabase released in 1994. The current version from 1999 used in this evaluation included new inputs, and consequently the results did not match the magnitude of capacity predictions from the older formulas. An English version of the Girabase manual revealed that the capacity model is of the hybrid type with basis in gap acceptance theory originally from Siegloch, modified to be sensitive to geometric parameters including entry width, splitter island width, circulating width, and radius of the central island [25]. Additionally, the model is sensitive to the environment: urban, rural, or suburban based on the inputs of the Girabase software package. Capacity predictions are aggregated per approach. Beyond choosing the environment type, no specific calibration parameters were identified.

2.4.4 NCHRP 572 Model

Published in 2007, NCHRP Report 572 represents the most recent and extensive evaluation of roundabout capacity in the U.S. Eighteen single-lane and seven two-lane sites were used to analyze relationships between various parameters and capacity. The analysis showed that driver behavior appeared to be a more significant factor in capacity compared to detailed geometric measurements [1, 5]. Regression of field data led to parameters for input into a simple lane based model, based on the gap acceptance theory of Siegloch's formula [3]. Two models resulted: one for a single lane entry, and one for the dominant lane of a two-lane entry. These equations are:

for a single-lane roundabout

$$c = 1130e^{-1.0\times10^{-3}q_c}$$

for the critical lane of a multilane roundabout

$$c = 1130e^{-0.7\times10^{-3}q_c}$$

where

$$\begin{aligned} c &= \text{Lane capacity (pcu/h)} \\ q_c &= \text{Circulating flow (pcu/h)} \end{aligned}$$

Essentially, the HCM 2010 models can be thought of as interchangeable with the findings in the NCHRP Report 572 with a few minor distinctions; the model names are used synonymously throughout this report. The HCM 2010 adopted the NCHRP Report 572 single lane model, and stated the two-lane entry model as follows:

$$c_R = 1130e^{-0.7\times10^{-3}q_c}$$

$$c_L = 1130e^{-0.75\times10^{-3}q_c}$$

where

$$\begin{aligned} c_R &= \text{Capacity for the right entry lane (pcu/h)} \\ c_L &= \text{Capacity for the left entry lane (pcu/h)} \end{aligned}$$

Differences between the right lane and left lane equations are small. Both have the same intercept of 1130 pcu/h, but not the same slope. Resulting differences reach a maximum of about 28 pcu/h lower capacity in the left lane compared to the right lane equation for circulating flows in the range of about 1100 to 1800 pcu/h. Calibration of the capacity formulas can be achieved by entering custom critical gap parameters into the equations, which affects the “A” and “B” terms related to both the intercept and slope of the model [1]. The generic capacity formula for calibration is:

$$c = Ae^{-Bq_c}$$

where

$$\begin{aligned} c &= \text{Capacity for an entry lane (pcu/h)} \\ A &= \frac{3600}{t_f} \\ B &= \frac{(t_c - \frac{t_f}{2})}{3600} \\ q_c &= \text{Conflicting flow (pcu/h)} \\ t_f &= \text{Follow-up headway (s)} \\ t_c &= \text{Critical gap (s)} \end{aligned}$$

Calibrating the A and B terms results in changing either or both the intercept and slope (shape) of the capacity function as seen in the three cases demonstrated in Figure 2.5. *Case i* shows the default right-lane capacity equation for a two-lane roundabout. Lower critical gap values alter the B term and result in flatter slopes with more capacity throughout the range of data, as in *Case ii*, while increased critical gap values result in steeper slopes, as in *Case iii*. Adjusting follow-up headway primarily affects the intercept but also slightly changes the slope, again demonstrated in *Case iii*.

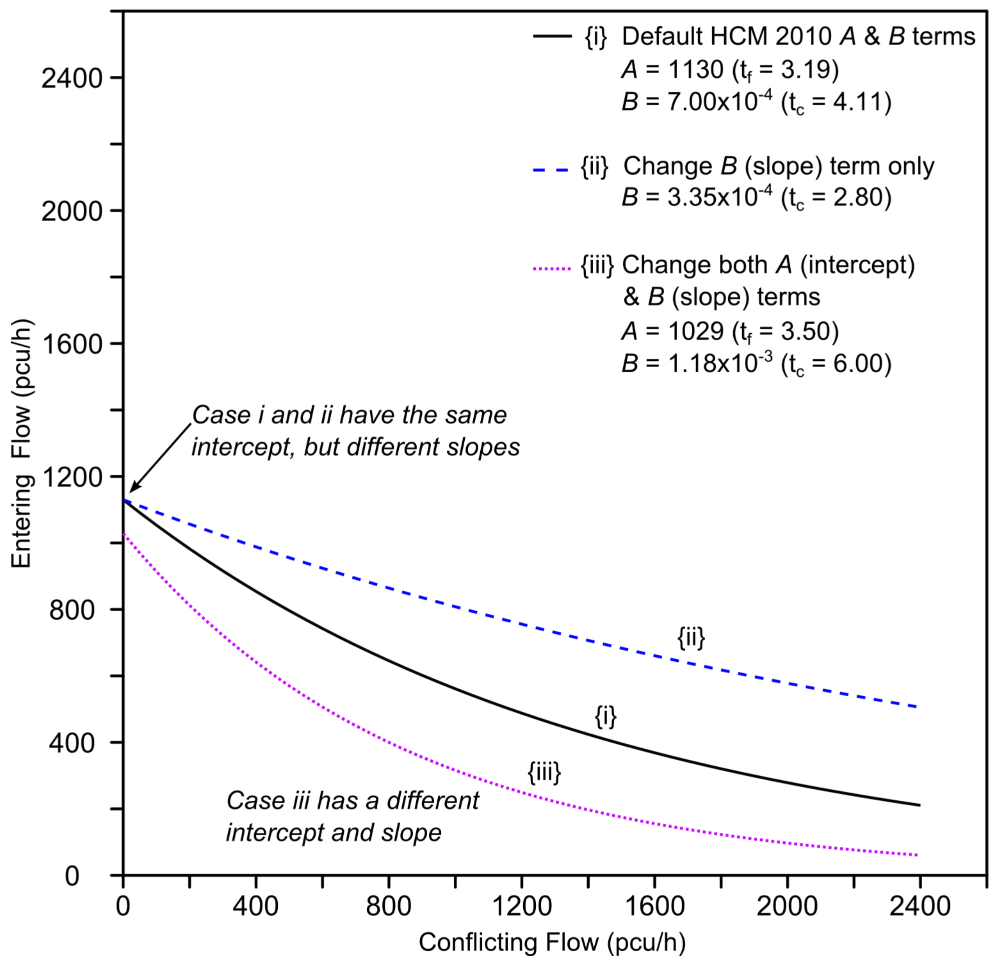


Figure 2.5. Effects of Calibration Parameters for the HCM 2010 Capacity Equations

2.4.5 Australian Method ARR 321

Based on research from the Australian Research Board, including work from Akcelik, Troutbeck, and others, the Australian capacity model has evolved from ongoing studies of many roundabouts. Sensitivity to traffic and geometric parameters have resulted in a complex lane-by-lane model, but each piece of the model can be understood through gap acceptance theory. The current version of SIDRA uses several proprietary functions that are not openly published. As such, this research uses the capacity formulas by the Australian Road Research Board report 321 (ARR 321) which is a comprehensive report published that SIDRA has since expanded upon [11].

Equations for the ARR 321 method can best be understood by making a comparison that capacity at a roundabout is analogous to capacity at a signal. At a signal, capacity (c) is proportional to the saturation flow rate (s) and the ratio between effective green time (g) and cycle length (C), resulting in the equation: $c = s(g/C)$. For roundabouts, the g/C ratio is analogous to the effective unblocked time where vehicles could enter the roundabout, and saturation flow rate is analogous to the maximum amount of entering flow possible with no conflicting vehicles ($3600/t_f$). The ARR 321 capacity equation used in this research is:

$$c = \max\left[Q_m, f_{od}Q_g\right]$$

with

$$\begin{aligned} Q_m &= \min\left[q_e, 60n_m\right] \\ Q_g &= \frac{3600}{\beta}\left(1 - \Delta_c\frac{q_c}{3600} + 0.5\beta\varphi_c\frac{q_c}{3600}\right)e^{-\lambda(\alpha-\Delta_c)} \\ f_{od} &= 1 - f_{qc}(p_{qd}p_{cd}) \end{aligned}$$

where

c = Capacity for an entry lane (veh/h)

Q_m = Minimum capacity of the opposed stream (veh/h)

Q_g = Capacity estimate using gap-acceptance method (veh/h)

q_e = Entry lane arrival flow (veh/h)

q_c = Conflicting flow for entry lane (veh/h)

n_m	=	Minimum entering vehicles (veh/min)
β	=	Follow-up headway (s)
α	=	Critical gap (s)
n_c	=	Number of conflicting lanes
Δ_c	=	Circulating stream intra-bunch headway (s)
		2.0 s for $n_c = 1$, 1.2 s for $n_c = 2$, 1.0 s for $n_c > 2$
φ_c	=	Proportion of unbunched (free) circulating vehicles
λ	=	Exponential arrival headway distribution model parameter
f_{od}	=	Origin-destination (O-D) pattern adjustment factor
f_{qc}	=	A calibration parameter for the O-D pattern effect
$p_{qd}p_{cd}$	=	Proportion of the total circulating stream flow that originated from, and were queued on, the dominant approach ($\approx$ 0.5 to 0.8)

Additionally, several parameters are calculated as follows:

for the proportion of unbunched (free) circulating vehicles:

$$\varphi_c = e^{-2.5\Delta_c q_c} - \delta\varphi_c$$

where

$\delta\varphi_c$	=	Extra bunching (platooning) in the circulating stream, calculated by SIDRA, using extra bunching data specified for the approaches

for the exponential arrival headway distribution model parameter:

$$\lambda = \begin{cases} \dfrac{\varphi_c q_c/3600}{1-\Delta_c q_c/3600} & \text{for } \dfrac{q_c}{3600} \leq \dfrac{0.98}{\Delta_c} \\[2ex] \dfrac{49\varphi_c}{\Delta_c} & \text{for } \dfrac{q_c}{3600} > \dfrac{0.98}{\Delta_c} \end{cases}$$

for the O-D adjustment calibration parameter:

with a single lane circulating flow

$$f_{qc} = \begin{cases} 0.04 + 0.00015 q_c & \text{for } q_c < 600 \\ 0.0007 q_c - 0.29 & \text{for } 600 \leq q_c < 1800 \\ 0.55 & \text{for } q_c > 1800 \end{cases}$$

with a single lane circulating flow

$$f_{qc} = \begin{cases} 0.04 + 0.00015 q_c & \text{for } q_c < 600 \\ 0.00035 q_c - 0.08 & \text{for } 600 \leq q_c < 1800 \\ 0.55 & \text{for } q_c > 1800 \end{cases}$$

Further, follow-up headway and critical gap are calculated by:

for the dominant lane, follow-up headway

$$\beta_d = \begin{cases} \beta'_d - \frac{q_e/q_c}{(q_e/q_c)_{max}} \left[\beta'_d - \beta_{om} - \frac{q_c}{q_{cm}} (\beta_{Lm} - \beta_{om}) \right] & \text{for } q_c \leq q_{cm} \\ \beta'_d & \text{for } q_c > q_{cm} \end{cases}$$

subject to $\beta_{Lm} \geq \beta_{om}$ and $q_e/q_c \leq (q_e/q_c)_{max}$

where

β_d	=	Dominant lane follow-up headway, adjusted for the ratio of entering to circulating flows (s)
β'_d	=	Unadjusted dominant lane follow-up headway (s)
	=	$\beta'_o - 3.94 \times 10^{-4} q_c$
		subject to $\beta_{min} \leq \beta'_d \leq \beta_{max}$ where β_{min} and β_{max} are set minimum and maximum values of follow-up headway, 1.2 s and 4.0 s respectively
β'_o	=	Follow-up headway at zero circulating flow (s)
	=	$3.37 - 0.0208 D_i + 0.889 \times 10^{-4} D_i^2 - 0.395 n_e + 0.388 n_c$
		subject to $20 \leq D_i \leq 80$
		where D_i = inscribed diameter (m)
		n_e = number of entering lanes, excluding bypasses
		n_c = number of circulating lanes
β_{om}	=	Minimum β_d for zero circulating flow ($\beta_{om} = 1.8$ s used)
		subject to $\beta_{om} \geq \beta_{min}$
q_{cm}	=	Limit on circulating flow rate above which the follow-up headway is not adjusted, ($q_{cm} = 900$ pcu/h used)

β_{Lm} = Value of follow-up headway when $q_c = q_{cm}$ in the unadjusted β'_d equation

q_e/q_c = Ratio of entry flow to circulating flow

$(q_e/q_c)_{max}$ = Upper limit on the q_e/q_c ratio (3.0 used)

for the subdominant lane follow-up headway

$$\beta_s = 2.149 + (0.5135\beta_d - 0.8735)r_{ds}$$

$$\text{subject to } \beta_d \leq \beta_s \leq \beta_{max}$$

where

r_{ds} = Ratio of entry lane flows

= q_d/q_s

where q_d = dominant lane entry flow rate

q_s = subdominant lane entry flow rate

for the dominant or subdominant lane critical gap

$$\alpha = \begin{cases} (3.6135 - 3.137 \times 10^{-4} q_c - 0.339 w_L - 0.2775 n_c)\beta & \text{for } q_c \leq 1200 \\ (3.2371 - 0.339 w_L - 0.2775 n_c)\beta & \text{for } q_c > 1200 \end{cases}$$

$$\text{subject to } 1.1 \leq \frac{\alpha}{\beta} \leq 3.0 \text{ and } \alpha_{min} \leq \alpha \leq \alpha_{max}$$

where

α = Dominant or subdominant lane critical gap, a_d or α_s respectively (s)

β = Dominant or subdominant lane follow-up headway β_d or β_s

w_L = Average entry lane width (m)

α_{min} = 2.2 s

α_{max} = 8.0 s

One aspect seen in the ARR 321 method is the sensitivity to the ratio of entry flow to circulating flow. This sensitivity helps the model to avoid underpredicting capacity at low circulating flow rates. With low circulating flow large gaps can occur that many entering vehicles could take advantage of, which in turn increases the amount of capacity. The effect of increasing capacity based on the entry to circulating flow ratio is constrained by limiting the minimum and maximum values that can be used for the ratio. When performing a capacity study on an existing roundabout, the ratio can be calculated directly from field data, however for future roundabouts, an assumption must be made about the extent of the adjustment.

2.4.5.1 Calibration and Differences Between ARR 321 and SIDRA

Several significant differences between the methods implemented in the current version of SIDRA and ARR 321 are noted in the SIDRA User guide, some of which include [26]:

- An introduction of an *environment factor* as a calibration parameter;
- Revision of follow-up headway, critical gap, and circulating vehicle headway parameters;

- New functions for the origin-destination pattern effect on capacity as well as the proportion of bunched (platooned) vehicles;
- Addition of capacity sensitivity to entry radius and entry angle parameters; and
- Changes for many parameters in terms of default values, boundary conditions, and other modifications to the original equations.

These differences cause the capacity results calculated from ARR 321 to be notably, but situationally dependent, from output from SIDRA, especially regarding the environment factor. The environment factor (EF) represents a calibration term to accommodate local conditions where capacity may be higher or lower than observed elsewhere, and the choice of an EF value can have a large influence on capacity. Higher EF values result in lower capacity estimates. Using an uncalibrated scenario with EF = 1.0 reflects typical conditions observed in Australia, while an EF of 1.2 is recommended in the SIDRA User Guide to better reflect capacity recently seen in the U.S [26]. Even though the exact capacity function for SIDRA could not be obtained, Figure 2.6, adapted from the SIDRA User Guide, allows an approximate comparison between environment factors and the ARR 321 method. Depending on the amount of conflicting flow, capacity can be about 100 to 200 pcu/hr lower for EF = 1.2 compared to EF = 1.0. The ARR 321 method can be seen as an estimated representation to the uncalibrated SIDRA scenario with EF = 1.0, and should be thought as such when interpreting capacity graphs throughout this research. For all calibrated scenarios using ARR 321, default critical gap and follow-up headway parameters were substituted by field values rather than attempting to approximate an appropriate SIDRA environment factor.

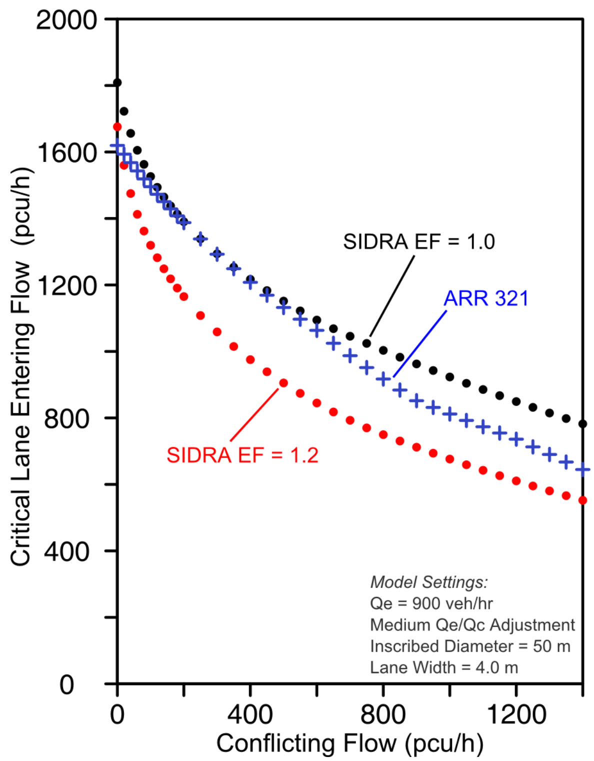


Figure 2.6. Comparison of SIDRA Capacity with Environment Factors and the ARR 321 Method *(Adapted from the SIDRA User Guide, Figure 19.4.2)*

2.4.6 Summary and Notes on Capacity Model Parameters

Table 2.2 summarizes the parameters in each model equation to give a sense of the similarities and differences. All models use the amount of circulating flow as an input, and thus has been omitted from the table. Parameters listed in Table 2.2 are not necessarily the same as what a user would need to enter in a software package implementing the models, especially regarding the ARR 321 method, because some parameters are automatically calculated from broader inputs such as traffic volumes. Others parameters have default values that only need to be changed for calibration purposes. Further, some software packages require additional inputs such as lane lengths and lane configurations. Section 6.6.1 discusses actual software inputs for implementing each model.

Table 2.2. Summary of Model Equation Parameters

UK	German (HBS 2001)	French (Girabase)	NCHRP 572 / HCM 2010	ARR 321
• Entry width • Approach width • Flare length • Entry radius • Entry angle • Inscribed circle diameter	• Critical gap • Follow-up headway • Minimum circulating headway • Number of lanes conflicting • Number of lanes entering	• Critical gap • Follow-up headway • Area type (urban, rural, suburban) • Entry width • Splitter island width • Circulating width • Radius of central island	• Critical gap • Follow-up headway	• Critical gap • Follow-up headway • Minimum circulating headway • Minimum entering flow • Ratio of entry flow to circulating flow • Origin-destination affect adjustment factor • Arrival headway distribution factor • Proportion of unbunched conflicting vehicles (platooning effect) • Inscribed diameter • Entry lane width

2.5 Other Recent Capacity Studies

Two recent studies, one with data collected from Michigan and one with data collected from Indiana, have also looked at roundabout capacity [27, 28]. Each study was presented in the year 2011 at the 3rd International Conference on Roundabouts. Data from these studies will be compared to this research in Section 5.2.

The first study of Michigan roundabouts focused on two sites, each with triple-lane entries, as an exploration of how well existing models extend to larger roundabouts. Conclusions showed that the triple-lane roundabouts analyzed had significant lane imbalance with the innermost lane servicing the highest amount of traffic, likely due to a downstream lane drop. Extending the HCM 2010 two-lane equation to these three-lane roundabouts tended to overestimate capacity due to more conservative driver behavior. Calibration improved the model prediction [27].

Three single lane entry sites in Indiana were analyzed in terms of capacity in the second study. In summary, field observations revealed considerably smaller critical gap and follow-up headway values compared to the default HCM 2010 values, suggested to be the result of potential driver familiarity with roundabouts in the Carmel, Indiana area. Consequently, the default HCM 2010 model was found to be conservative and underpredicted capacity [28].

2.6 Software Background

Other transportation software comparison studies have been completed [29-33], but none for comprehensively evaluating roundabout software, in terms of usability and performance, were found to be published to date. The most similar report to this research was on comparing signalized intersection software, which compared seven software packages, including SIDRA [32]. For roundabout analysis, this research is timely as other agencies have been investigating the various models and software packages available [33]. A brief description of each software package used in this study follows.

RODEL Originally released in 1992, RODEL (ROundabout DELay) was developed in England by Barry Crown as a way to analyze roundabouts with the U.K. model [34, 35]. Many state DOTs, including Wisconsin, currently uses this program as the standard for roundabout analysis as outlined in the FDM [6]. Version 1.9.7, which uses a DOS interface, was identified as the most widely used and released version identified at the beginning of this research.

ARCADY Developed by the U.K.'s Transport Research Laboratory (TRL), ARCADY (Assessment of Roundabout Capacity and Delay) also implements the U.K. model. ARCADY provides many features beyond capacity modeling as well. With about 30 years of development, TRL is now on version 7.1 of ARCADY which has been used for this evaluation [36].

RCAT Roundabout Capacity Analysis Tool (RCAT), copyrighted in 2009 by Diodos Software, uses Microsoft Excel to implement analysis using the U.K. model, similar to RODEL and ARCADY [37].

Kreisel Many capacity models from around the world, including some not discussed here such as the Swedish and Israeli methods, can be evaluated within Kreisel. but this evaluation focused on using the German Highway Capacity Manual (HBS 2001) method. An English interface for version 7.0 of the software was used throughout the study.

Girabase The Center for Studies on Networks, Transport, Urban Planning and Public Buildings (CERTU) in France, published Girabase software to implement the French model for roundabout capacity. CERTU was formed in 1994 from the distillation of two prior French agencies. Version 4 of this software, released in 1999 with a French interface, was used for the evaluation [38].

HCS The Center for Microcomputers in Transportation (McTrans) was formed in 1986 and has ties to the University of Florida as well as the Federal

Highway Administration (FHWA) [39]. Many types of transportation facilities, including roundabouts, can be evaluated in their Highway Capacity Software (HCS) product. HCS 2010 fully implements the analysis methods described in the recent release of the HCM 2010.

SIDRA Formally called SIDRA INTERSECTION, this software has evolved over 30 years of research in signalized and unsignalized intersections under the guidance of the Australian Research Board and Akcelik & Associates [26, 40]. Version 5.1 of SIDRA was used for this evaluation. In terms of capacity analysis, Some proprietary functions and parameters based on recent research have been implemented in SIDRA and are not reflected in the source material used during this research. Section 2.4.5.1 includes specific details and implications of the differences between the SIDRA model and the ARR 321 method used within.

In summary of the literature review, many roundabout capacity models and software packages are available for analysis purposes. Research and development from around the world has led to models that successfully incorporate either or both gap acceptance and geometric parameters. Many countries, including the U.S. have undergone various model revisions and will likely continue to do so in the future as research continues to refine understanding. Software has evolved along with each model and, like most technology, versions can change quickly. Therefore, any commentary on software is only relevant to the version evaluated.

3 Study Design

A systematic approach was maintained for this research in order to remain as unbiased as possible. Also, a philosophy of thinking about models before software, was kept in mind to ensure analyses and comparisons were based on scientific evidence and engineering judgment. Communication and input from the vendors, however, occurred throughout the research as a way to build relationships and gain insight to features and correct use of the software that may have been otherwise overlooked. Figure 3.1 shows a high level overview of the methodology used for the evaluation, with each of the seven milestone steps further described in this section. Key to this research, *Steps 2* and *3*, drove the science behind the major findings and fulfilled the objectives of comparing capacity models. *Steps 4* and *5* satisfied the objective of comparing software usability. *Step 6* fulfilled the objective of summarizing findings in an evaluation matrix.

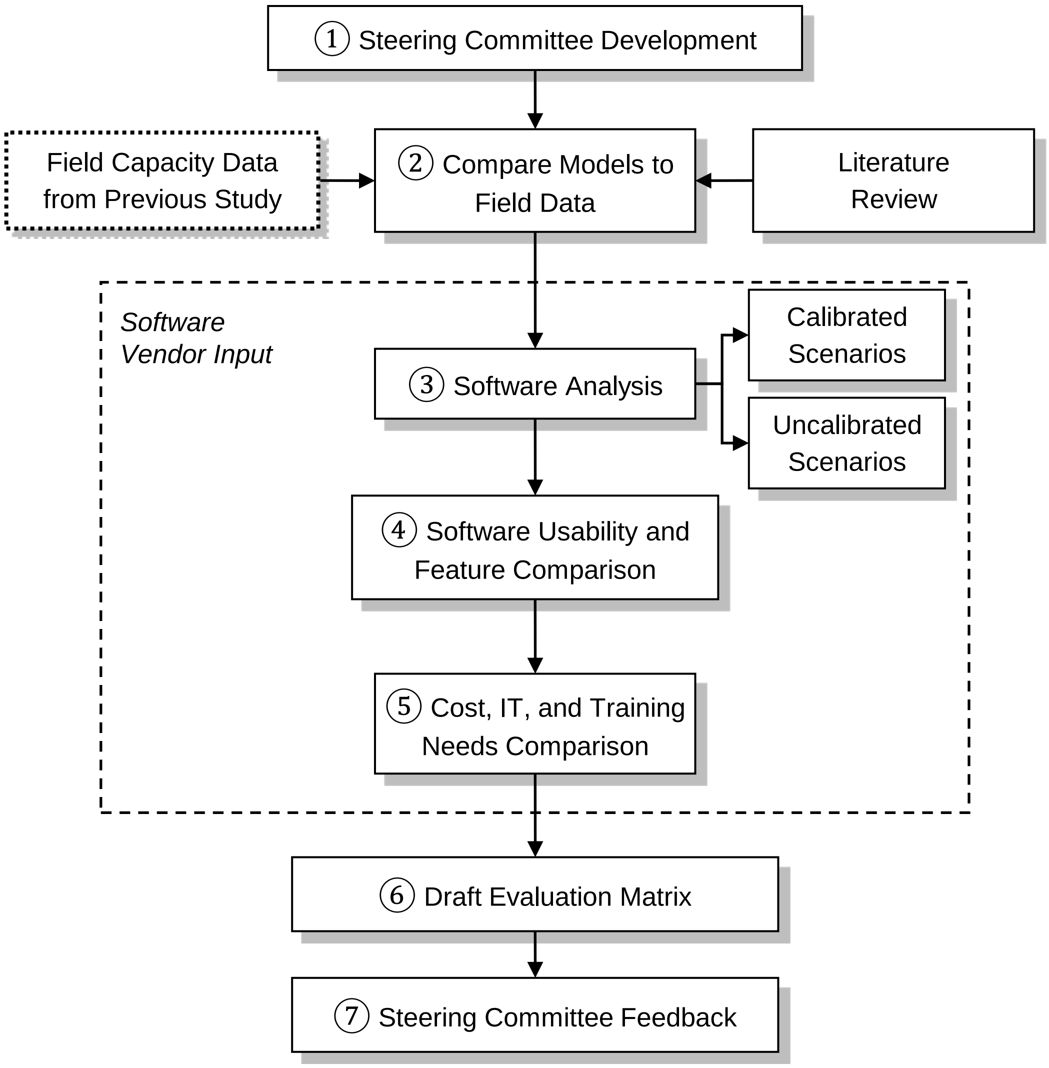


Figure 3.1. Software Evaluation Methodology

Step 1: A diverse steering committee was formed to provide a comprehensive range of perspectives during the evaluation. Members consisted of WisDOT staff from each region, the central office, and Information Technologies (IT) department. Transportation consultants were also part of the steering committee, which allowed needs to be expressed from both the public and private sectors. The large group also covered the range of a project lifecycle from different members having expertise in planning, design, and operations. After forming the committee, a set of needs and outcomes were identified to form the basis for the evaluation as listed in Table 3.1. Meetings were held at intermediate milestones to discuss preliminary results and identify future investigations.

Table 3.1. Evaluation Criteria

Category	Criteria
Technical Accuracy	Difference between software prediction and field observations
Usability	List of inputs to reflect data collection and software input intensity
	Ease of software use
	Listing of advanced features
	Training availability and technical support
	Other miscellaneous features as needed
IT Requirements	Installation Requirements
	Licensing Type
Cost	Licensing Cost

Step 2: Entering and circulating flow data, which form the basis for capacity analysis, were compared to theoretical capacity models to help in evaluating technical accuracy. Microsoft Excel spreadsheets were developed and based on research papers from the primary sources of each capacity model. Both uncalibrated and calibrated models were used in the comparison. Calibration of the capacity model spreadsheets is discussed in Section **??**. Graphing entering flow versus circulating flow from the field data and fitting each theoretical model allowed root-mean-square error (RMSE) computations for a quantitative estimate to compare the differences between each model. Section **??** further discusses error measurement.

Step 3: Software analysis consisted of evaluating default, uncalibrated scenarios as well as calibrated scenarios. In each case, data input was kept to the essential minimum in order to simulate future analysis where the analyst would have projected estimates and limited field data. Analyzing from a future perspective was more useful because much of the practical work in the roundabout field is focused on design. Essential data input included:

- Peak hour volumes and peak hour factor,
- Percent trucks, and
- Geometric information, if needed for the particular model.

Software calibration was kept consistent with the calibration and comparisons performed in *Step 2*, with further details of calibration procedures described in Chapter 6. Because field data were only collected for certain approaches, only the studied approaches received calibrated parameters in the software. All other approaches retained their default parameters. Further, only the capacity model was calibrated, either by observed gap acceptance parameters or entering-circulating flow relationships where applicable. No other parameters were changed in the calibrated scenarios. Software output was recorded for each approach but the emphasis was placed on the field study approaches. Not all software allowed for calibration of the models being evaluated, including RODEL 1.9.7, RCAT 1.4, Kreisel 7.0, and Girabase 4.0; these packages were excluded from calibrated comparisons.

Step 4: While a user can become accustomed to any interface and limitations, the software should not present a barrier to quality analysis. Software usability was evaluated holistically based upon the experiences during *Step 3*. A major complication of evaluating usability are first defining usability and second dealing with subjective biases. Usability was defined and evaluated by considering the following points:

- Initial learning curve,
- Logical layout and data input ease,
- User feedback and error prevention features, as well as
- Long-term memory load for infrequent users.

Subjective biases in terms of the presented usability definition would be best minimized by having multiple evaluators. However, logistical and budget needs presented a barrier to conducting large scale usability testing. As such, the usability results should be treated with caution as the results are based on opinion.

Step 5: Each software vendor was given the same list of questions in order to compare the IT needs and licensing costs. Three questions were asked to complete this step:

1. What are the installation requirements for the software (CPU, RAM, Operating System, etc)?
2. What type of licensing requirements and options are available (Standalone, Network Based, etc) and what is the cost associated with the licensing?
3. What is the availability and cost of support services? Is any training available and at what cost?

Step 6: As a result of all of the previous steps, findings were summarized in tables, called evaluation matrices, to allow side-by-side comparisons. The matrices present preliminary findings to the steering committee. Responsibility was placed on the steering committee to assign weights to the importance of each feature for refinements and future decision making. At the time of this writing, weighting criteria was beyond the scope of this thesis and subject to future research.

Step 7: Presenting the draft evaluation matrix to the steering committee gave an opportunity for all public and private sector stakeholders to review the work, ask questions, and identify issues that need to be investigated further before decision making. Again, at the time of this writing, final decisions of the steering committee were beyond the scope of this thesis and subject to future research.

These seven steps represented a highly exploratory process where certainly more questions arose throughout the journey. Upon completion of these seven steps, however, valuable insights were gained in regards to how capacity models compare, what current software packages provide, and an understanding of what future steps may be necessary.

4 Data Collection and Site Descriptions

Data collection proceeded by selecting locations for study, gathering field operational data, and finally reducing data. Gathering operational data was one part of a larger comprehensive evaluation of roundabouts, which has formed the basis for other studies [41]. This section describes only the data collection procedures that were relevant to gathering the operational parameters for this particular research.

4.1 Site Selection and Descriptions

Roundabout locations were chosen primarily based upon the potential to observe queued operations. Both multilane (maximum of two entering lanes) and single-lane roundabouts were considered. Based on the goals of this research, several sites were identified for inclusion in data collection. Once the field data was collected, however, only two sites experienced enough queuing for capacity data analysis and will be described in this section. The two sites will be distinguished by referring to them as the "Canal St" and "De Pere" sites. Relative locations can be seen in Figure 4.1. Within each site, the local street names will be used to reference each roadway approach.

Figure 4.1. Study Locations

4.2 Canal St Site

Located in Milwaukee, WI the Canal St roundabout is in an urban, industrialized location, just southwest of the major interchange between I-94 and I-43. Average daily traffic on the east-west Canal St is over 6000 veh/day [42]. Figure 4.2 shows the layout of the t-intersection roundabout. Canal St is the major road with two-lane approaches in the east-west direction. The southbound 25th St is the minor approach with one entering lane conflicted by two lanes. Extra entry width is provided for heavy vehicles. Complete intersection geometry details are presented in Section 5.3. At the time of data collection, lane striping was minimal in the circulatory roadway, unlike other roundabouts in Wisconsin. Notably, the 25th St approach experienced the most queuing due to heavy through-movement traffic on Canal St and was the approach used for this study.

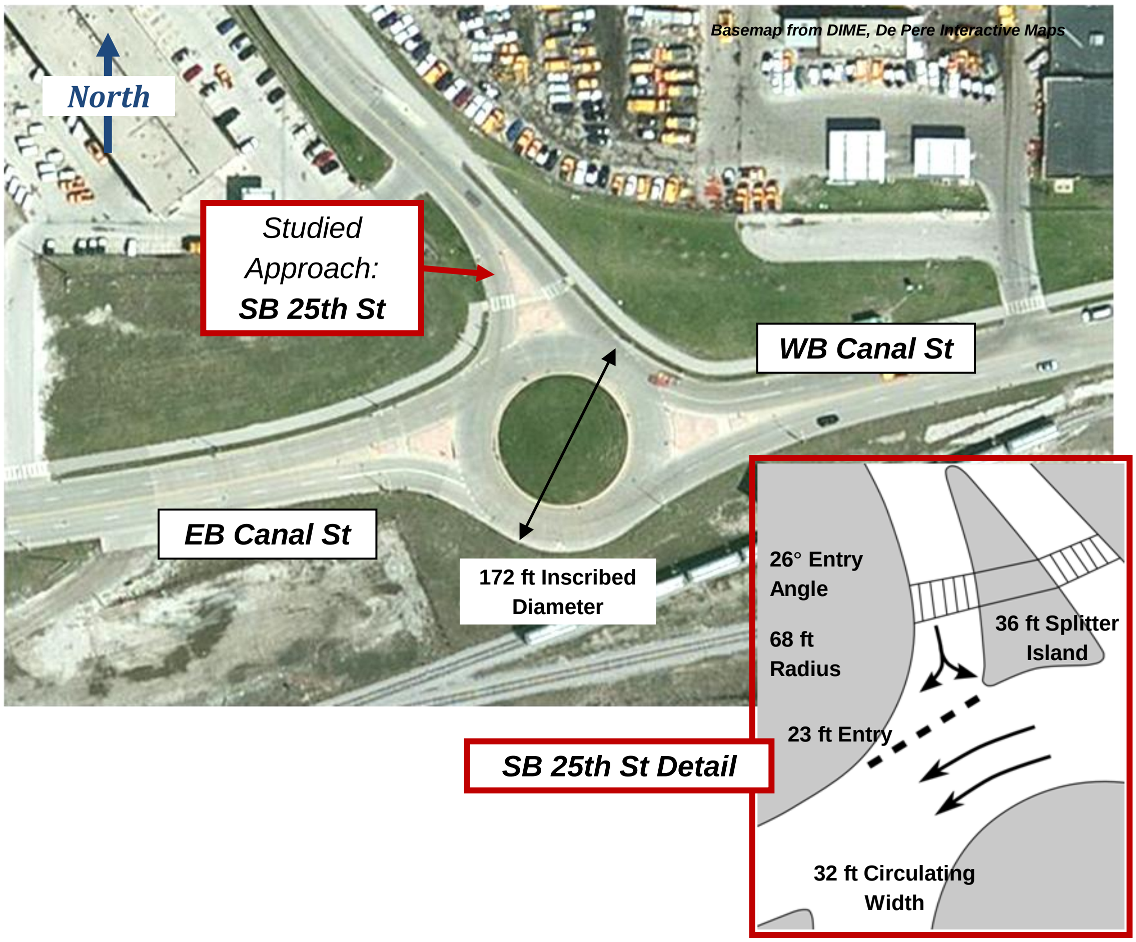


Figure 4.2. Canal St Site Configuration

4.3 De Pere Site

The De Pere site, named in part because of its connection to the De Pere bridge (formally the Claude Allouez Bridge), is located in the downtown of De Pere, WI along the Fox River, near Green Bay. De Pere is home to many roundabouts, and this particular location is the hub of major routes including STH 32 and STH

57, as well as CTH G and CTH X for Brown County. There are five bridges to the north of this roundabout, the nearest being two miles north where STH 172, which connects I-43 and US-41, crosses the river. To the south, there are no other bridges crossing the Fox River for 11 miles. Average daily traffic counts from 2009 for the eastbound bridge approach were almost 30,000 veh/day and 21,000 veh/day for the northbound approach [42]. Construction along STH 172 caused extra traffic to detour through the De Pere roundabout, creating the congestion necessary for capacity measurements. Every approach has two lanes entering (assigned through-left and through-right) with two lanes conflicting, as shown in Figure 4.3. Studied approaches included northbound Broadway St and eastbound Main Ave (from the bridge). Complete intersection geometry details are presented in Section 5.3.

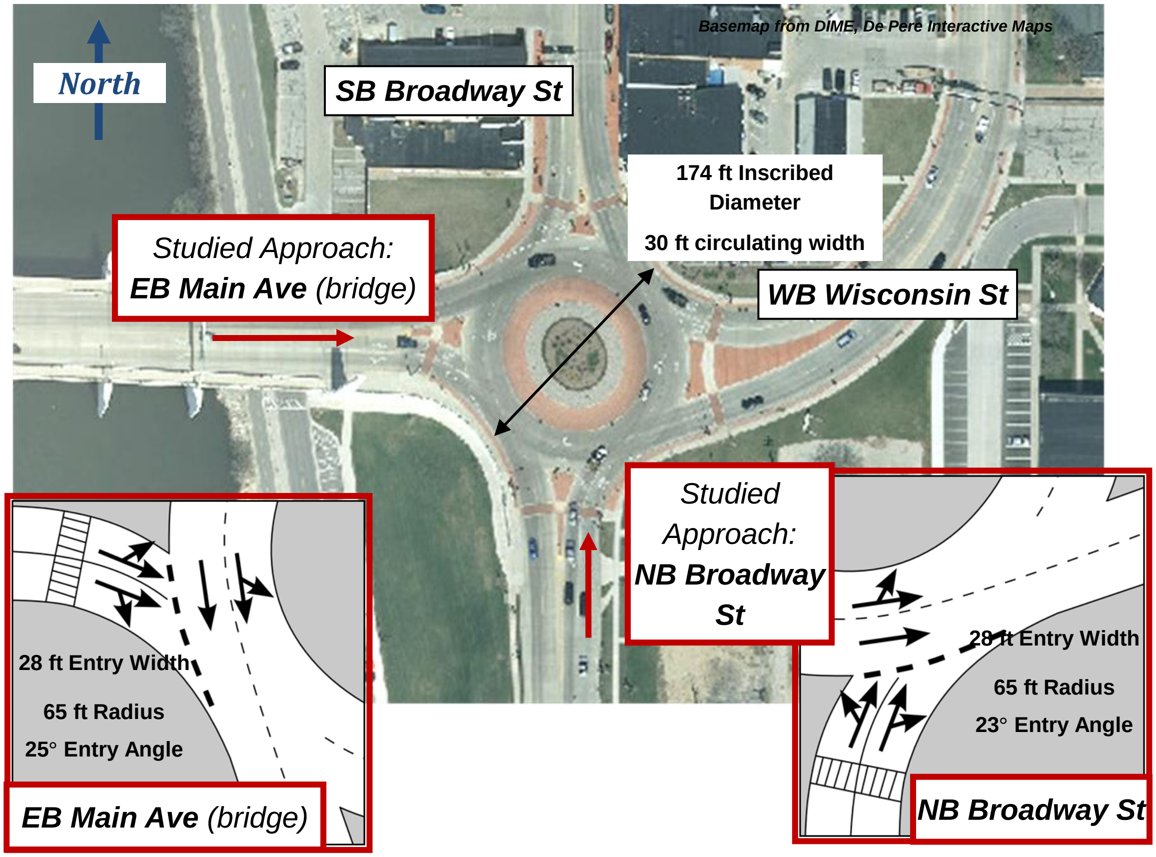


Figure 4.3. De Pere Site Configuration

4.4 Field Data Collection

Time periods for collection were chosen based upon collecting traffic operations representative of normal conditions:

- Dry weather conditions,
- Daytime traffic operations, and
- Typical weekday peak operations.

At the chosen sites, only the approaches with the most queuing were further analyzed. Field operational data was obtained by means of video recordings, typical of the setup shown in Figure 4.4. High definition cameras were set up to observe the studied approach and corresponding exit of the major movement. Camera placement was as close to the roadway as possible, typically 200 to 400 ft away. A Miovision™ proprietary fish-eye camera was set up to observe the central island and circulating traffic. Mounting and location of each camera was done in such a way to minimize disruption to traffic and not cause a distraction to drivers during recording.

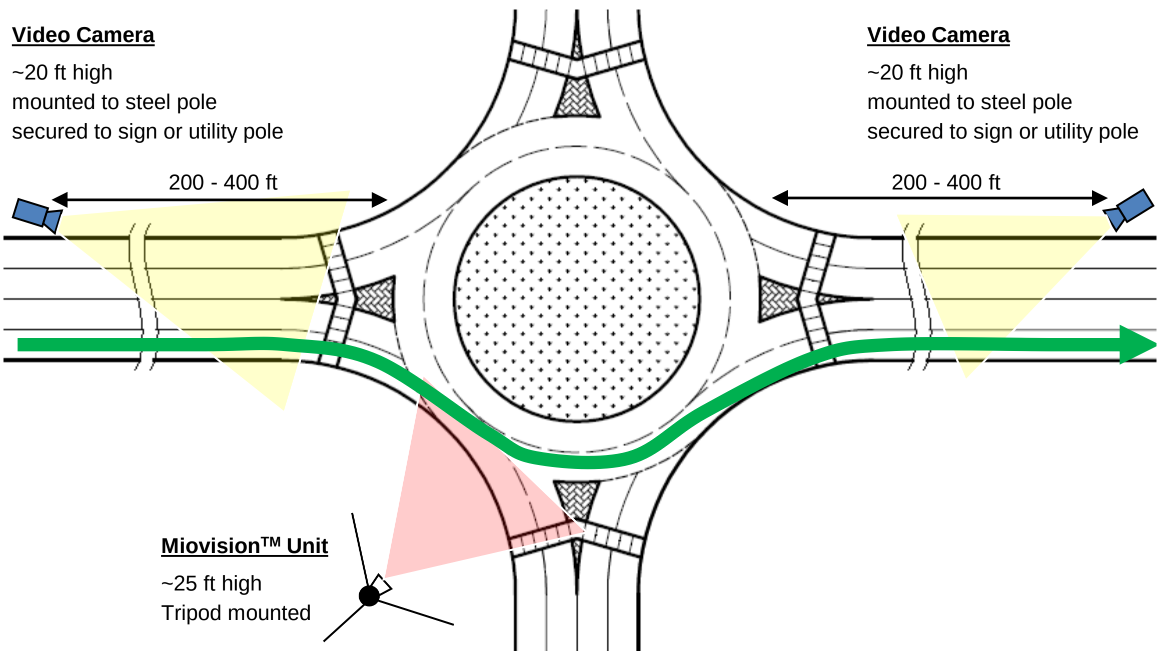


Figure 4.4. Typical Camera Setup for Recording Traffic

(Adapted from Reference 41)

All video recording was done during good weather and daytime hours, typically between 12:00 PM and 6:00 PM for PM peak observations and 6:30 AM to 9:00 AM for AM peak observations. Videos from each camera were combined in post-processing using Sony Vegas 9.0 to obtain a single synchronized video for data reduction as shown in Figure 4.5.

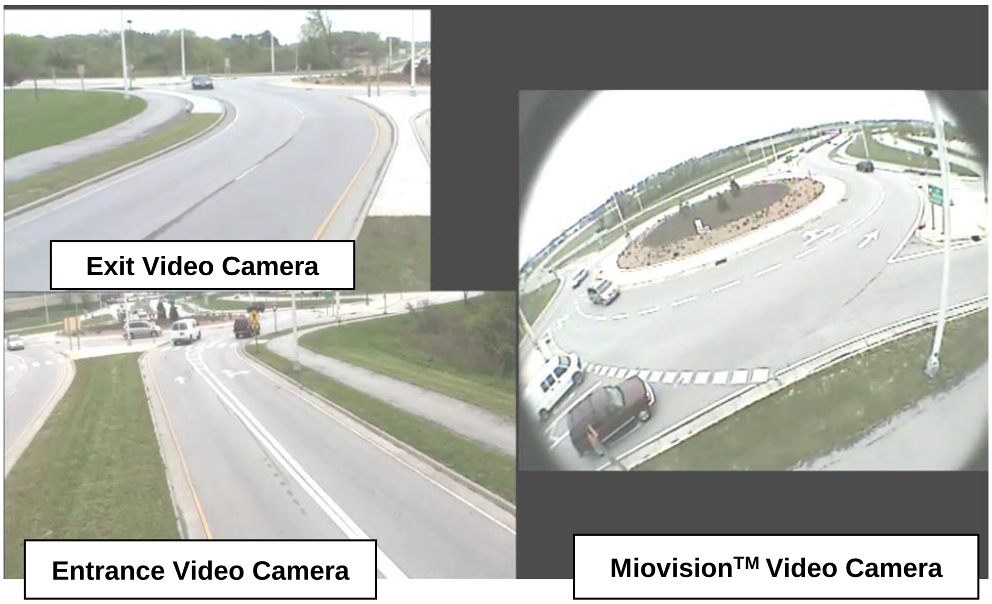


Figure 4.5. Sample Synchronized Video Screenshot used for Data Reduction

(Adapted from Reference 41)

Geometry measurements for each roundabout were obtained from as-built construction plans or from scaled aerial photos imported into CAD software, in accordance with the original documentation for each model. Measurements for all approaches were recorded in order to provide the necessary inputs for operational modeling in the various software packages. Complete geometry details for each intersection are presented in Section 5.3.

4.5 Field Data Reduction

Reduction of the video data occurred through the use of software developed at the University of Wisconsin Traffic Operations and Safety (TOPS) Laboratory [43].

Figure 4.6 shows a screenshot of the software interface.

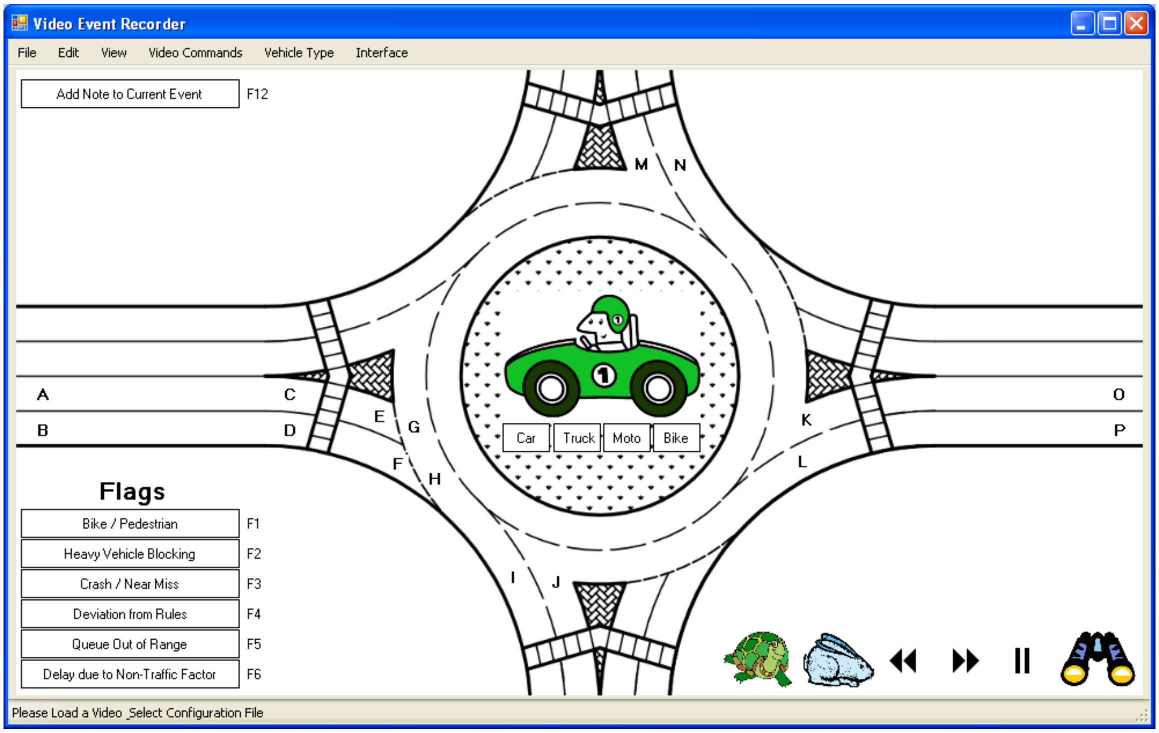


Figure 4.6. Time Stamp Extraction Software User Interface

Essentially, the software allows the user to manually record timestamps while watching a synchronized video by typing a letter correspond to specific events for each vehicle. The letters shown in each lane of Figure 4.6 coincide with the following events [41]:

- Upstream approach time (letters A/B) – a time stamp was recorded when vehicles passed a point of known distance upstream of the roundabout;
- Back of queue time (letters C/ D) – a time stamp was recorded when vehicles joined the back of a queue; First in server time (letters E/F) – a time stamp was recorded when vehicles arrived at the first in server or first in queue position;

- Entry time (letters G/H) – a time stamp was recorded when vehicles began their entrance in to the roundabout;
- Exit time (letters I/J, K/L, M/N) – a time stamp was recorded when vehicles exited the roundabout;
- Downstream exit time (letters O/P) – a time stamp was recorded when vehicles making a through movement passed a point of known distance downstream of the roundabout;
- Conflicting vehicle time (letters Q/R) – a time stamp was recorded when circulating vehicles passed a point perpendicular to the yield line;
- Exiting vehicle time (letters S/T) – a time stamp was recorded when circulating vehicles exited the roundabout at the approach in question.

Collecting timestamps was done to the maximum extent possible, limited by the camera field of view. For tracking queuing, times were noted when the queue extended beyond the camera, which was especially prevalent at the De Pere site. From these timestamps, gap acceptance parameters, entry flow, and conflicting flow data could be identified. Critical gap and follow-up headway were derived in a manner similar to that of "Method 2" used in NCHRP 572, where vehicles needed to have rejected a gap in order for inclusion in the data set [5]. Additionally, turning movement counts were obtained by means of the Miovision™ data reduction service.

5 Capacity Analysis

This chapter presents the data and analysis for the capacity study which forms the basis for model comparisons.

5.1 Observed Queuing Data

Reduction of the video data collection resulted in a number of one-minute intervals that were fully queued in order to evaluate capacity. Queues had to be at least five vehicles long throughout the entire minute in order to qualify as fully queued to be compatible with previous research [7]. Table 5.1 summarizes the number of observations made during the PM peak studies. Times of day shown reflect the hours observed. Also an approximate number of the total subset of minutes used for capacity analysis within the observed hours is listed. The Canal St site was characterized by steady but sometimes sporadic queues during the study period, and resulted in one data set for the studied single-lane approach. Three different data sets for each studied approach resulted for the two-lane De Pere site:

- A data set for whenever the left lane was queued (queuing may or may not have been present in the right lane);

- A data set for whenever the right lane was queued (queuing may or may not have been present in the left lane); and
- A data set for when both the left lane and right lane were queued.

The De Pere site had more consistent queues in the PM peak period compared to the Canal St site. Especially the northbound Broadway approach which experienced queues in the left lane for 268 minutes of the 300 minutes of video data. Due to limited resources, data for an AM peak period was only collected for the De Pere site and is shown in Table 5.2. No queuing was observed on the eastbound (bridge) Main Ave approach during the AM peak, but the northbound approach still exhibited queuing. Unless otherwise specified, all entering-circulating graphs, gap acceptance parameters, and other comparisons are based on PM peak data. AM peak data followed similar trends and is summarized in Appendix A. An exploration of combining AM and PM peak data is presented in Section 5.5.2.

Table 5.1. Summary of Observed PM Peak Minutes of Queuing

PM Peak	
Studied Approach	**Number of One-Minute Queuing Intervals**
Canal St Site	
Thursday April 15, 2010	
Between 1:30 pm to 6:00 pm	
SB 25th St [Out of approx. 250 min]	71
De Pere Site	
Wednesday May 19, 2010	
Between 11:30 am to 6:30 pm	
EB Main Ave (bridge)	
[Out of approx. 200 min]	
Left Lane	82
Right Lane	125
Both Lanes	66
NB Broadway St	
[Out of approx. 300 min]	
Left Lane	268
Right Lane	77
Both Lanes	76

Table 5.2. Summary of Observed PM Peak Minutes of Queuing

AM Peak	
Studied Approach	**Number of One-Minute Queuing Intervals**
De Pere Site	
Thursday May 20, 2010	
Between 6:30 am to 8:50 am	
EB Main Ave (bridge)	
[Out of approx. 120 min]	
Left Lane	1
Right Lane	2
Both Lanes	1
NB Broadway St	
[Out of approx. 120 min]	
Left Lane	84
Right Lane	27
Both Lanes	24

In addition to one-minute queued intervals, peak hour turning movement counts and percentages of heavy vehicles were obtained from the Miovision^{TM} video and data reduction. Consecutive one-minute turning movement counts for the entire data collection period were aggregated into 15-minute counts, of which the four highest consecutive fifteen minute periods was considered the peak hour. Heavy vehicle percentages were determined for each roadway approach by dividing the number of heavy vehicles counted in the peak hour by the total number of vehicles counted for the hour. Figure 5.1 shows the resulting vehicle counts for the Canal St site with the peak hour occurring between 3:30 PM and 4:30 PM. Noticeably, the eastbound and westbound through movements were dominant and resulted in the queuing on the southbound approach used for this research.

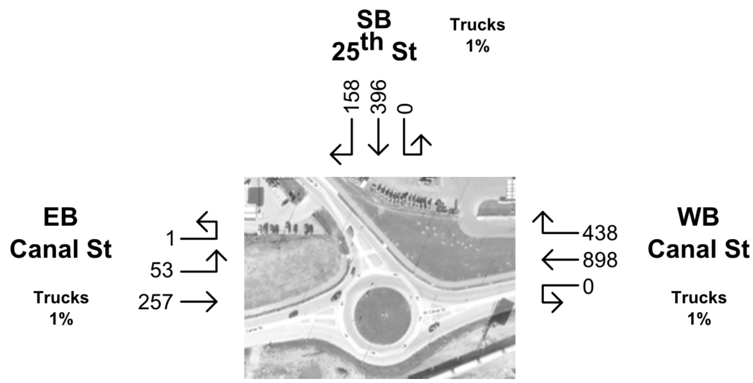


Figure 5.1. Canal St Site Peak Hour Volumes

Figure 5.2 shows the resulting vehicle counts for the De Pere site for the peak hour between 5:00 PM and 6:00 PM. Heavy northbound and eastbound volumes were causal factors for the queuing and lane utilization patterns observed.

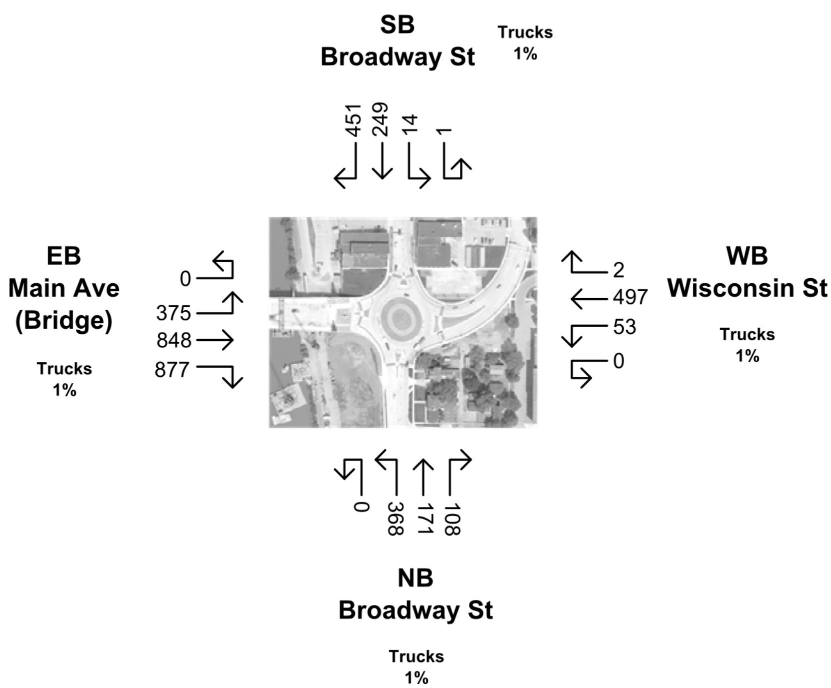


Figure 5.2. De Pere Site Peak Hour Volumes

5.2 Observed Gap Acceptance Data

Gap acceptance parameters were obtained from the data collected during the PM study periods in a manner consistent with the NCHRP 572 study using the maximum likelihood method and only considering vehicles that rejected at least one gap before accepting a gap in order to be included in the data set. Table 5.3 and 5.4 show the obtained critical gap and follow-up headway parameters as well as comparisons to the field data from the NCHRP 572 sites. "Method 2" gap acceptance values from the NCHRP 572 study, where vehicles needed to have rejected gap, were used for comparison due to the alike data collection used in this research. Both the single lane and multilane NCHRP data are shown on Southbound 25th St approach because the roundabout is a single-lane site but has characteristics of a multilane site due to the presence of two conflicting lanes. Standard deviations for all measurements are shown in parenthesis.

Table 5.3. Canal St Site Gap Acceptance Parameters

	SB 25th St	NCHRP 572 Single-lane	NCHRP 572 Multilane
Critical gap (s)	5.5 (2.0)	5.0 (1.2)	4.5 (1.7)
Follow-up headway (s)	2.6 (1.4)	3.2 (1.1)	3.1 (1.1)

Table 5.4. De Pere Site Gap Acceptance Parameters

Critical Gap (s)	NB Broadway St	EB Main Ave (Bridge)	NCHRP 572
Left lane	4.1 (1.0)*	4.4 (1.6)	4.8 (2.1)
Right lane	3.4 (1.0)	4.3 (1.4)*	4.3 (1.5)
Approach	3.8 (1.1)	4.3 (1.5)	4.5 (1.7)

Follow-up Headway (s)	NB Broadway St	EB Main Ave (Bridge)	NCHRP 572
Left lane	3.1 (1.3)*	2.8 (1.2)	3.2 (1.1)
Right lane	3.0 (1.2)	2.8 (1.1)*	3.0 (1.2)
Approach	3.0 (1.2)	2.8 (1.1)	3.1 (1.1)

*Data point from dominant lane on the subject approach

Data from the Canal St site showed higher critical gap values than either the NCHRP single or multilane sites, but follow-up headway was about 0.5 s less than the NCHRP sites. The recent single-lane roundabout study in Indiana found gap acceptance values much lower than the Canal St site, with critical gap ranging from 3.39 to 3.79 s and follow-up headway ranging from 2.10 to 2.43 s [28].

Data from the De Pere site showed lower or equal critical gap and follow-up headway, ranging from 0.0 to 0.7 s lower in all cases compared to the NCHRP sites. Standard deviation from all sites in this study ranged from 1.0 s to 2.0 s which was similar to the range 1.1 s to 2.1 s in the NCHRP study. A reoccurring trend from two-lane entry roundabout studies was also observed at the De Pere site: the right lane tends to have a lower critical gap value than the left lane, perhaps because drivers making a right turn maneuver feel somewhat protected by vehicles entering the roundabout in the left lane.

Comparing to the three-lane entry roundabout study in Michigan, gap acceptance parameters for the dominant lane at the Michigan sites were higher with their critical gap reported as 4.66 s and follow-up headway as 3.34 s [27].

5.3 Measured Site Geometry

Geometry from each site was found from construction plans or scaled aerial photos. The results used for the spreadsheet capacity modeling, as well as software analysis are shown in Table 5.5 for the Canal St site and Table 5.6 for the De Pere site. Metric measurements are required for model input and are shown along with U.S. customary units. The WisDOT adjusted U.K. model used 4.3 m for any single lane entry and 8.0 m for any two-lane entry, overriding the actual measured widths shown. One assumption was made for the De Pere site on the eastbound approach: no flare was observed because the bridge was the same or slightly wider than the entry width. For modeling, this meant that the half-width parameter needed to be modified to 8.0 m to match the entry width to satisfy the requirement that half-width cannot exceed entry width.

Table 5.5. Canal St Site Geometry and Characteristics

Parameter	SB 25th*	EB Canal	WB Canal
E - Entry width (actual width measured)	7.01 m (23 ft)	8.53 m (28 ft)	8.53 m (28 ft)
E - WisDOT Adjusted	4.3 m (14 ft)	8.0 m (26 ft)	8.0 m (26 ft)
l' - Effective flare length	15.85 m (52 ft)	21.95 m (72 ft)	39.32 m (129 ft)
V - Approach road half-width	4.27 m (14 ft)	7.32 m (24 ft)	7.32 m (24 ft)
R - Entry radius	20.73 m (68 ft)	28.35 m (93 ft)	22.25 m (73 ft)
PHI - Entry Angle	26°	39°	10.5°
D - Inscribed circle diameter	52.43 m (172 ft)	52.43 m (172 ft)	52.43 m (172 ft)
Splitter Island Width	10.9 m (36 ft)	9.7 m (32 ft)	9.7 m (32 ft)
Approach Speed	30 mph	30 mph	30 mph

*denotes studied approach

Table 5.6. De Pere Site Geometry and Characteristics

	Approach			
Parameter	**EB Main (Bridge)***	**NB Broadway***	**WB Wisconsin**	**SB Broadway**
E - Entry width (actual width measured)	8.53 m (28 ft)	8.53 m (28 ft)	9.14 m (30 ft)	8.53 m (28 ft)
E - WisDOT Adjusted	8.0 m (26 ft)	8.0 m (26 ft)	8.0 m (26 ft)	8.0 m (26 ft)
l' - Effective flare length	0 m (0 ft)	12.19 m (40 ft)	32.31 m (106 ft)	23.01 m (75.5 ft)
V - Approach road half-width	8.53 m (28 ft)	7.32 m (24 ft)	7.01 m (23 ft)	7.01 m (23 ft)
R - Entry radius	19.81 m (65 ft)	19.81 m (65 ft)	29.87 m (98 ft)	19.81 m (65 ft)
PHI - Entry Angle (deg)	25°	23°	24°	21°
D - Inscribed circle diameter	53.04 m (174 ft)	53.04 m (174 ft)	53.04 m (174 ft)	53.04 m (174 ft)
Splitter Island Width	7.3 m (24 ft)	7.3 m (24 ft)	15.6 m (51 ft)	7.3 m (24 ft)
Approach Speed	25 mph	25 mph	25 mph	25 mph

*denotes studied approach

5.4 Capacity Data Analysis

In order to compare collected field data to capacity models, spreadsheets were developed based on the original literature explaining each model. Such comparisons give insight into explaining software results. The difference between capacity spreadsheets and software output is that software only analyzes one entering-circulating data point at a time based on traffic volume input and any assumed interaction between traffic volumes on other approaches. Capacity spreadsheets on the other hand, analyze multiple entering-circulating data points at a time and compare them directly to field observations which already reflect any interaction between the approaches.

All spreadsheets used equations directly from the original research in each model. Four other important items related to the capacity spreadsheet analysis are:

1. Because of the difficulties in obtaining detailed English documentation for the capacity model currently used in Girabse as mentioned in Section 2.4.3, a spreadsheet could not be adequately developed to replicate results compatible with the Girabase software. Therefore further discussion of the French model has been omitted from all applicable capacity graphs. 2.4

2. Results from the U.K. model reflect the 'WisDOT adjusted' entry width unless otherwise stated.

3. The ARR 321 method is sensitive to the ratio between the entry flow and circulating flow. Because data was collected for both these flows, the ratio could be calculated precisely. However, to be consistent with all other models and the fact that SIDRA defaults to a "medium" level of adjustment, this parameter was estimated at an average value of 1.5, based on the maximum and minimum allowable range, rather than computed from field data. These assumptions allow the uncalibrated ARR 321 method to approximate SIDRA with an environment factor of 1.0 as discussed in Section 2.4.5.1.

4. One-minute entering and circulating counts were converted to passenger car equivalents, with heavy vehicles counting as 2.0 passenger cars, and motorcycles and bicycles counted as 0.5 passenger cars. Equivalent passenger car

hourly flows (pcu/hr) were obtained by multiplying one-minute counts by 60 minutes/hour.

5.4.1 Calibration

For the spreadsheet analysis, models were calibrated based on the collected gap acceptance and entering-circulating field data. Each roadway approach studied was calibrated separately. Gap acceptance model equations shown in Section 2.4 including the German, NCHRP, and ARR 321 methods, were calibrated by replacing the default critical gap and follow-up headway values with those obtained by the field data from Table 5.3 and 5.4. As a feature of the ARR 321 method, there is no environmental factor as part of the equations and therefore no approximations were possible to establish what environmental factor would be most appropriate for SIDRA software analysis.

Calibration of the linear U.K. model followed the procedure outlined in Section 2.4.1 where only the intercept was changed based on average entering-circulating field data. Observed averages are shown in Table 5.7. Resulting calibrated and uncalibrated intercepts follow in the discussions contained in Section 5.4.4 for the Canal Site and Section 5.4.5 for the De Pere site.

Table 5.7. Average Entering and Circulating Flows Used for U.K. Model Calibration

Studied Roadway Approach	Average Approach Entering Flow (pcu/hr)	Average Approach Circulating Flow (pcu/hr)
Canal St Site: SB 25th St PM Peak	538	812
De Pere Site: EB Broadway PM Peak	1900	366
De Pere Site: NB Broadway PM Peak	788	1334
De Pere Site: NB Broadway AM Peak	1099	963

As a starting point for calibration of the U.K. model, field measured geometry was used to remain independent of any 'WisDOT adjusted' parameters not specified in the original model documentation. Doing so resulted in slightly larger slopes, which improved the fit to field data, but had negligible impact on overall capacity results. A comparison of the different slopes and intercepts from using field measured versus effective geometry is presented in Section 5.5.1.

5.4.2 Error Measurement

One common method of comparing statistical models is by computing the root-mean square-error for each model. RMSE is an estimate of precision and represents the average difference between the model prediction and observed data. To make a fair comparison between approach based models and lane based models, RMSE was divided by the number of lanes, resulting in estimates of RMSE per lane, with units of pcu/hr/ln. Formulaically, RMSE was determined by:

$$RMSE = \frac{\sqrt{(\text{Model Prediction} - \text{Field Observation})^2/n}}{\text{Number of Lanes}}$$

where

Model Prediction	=	entering flow predicted for a given circulating flow
Field Observation	=	entering flow observed from a one-minute entering-circulating capacity datapoint
n	=	Number of observations

Lower errors indicate a better fit of the model to the data. There is no rule about what a "good" RMSE value is, goodness depends on how precise the model needs to be. Typically, a model with lower RMSE is chosen as the best model, but understanding why the model shows a fits to the data and any underlying assumptions need to be considered in choosing a model. A model could show a good prediction of capacity but use parameters that do not actually have any causal effect on capacity; that is to say correlation does not imply causation.

5.4.3 Model Characteristics

Trends in the field entering versus circulating data were highlighted by performing simple linear regression. Linear regression models reveal characteristics such as the maximum capacity and how rapidly capacity decreases with increasing circulating flow. Regression was performed not in an attempt to develop a new capacity model, but rather for comparative purposes only. Two models were fit, with the first being:

$$Q_e = A + BQ_c$$

where

Q_e	=	Entering flow (pcu/hr)
Q_c	=	Circulating flow (pcu/hr)
A	=	Intercept constant
B	=	Slope constant

and the second linear model:

$$\ln(Q_e) = A + BQ_c$$

which can be re-expressed as an exponential relationship in the form of:

$$Q_e = Ae^{BQ_c}$$

where

Q_e	=	Entering flow (pcu/hr)
Q_c	=	Circulating flow (pcu/hr)
A	=	Intercept constant
B	=	Slope constant

These two models were chosen to be fit to the field data collected because of their similarity to the forms of existing capacity models, for example the U.K. model exhibits the first linear form shown above, and the NCHRP 572 model is in the form of the second model shown above. Further, such regression techniques were used in the development of both the U.K. and NCHRP 572 models [5, 7].

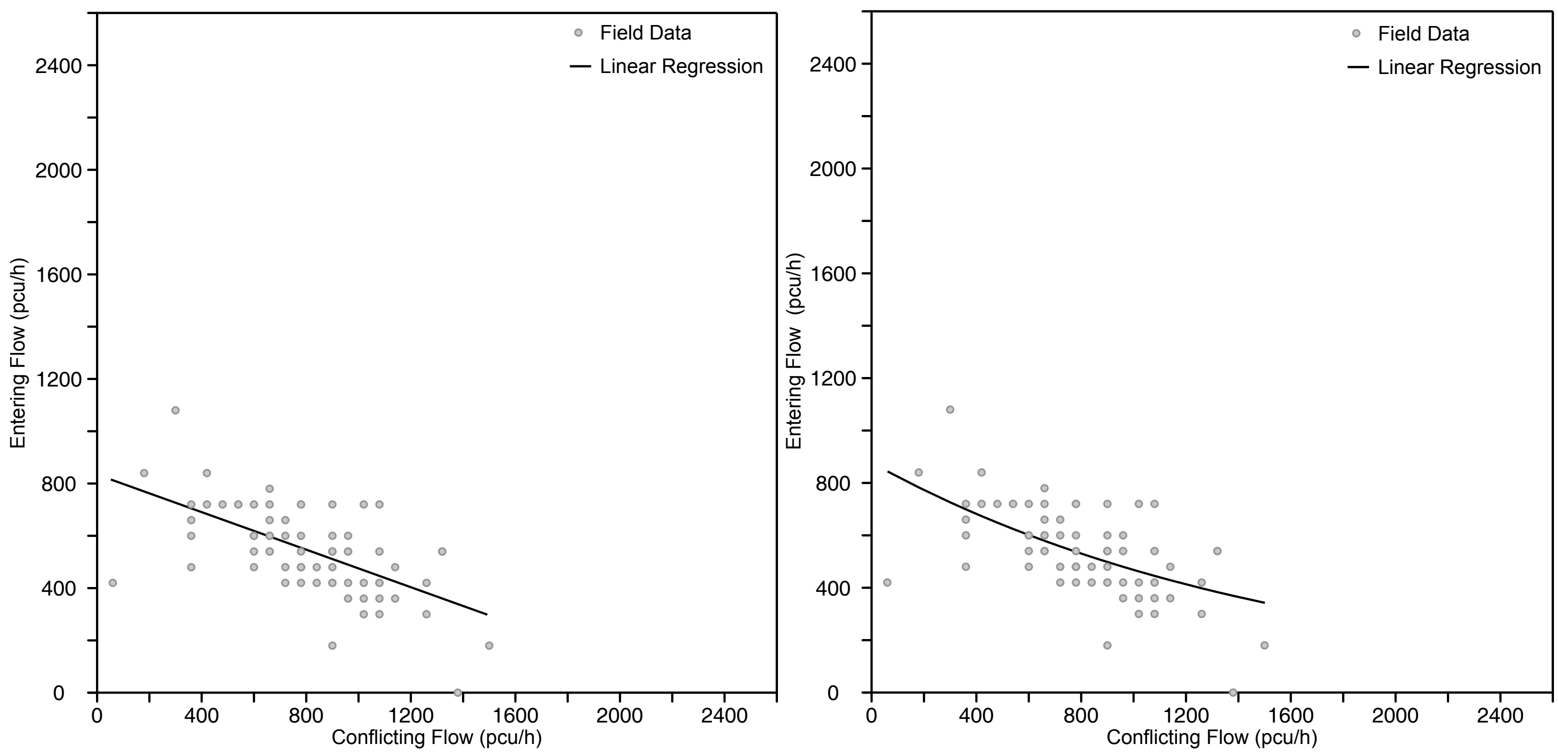
Slope and intercept terms in the linear models describe the maximum capacity and rate of decrease toward minimum capacity, respectively. The larger the slope, the less conflicting flow is needed to reach minimum capacity. For the exponential relationship in gap acceptance models, the slope is constantly changing, but the slope can be represented by the constant term within the exponent. The larger the exponent constant, the larger the rate of change in the capacity prediction. As a general rule, lower intercepts and higher slopes are an indication of lower capacity predictions. Slope is not readily determinable for the ARR 321 method due to the piecewise nature of the capacity function, resulting in slopes shown as "N/A" in the following model characteristics tables.

5.4.4 Canal St Site Capacity Analysis

The Canal St site analyzed the single lane approach of southbound 25th St. Most of the observations were during periods of medium conflicting flow of about 600 to 1000 pcu/h. Queues were typical on this minor street approach because of the heavier through movements on the major street. Field data, along with linear and exponential regressions, are shown in Table 5.8 and Figure 5.3.

Table 5.8. Canal St Field Data Regression Results

Regression	Intercept (pcu/h)	Slope	n	R^2	RMSE (pcu/h/ln)
Linear	829	0.359	71	0.367	67
Exponential	869	6.35×10^{-4}	71	0.314	69



(a) Field Data with Linear Regression

(b) Field Data with Exponential Regression

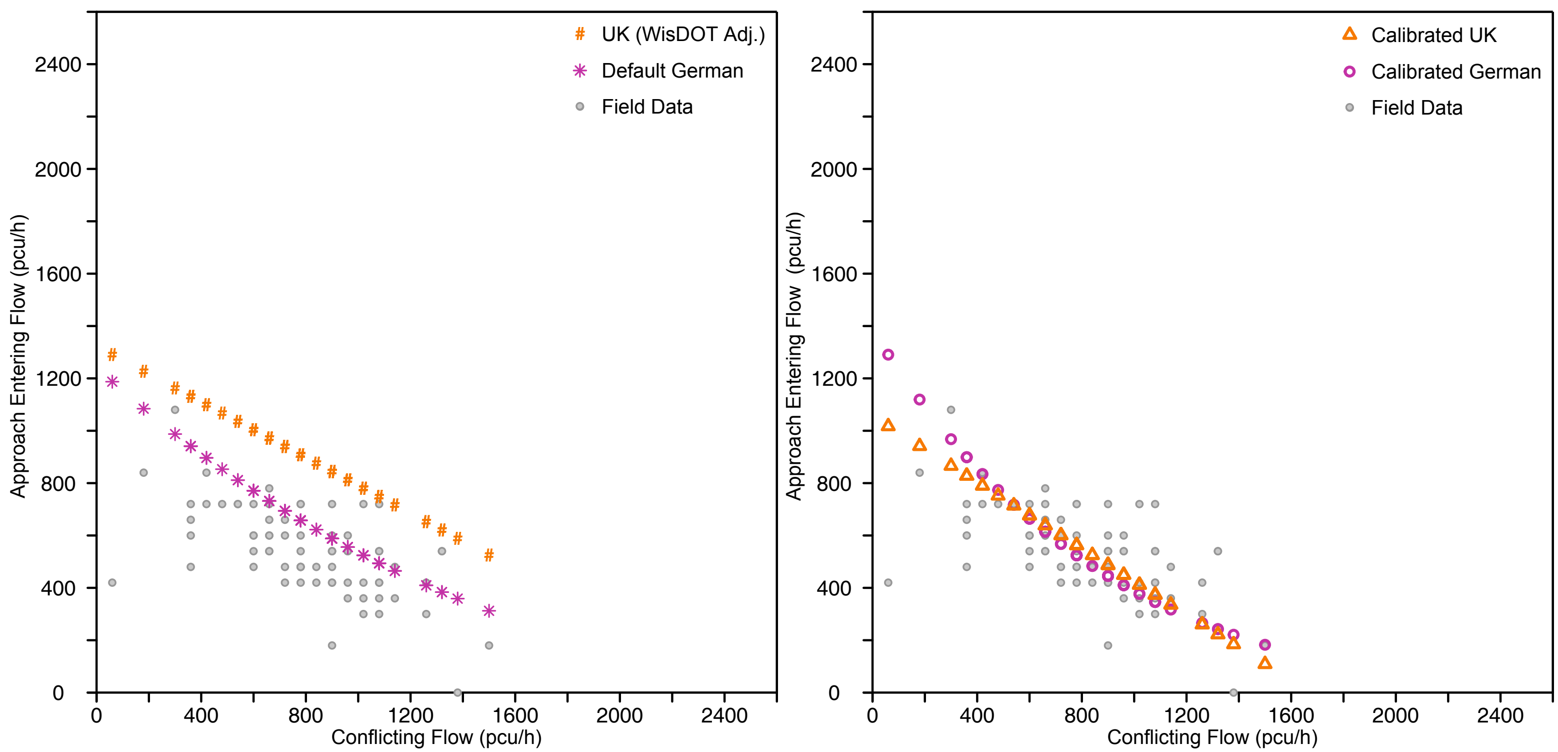
Figure 5.3. Canal St Field Capacity Data

Table 5.9 and Figure 5.4 compare the approach based models for the Canal St site. The WisDOT adjusted U.K. model predicted a higher capacity than the average observed data with a RMSE value of 381 pcu/h. Capacity prediction from the default German model was closer to the observed data and slightly on the upper end, with an RMSE value of 193 pcu/h/ln. Calibrating both the U.K. and German models provided similar fits to the data, with the German model predicting a higher intercept.

Table 5.9. RMSE and Model Characteristics from the Canal St Approach Based Analysis

	Uncalibrated				Calibrated			
Model	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**
U.K.	1323	0.532	71	381	1055	0.631	71	156
German	1241	1.53×10^{-4}	71	193	1385	5.83×10^{-4}	71	183

Overprediction from the U.K. model may be due to the periodic, but steady, queuing that was observed rather than having longer sustained queuing indicative of at-capacity operation that the original model was formulated from. Intercept values from the regression analysis were also smaller than those seen in the NCHRP 572 research, suggesting that the site may not have been operating continuously under capacity conditions.



(a) Uncalibrated Approach Based Models

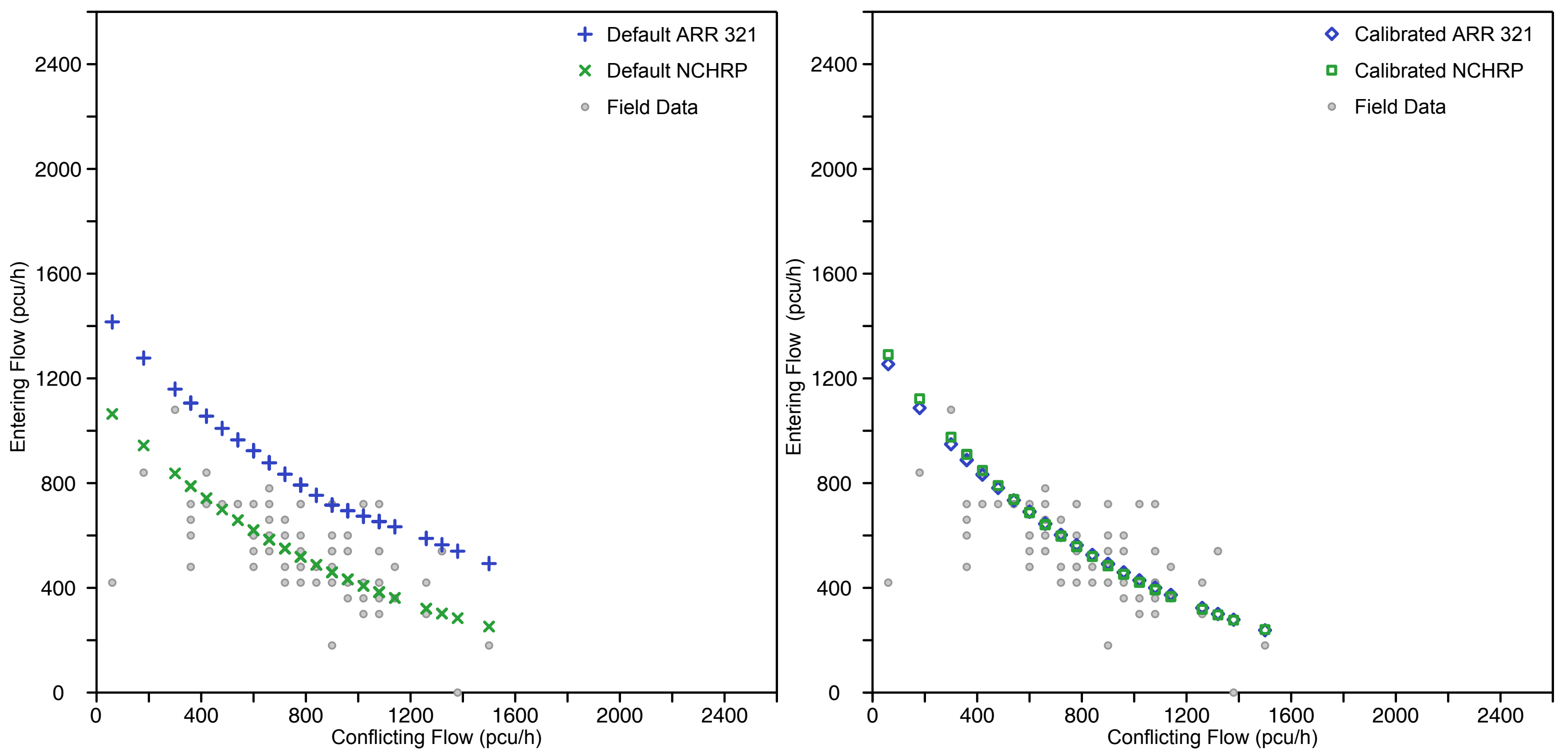
(b) Calibrated Approach Based Models

Figure 5.4. Canal St Approach Based Capacity Comparison

Lane based models for the Canal St site are shown in Figure 5.5 and Table 5.10. For both the ARR 321 and NCHRP 572 results, discrepancies appear to be exaggerated for low circulating flows due to lack of congested observations. The default ARR 321 method predicted capacity at the upper end of the observed data, while the default NCHRP 572 model was closer to the observation averages with RMSE of 310 and 153 pcu/h/ln, respectively. Calibration resulted in the models being nearly indistinguishable in terms of slope and intercept, which gave similar RMSE values of approximately 175 pcu/h/ln.

Table 5.10. RMSE and Model Characteristics from the Canal St Lane Based Analysis

	Uncalibrated				Calibrated			
Model	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**
ARR 321	1494	N/A	71	310	1351	N/A	71	173
NCHRP	1130	1.00×10^{-3}	71	153	1165	1.17×10^{-3}	71	178



(a) Uncalibrated Lane Based Models **(b)** Calibrated Lane Based Models

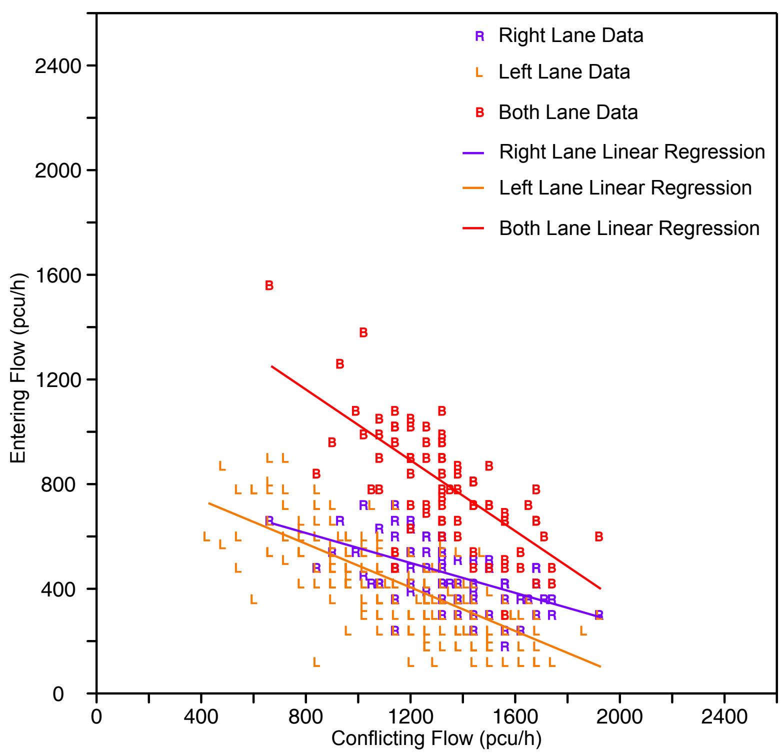
Figure 5.5. Canal St Lane Based Capacity Comparison

5.4.5 De Pere Site Capacity Analysis

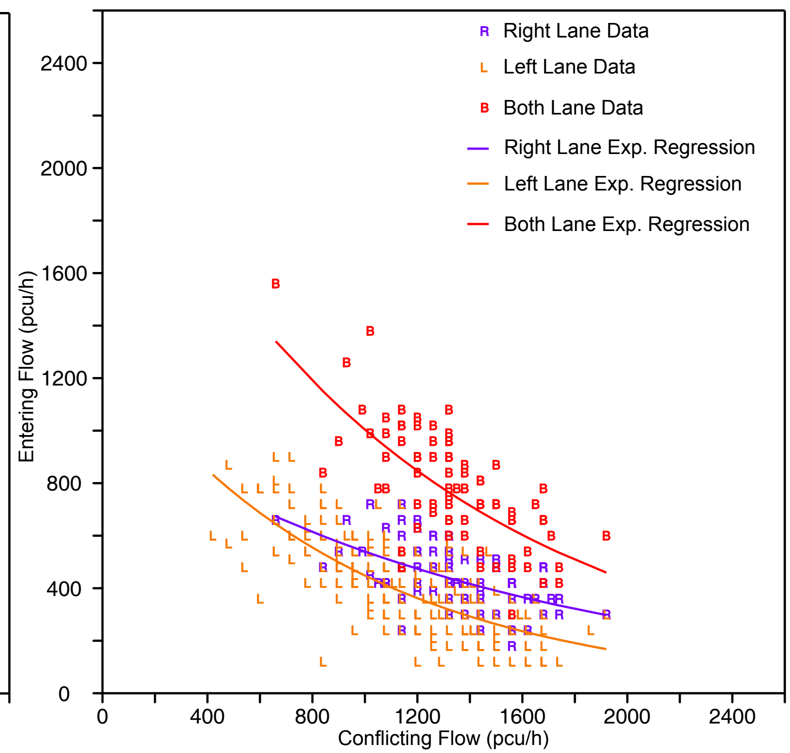
Two roadway approaches at the De Pere site were analyzed during AM and PM peak periods. Data from the PM analysis is presented in this section, with AM results having similar trends which are shown in Appendix A. Queuing was consistent on both of these approaches in the PM peak (268 of 300 min queued for the northbound critical lane, 125 of 200 min queued for the critical eastbound lane) allowing for capacity observations. For lane based models, only the critical lane was analyzed due to the interest in analyzing high volume operations. First, the PM peak data from northbound Broadway St was analyzed which showed characteristics of high circulating flows between 1100 and 1800 pcu/h. Figure 5.6 and Table 5.11 show the field capacity data along with regressions of the data in linear and exponential form. Data at low circulating flow rates is more indicative of an actual intercept for a capacity model. Because no such data was observed on the northbound approach, the actual intercept may differ from the value obtained by regressing only data from the higher circulating flow rates.

Table 5.11. De Pere Northbound PM Field Data Regression Results

Lane	Regression	Intercept (pcu/h)	Slope	n	R^2	RMSE (pcu/h/ln)
Right	Linear	832	0.286	77	0.306	100
	Exponential	1031	6.47×10^{-4}	77	0.281	101
Left	Linear	895	0.471	268	0.53	109
	Exponential	1303	1.07×10^{-3}	268	0.475	111
Approach (Both Lanes)	Linear	1689	0.676	76	0.494	80
	Exponential	2349	8.50×10^{-4}	76	0.454	79



(a) Field Data with Linear Regression



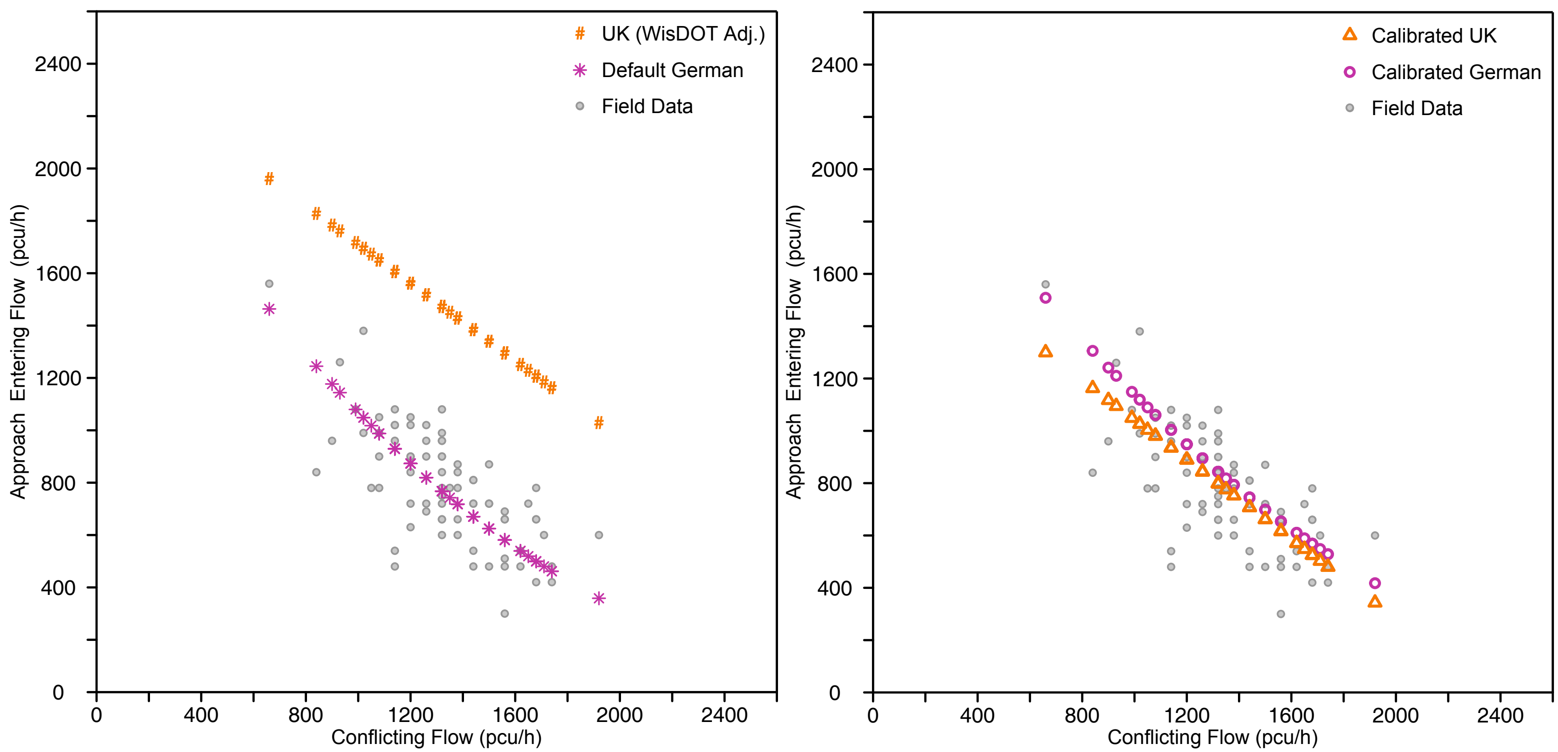
(b) Field Data with Exponential Regression

Figure 5.6. De Pere Northbound PM Field Capacity Data

Approach models for northbound Broadway St are shown in Figure 5.7. Model error and characteristics and are shown in Table 5.12. The WisDOT adjusted U.K. model predicted a higher capacity than the observed data with a RMSE of 347 pcu/h/ln. German capacity model results showed predictions nearer to the observed data with a low RMSE of 82 pcu/h/ln. Calibration of both models lowered the capacity estimates compared to their respective default predictions and resulted in RMSE averaging at 83 pcu/h/ln.

Table 5.12. RMSE and Model Characteristics from the De Pere NB Approach Based Analysis

	Uncalibrated				Calibrated			
Model	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**
U.K.	2450	0.740	76	347	1801	0.759	76	80
German	2483	1.53×10^{-4}	76	82	2400	5.56×10^{-5}	76	86



(a) Uncalibrated Approach Based Models **(b)** Calibrated Approach Based Models

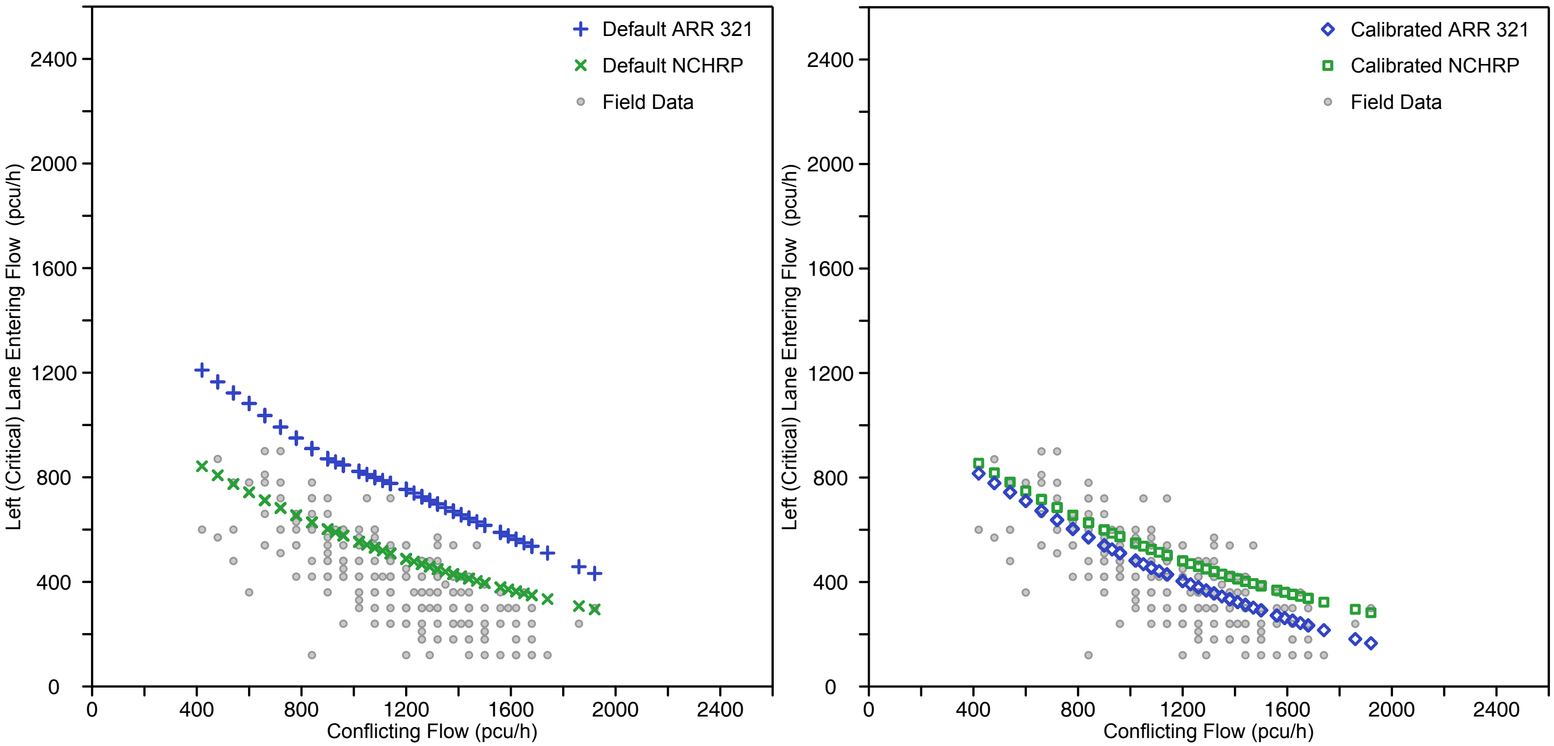
Figure 5.7. De Pere Northbound Approach Based Capacity Comparison

A possible explanation for the overprediction in the U.K. model is a difference in driver behavior under high circulating flows. The U.K. model was based on the regression of capacity data that included periods of priority reversal, where circulating drivers yield to entering vehicles, which would increase capacity at high circulating flows. Priority reversal was not observed during the data collection in this research. Another possible explanation for the overprediction is that the U.K model predicts capacity for all lanes at the entry, but most of the demand traffic was in the left lane during the times observed. If the right lane did not have sufficient demand to reflect capacity operations, the approach-based model would overpredict field data from a partially saturated entry. Exploration of using the U.K. model on lane-by-lane basis is presented in Section 5.5.2. Comparatively, a close fit from the German model is likely due to the default values of critical gap and follow-up headway being near the observed field values.

Figure 5.8 and Table 5.13 show results and comparisons from lane based models for the critical left lane of northbound Broadway St. The uncalibrated ARR 321 method predicted capacity above the observed data with a RMSE of 376 pcu/h/ln. Results from the default NCHRP 572 model were lower than the ARR 321 method but near the higher capacity observations. Calibration brought the ARR 321 method in line with the field data with a RMSE value of 110 pcu/h/ln. Little changed between the uncalibrated and calibrated versions of the NCHRP 572 model because the gap acceptance values observed were near the default uncalibrated values.

Table 5.13. RMSE and Model Characteristics from the De Pere NB Lane Based Analysis

	Uncalibrated				Calibrated			
Model	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)
ARR 321	1633	N/A	268	376	1133	N/A	268	110
NCHRP	1130	7.00×10^{-4}	268	149	1165	7.38×10^{-4}	268	145



(a) Uncalibrated Lane Based Models

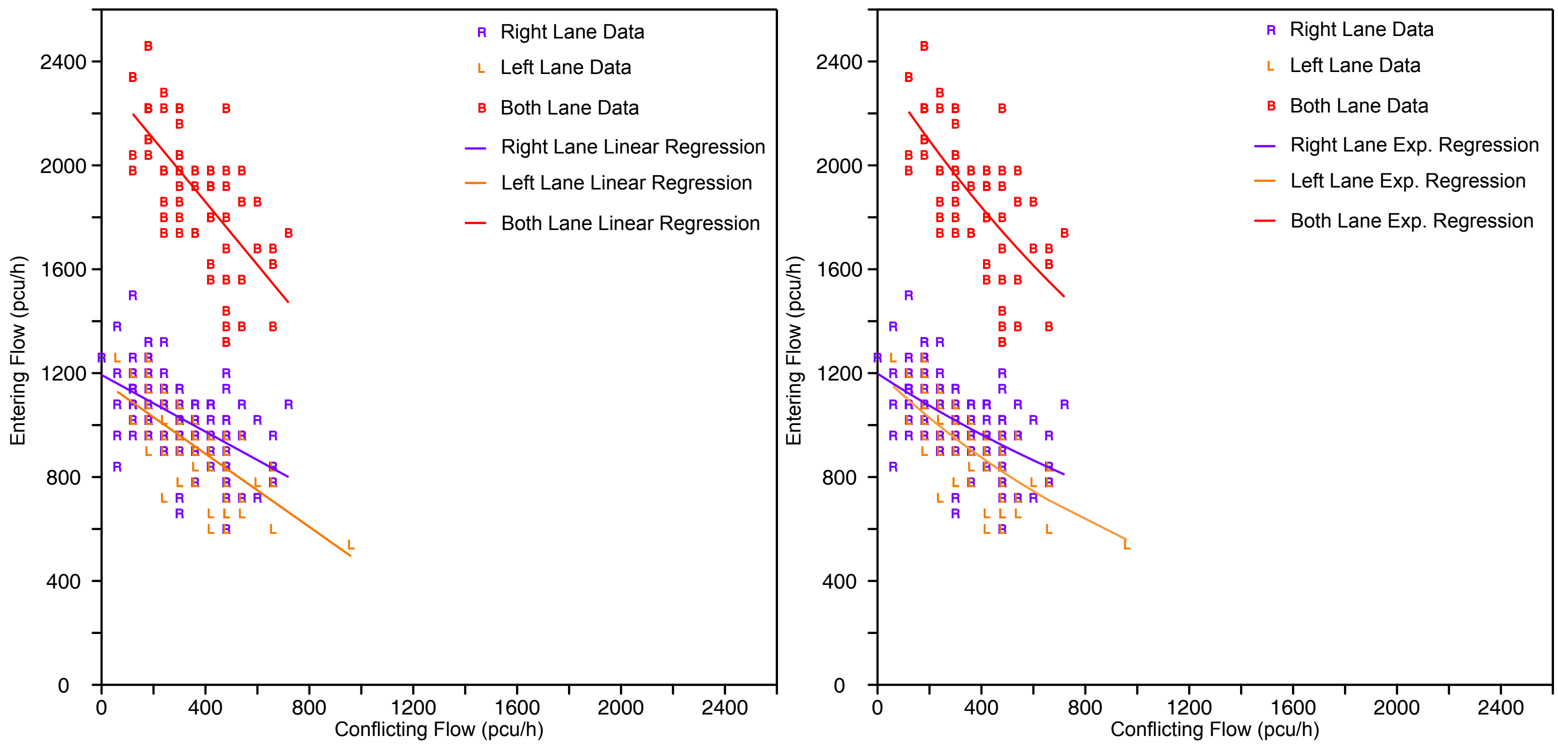
(b) Calibrated Lane Based Models

Figure 5.8. De Pere Northbound Lane Based Capacity Comparison

Turning to the eastbound (bridge) approach at the De Pere site, Main Ave experienced low circulating flows between 200 and 600 pcu/h in contrast to the high circulating flows of the northbound approach. Figure 5.9 and Table 5.14 show the field data and regressions. Because of the low circulating flow, the intercept of the regressions may be more reliable than that observed for the northbound Broadway St approach; however, slope may not due to lack of observations throughout the entire range of circulating flows (low and high). Intercepts from the regression of the eastbound approach were slightly higher than that observed by the NCHRP 572 research.

Table 5.14. De Pere Eastbound PM Field Data Regression Results

Lane	Regression	Intercept (pcu/h)	Slope	n	R^2	RMSE (pcu/h/ln)
Right	Linear	1193	0.546	125	0.318	126
	Exponential	1198	5.44×10^{-4}	125	0.309	126
Left	Linear	1171	0.704	82	0.514	108
	Exponential	1207	8.03×10^{-4}	82	0.511	107
Approach (Both Lanes)	Linear	2344	1.212	66	0.472	99
	Exponential	2386	6.51×10^{-4}	66	0.456	98



(a) Field Data with Linear Regression

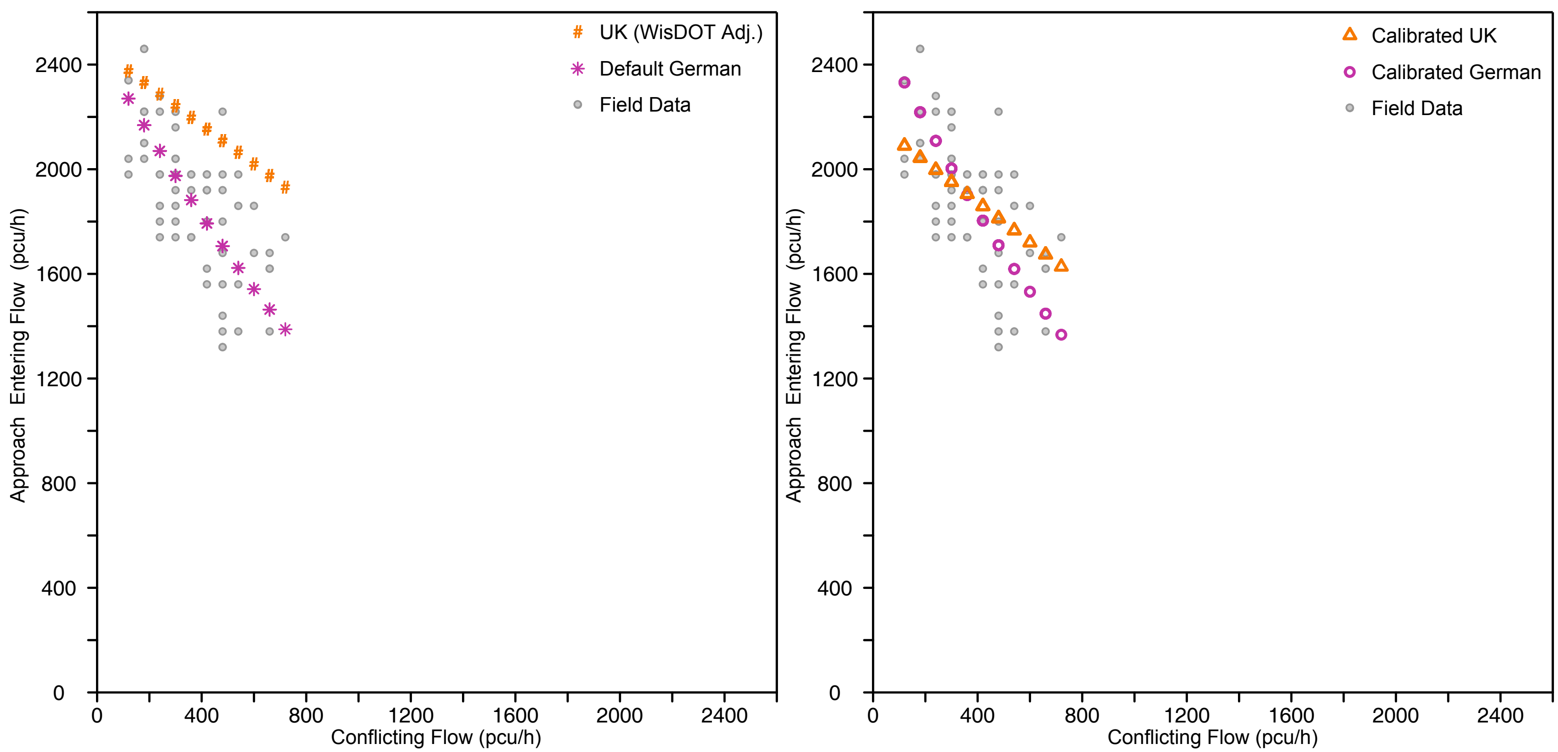
(b) Field Data with Exponential Regression

Figure 5.9. De Pere Eastbound PM Field Capacity Data

Figure 5.10 and Table 5.15 show the approach based model results. While some lane imbalance was present, the approach based aggregation from the WisDOT adjusted U.K. model was only slightly above the average capacity observations near the intercept, but diverged with increasing conflicting flow. German model results were comparable to the field data throughout the range of data. One noticeable difference between these two models was the shape of the capacity curve in this particular range of low circulating flow data. The linear U.K. model showed a more gradual decline in capacity with increasing conflicting flow, while the German exponential model predicted a steeper decline more similar to the observed data.

Table 5.15. RMSE and Model Characteristics from the De Pere EB Approach Based Analysis

	Uncalibrated				Calibrated			
Model	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**
U.K.	2465	0.74	66	181	2182	0.771	66	105
German	2483	1.53×10^{-4}	66	101	2571	2.22×10^{-4}	66	103



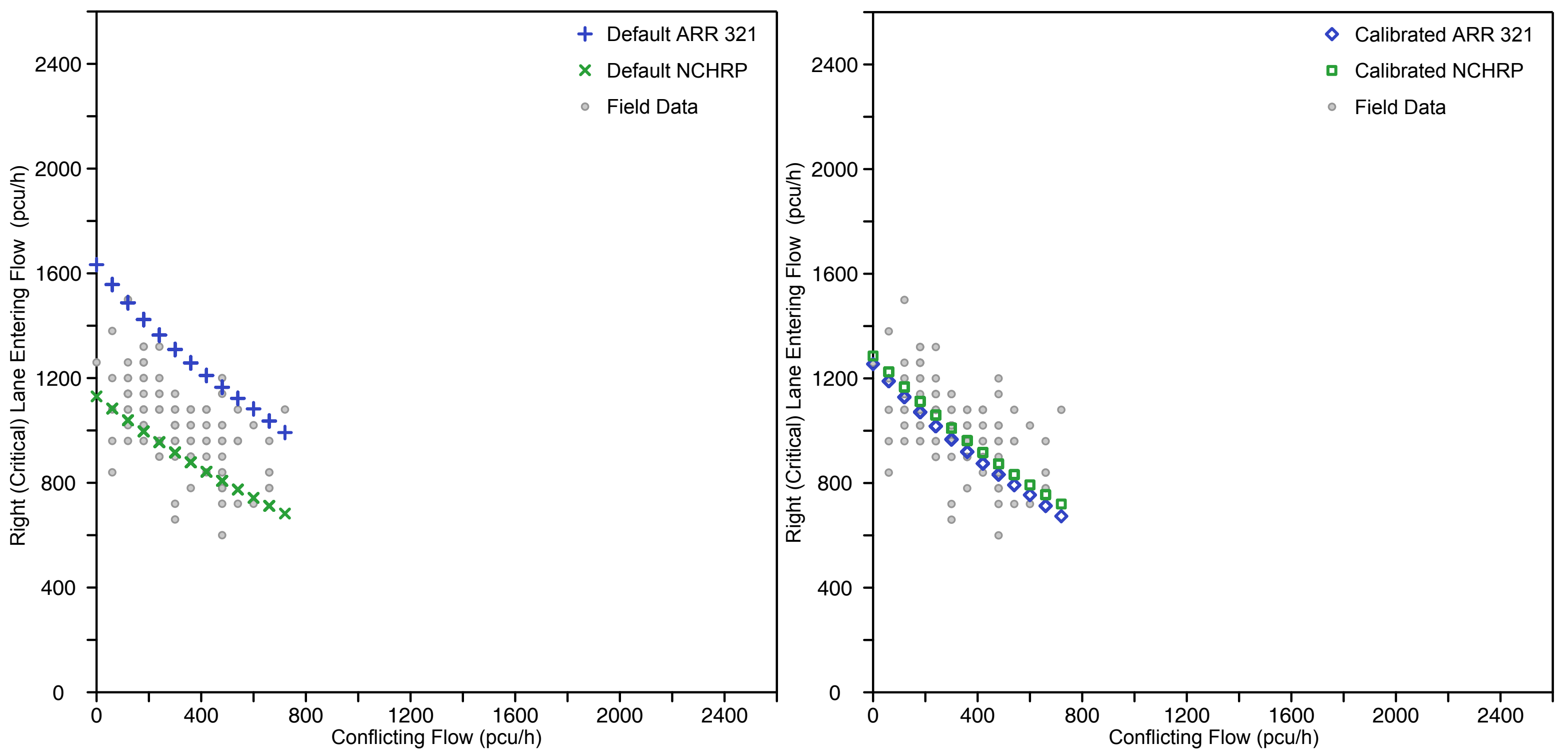
(a) Uncalibrated Approach Based Models **(b)** Calibrated Approach Based Models

Figure 5.10. De Pere Eastbound Approach Based Capacity Comparison

Lane based model results for the eastbound approach are presented in Figure 5.11 with error and model characteristics in Table 5.16. The right lane was critical in this case due to the high volume of right turning vehicles. Capacity predictions from the uncalibrated ARR 321 method were near the maximum capacity observations. On the other hand, the NCHRP 572 model showed results on the lower end of the observed data. Calibration brought the capacity results from ARR 321 method down to a RMSE of 144 from 316 pcu/h/ln. Capacity prediction also improved from the default scenario after calibrating the NCHRP 572 model to a RMSE of 132 pcu/h/ln, resulting in higher capacity predictions per conflicting flow compared to the uncalibrated scenario.

Table 5.16. RMSE and Model Characteristics from the De Pere EB Lane Based Analysis

	Uncalibrated				Calibrated			
Model	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**
ARR 321	1633	N/A	125	316	1255	N/A	125	144
NCHRP	1130	7.00×10^{-4}	125	167	1165	7.38×10^{-4}	125	132



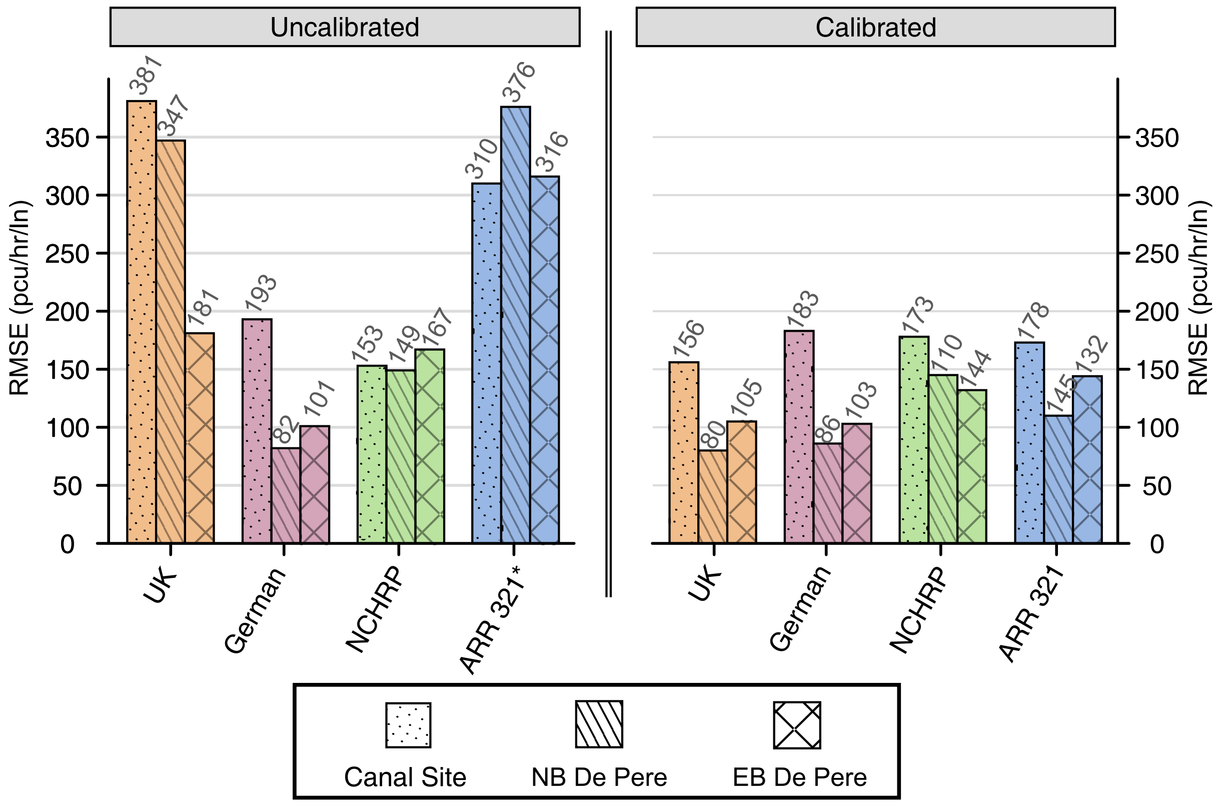
(a) Uncalibrated Lane Based Models

(b) Calibrated Lane Based Models

Figure 5.11. De Pere Eastbound Lane Based Capacity Comparison

5.4.6 Capacity Data Analysis Summary

To summarize the above capacity comparisons, all of the root mean square error results are presented in the column chart of Figure 5.12. Importantly, all of the models performed well when calibrated, as is expected because calibration fits the model to the data. However, calibration can only be performed in retrospect on existing roundabouts, and therefore default models provide a starting point for analyzing future situations. Some default models consistently performed better than others such as the German and NCHRP models. The fact that the German model showed a good fit is likely due to the fact that the default gap acceptance parameters in the model were similar to those found in this research. Error values may be overrepresented for the Canal St site because the site experienced less demand volume and congestion compared to the De Pere site. Because of differences between the SIDRA Standard Model and the ARR 321 method, RMSE values shown here may not reflect error from SIDRA software analysis. For example, instead of calibrating by using gap acceptance parameters, using an environment factor of 1.2 would lower the RMSE in the uncalibrated scenarios by approximately 100 pcu/hr/ln using estimates of the differences between models discussed in Section 2.4.5.1.



* Uncalibrated ARR 321 approximates SIDRA with an environment factor, EF = 1.0.
Using EF = 1.2 would lower uncalibrated RMSE by approximatedly 100 pcu/hr/ln in these scenarios.

Figure 5.12. Root Mean Square Error Summary

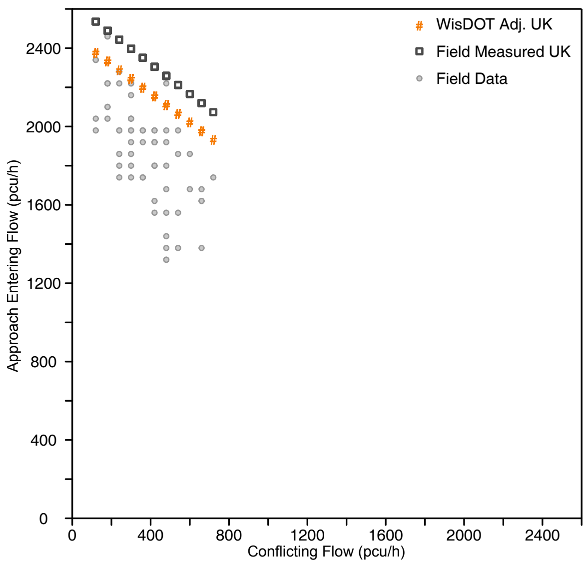
Error between any model and observed data could be due to numerous factors. Sampling error due to observing limited regions, sites, approaches, time periods, driver populations, geometric configurations, etc, all contribute to variance within the data.

5.5 Capacity Modeling Extensions

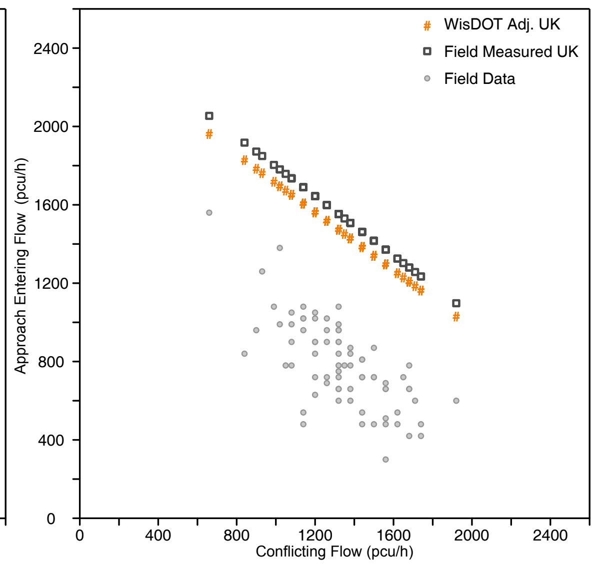
Two additional analyses were performed with the capacity data, which were: looking at the effects of using field measured geometry versus using a reduced effective geometry measurement in the U.K. method , and using the U.K. approached based method for a lane-by-lane analysis.

5.5.1 Adjusting for Effective Geometry

Geometric inputs require careful consideration in the U.K. model because these are the only parameters to which capacity is sensitive based on inspection of the capacity equation. Further, each geometric parameter is treated as a continuous variable allowing for minute changes to affect capacity. Figure 5.13 and 5.14 show the difference in the capacity predictions for the studied approaches when field measured entry widths are used in lieu of ’effective’ entry widths specified by the FDM. Table 5.17 and 5.18 show the respective comparisons of model parameters. Using effective geometry improves the capacity prediction dramatically for the Canal St site, which emphasizes the sensitivity of the entry width parameter. Capacity prediction only improves slightly for the De Pere site. If the influence or interactions between input parameters and output capacity are not fully understood, erroneous predictions could easily be obtained from extrapolating the model to situations beyond the original model scope.



(a) EB De Pere Approach



(b) NB De Pere Approach

Figure 5.13. U.K. Model Effective Geometry Comparison from the De Pere Site

Table 5.17. RMSE and Model Characteristics from the De Pere Effective Geometry Comparison

	EB - PM Main Ave				NB - PM Main Ave			
Model	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**
WisDOT Adj. U.K.	2465	0.740	66	181	2450	0.740	76	347
Field Measured U.K.	2628	0.771	66	246	2555	0.759	76	386
Calibrated U.K. (not depicted)	2182	0.771	66	105	1801	0.759	76	80

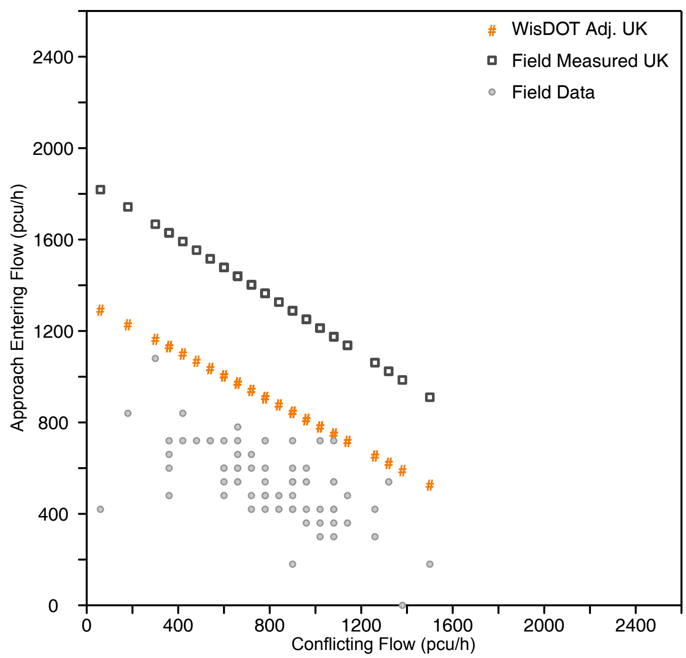


Figure 5.14. U.K. Model Effective Geometry Comparison from the Canal St Site

Table 5.18. RMSE and Model Characteristics from the Canal St Effective Geometry Comparison

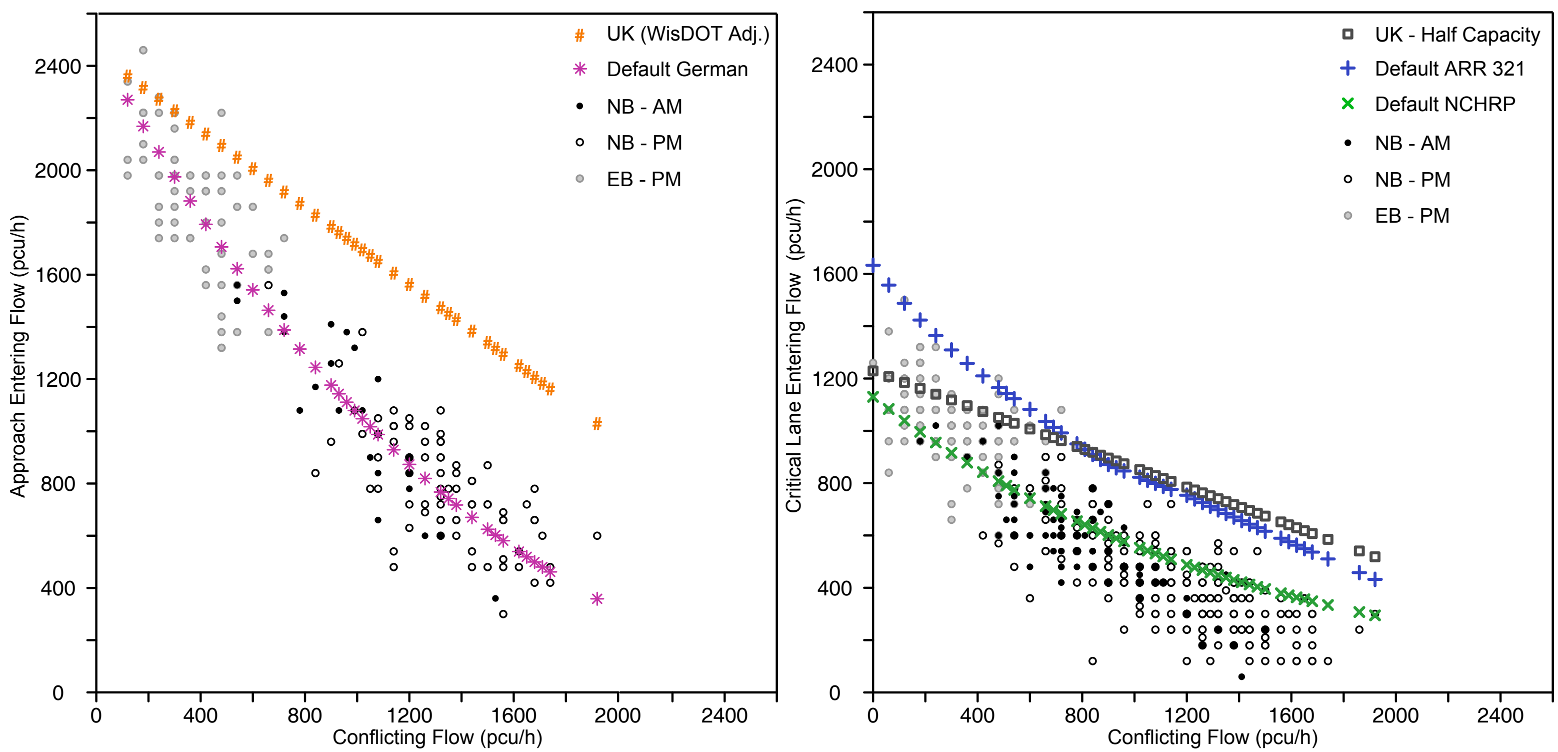
Model	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)
WisDOT Adj. U.K.	1323	0.532	71	381
Field Measured U.K.	1856	0.631	71	821
Calibrated U.K. (not depicted)	1055	0.631	71	156

5.5.2 Combined De Pere Eastbound and Northbound Data Analysis

Both studied approaches from the De Pere site had similar geometric parameters for the U.K. model and therefore would have a similar capacities based on the model assumptions. The following assumptions were made when combining the data:

- Data from different approaches with similar geometries are combinable;
- Lane data can be combined from differing critical lane positions (northbound left critical lane, eastbound right critical lane); and
- Differing time periods can be combined (AM northbound data was included).

The resulting combined entering-circulating data is shown in Figure 5.15, with (a) combining approach based data and (b) combining critical lane data. Circulating flows observed from the northbound AM peak fell between the eastbound PM peak and northbound PM peak, with corresponding entering flows also between the other data sets. Figure 5.15 also overlays the appropriate uncalibrated approach and lane based models. Calibration was not performed due to lack of appropriate means to combine the gap acceptance data for lane based models. A "half capacity" U.K. model was applied to the critical lane data, which is a technique available in RODEL and ARCADY to examine a single lane from a multilane site with an approached based model. The assumption is that 50 percent of the approach capacity will be dedicated to each lane. A "half-German" model is not shown for the lane-based data, but does exhibit a similar fit as in the approach based prediction.



(a) Uncalibrated Approach Based Models

(b) Uncalibrated Lane Based Models

Figure 5.15. Combined De Pere Capacity Data Comparison

Table 5.19 contains the characteristics of each model used in comparison to the combined capacity data. An average of the slope and intercept values from the northbound and eastbound approaches was used to represent the U.K. model. For comparison, Table 5.20 shows the results of regression analysis of the combined data. Because a wide range of circulating flow data was observed, from 0 to 1920 pcu/h in the case of the combined critical lane data, regression slope and intercept parameters are more representative of the data compared to regressing subsets of circulating flows. Intercepts from the regression analysis showed higher results than the NCHRP model and lower results than the U.K., ARR 321, and German models. Regression slopes were steeper than the NCHRP, U.K., and German models.

Table 5.19. Model Characteristics from the Combined De Pere Capacity Data Comparison

Approach Based

Model	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)
U.K.	2458	0.74	166	292
German	2483	1.53×10^{-4}	166	90

Critical Lane Based

Model	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)
U.K. - Half Cap.	1229	0.74	477	348
NCHRP	1130	7.00×10^{-4}	477	151
ARR 321	1633	N/A	477	362

Table 5.20. Combined De Pere Capacity Data Set Regression

Data Set	Regression	Intercept (pcu/h)	Slope	n	R^2	RMSE (pcu/h/ln)
Critical Lane	Linear	1158	0.632	477	0.826	128
	Exponential	1404	1.13×10^{-3}	477	0.773	123
Approach	Linear	2269	1.110	166	0.889	97
	Exponential	2625	9.35×10^{-4}	166	0.866	91

Trends in the combined scenario are logically the same as the trends observed when analyzing data from each approach separately. At lower circulating flow rates the U.K. model is closer to the average observed data, but diverges at high circulating flow rates, leading to the relatively large RMSE values of 292 and 348 pcu/h/ln for the approach and lane based models, respectively. The German approach based model fits the data well, with a RMSE value of 90 pcu/h/ln. For lane based models, the NCHRP model tended to underpredict capacity at low circulating flows and overpredict at high circulating flows, with the second lowest RMSE value of 151 pcu/h/ln. The ARR 321 method showed overprediction with an RMSE of 348 pcu/h/ln, but the slope visually appears to follow the general trend of the data.

At higher circulating flow rates, the capacity prediction becomes increasingly important. High circulating flow rates means that drivers will have fewer gaps to choose from and have the potential to experience more delay. Linear models predict a constant decrease in capacity toward a distinct x-axis intercept, beyond which capacity is predicted at zero entering vehicles. Exponential models have a more horizontal relationship at high circulating flow rates, converging quicker to an asymptote above zero entering vehicles, similar to how left turn lanes at signals can experience vehicles sneaking into the intersection on the yellow indication which adds capacity. For roundabouts, extra capacity could be gained by aggressive drivers forcing gaps or having periods of priority reversal. These aggressive characteristics would explain why the U.K. model has a lower slope. Exponential gap acceptance models would need a more complex relationship, such as the ARR 321 method, or consider a range of critical gap and follow-up headway values for different circulating flows to account for such behaviors.

6 Software Output and Usability

All software modeling was conducted with a philosophy as if the roundabouts studied did not exist yet. This philosophy led to comparing essentially 'default' situations where if little is known about future conditions, an analyst may rely on uncalibrated software based default values. This default scenario resulted in the most basic analysis and the following assumptions were further used for comparing software results:

- Turning movement counts were used to determine the peak hour volume, percentage of trucks, and peak hour factor. While turning movement counts are a measure of departure volume, the counts were input in place of true demand volumes;

- Even with entering departure volumes, no restriction was placed on volume to capacity (v/c) ratios. Departure volumes should never allow a v/c ratio greater than 1.0, but the software was allowed to compute and report any v/c ratio, including values exceeding 1.0. This allowed for identification of conservative model results;

- Default lane utilization was assumed, allowing for the software to identified lane imbalance, if any;

- Exact queues from the field data were not known and therefore only an approximation could be determined if software queue results were too low based on the field of view in the video data collection; and

- SIDRA delay and level of service was setup to maximize compatibility to the HCM 2010 while still using the SIDRA Standard capacity model. As such, the default environment factor of 1.2 for U.S. conditions was used to better represent typical software analysis.

- Calibration was performed by adjusting gap acceptance parameters only. SIDRA software defines gap acceptance parameters by-movement rather than the by-lane method used in this research. By-movement values present a difficulty in assigning values for through movements where more than one through lane exists. An assumption was made to assign the gap acceptance values for the through movement based on the gap acceptance values from the lane most utilized by the through movements.

Calibrated scenarios then expanded upon the default scenario by making the same model calibration adjustments performed in the spreadsheet analysis, described in Section 5.4.1, on the field studied approaches. No additional parameters were changed in the calibrated scenarios. Approaches not studied were untouched and default values were used in the calibrated scenarios. Table 6.1 presents a summary of the calibration procedures used in each software package, with noticeably only ARCADY, HCS, and SIDRA allowing for calibration.

Table 6.1. Software Calibration Procedure Summary

Software Package	Software Allows Calibration?	Software Calibration Method
RODEL 1.9.7	No	N/A
ARCADY 7.1	Yes	Replace default slope and intercept with calibrated values based on field observed average entering and circulating flow
RCAT 1.4	No	N/A
KREISEL 7	No	N/A
GIRABASE 4	No	N/A
HCS 2010 6.1	Yes	Replace default critical gap and follow-up headway values with field observed values
SIDRA 5.1	Yes	Disable software calculated critical gap and follow-up headway values. Enter user defined, field observed values.

Some software packages use slightly different definitions or calculations for capacity, delay and queuing. Consistency was sought to make sure that all results were equally comparable. Some notable exceptions were: All packages implementing the U.K. model were based on maximum queue length compared to 95th percentile queue length from Kreisel, HCS, and SIDRA. Girabase queue length was based on an average and maximum; RODEL and Girabase did not output LOS for each approach; and Girabase capacity was based on "reserve capacity" from which capacity comparable to other software was derived by hand. The number of significant digits reported for each performance measure varied by software package. The values shown in Sections 6.1 and 6.2 reflect exactly what the user would see within the software for comparison purposes. Table 6.2 shows the resulting number of decimal places reported by each software. In some cases, rounding makes a large difference, especially regarding delay where rounding to the nearest second or half second can alter the level of service reported.

Table 6.2. Difference in Decimal Places Reported for Performance Measures

	# of Decimal Places		
	v/c Ratio	Delay	Queue
RODEL 1.9.7	2	1	1
ARCADY 7.1	2	2	2
RCAT 1.4	2	2	1
KREISEL 7	2	0	0
GIRABASE 4	2	0	0
HCS 2010 6.1	2	1	1
SIDRA 5.1	3	1	1

All level of service (LOS) scores were based on the definition from the Highway Capacity Manual 2010, which assigns LOS F to any lane with volume to capacity ratio (v/c) greater than 1.0, and with other LOS assignments based on unsignalized intersection delay as shown in Table 6.3 [1]. A full list of differences between performance measure variations between software packages is presented with the software output from all approaches in Appendix B.

Table 6.3. Control Delay Criteria for Level of Service

Control Delay (s/veh)	Level of Service
0 - 10	A
> 10 - 15	B
> 15 - 25	C
> 25 - 35	D
> 35 - 50	E
> 50	F

6.1 Canal St Site Software Results

Uncalibrated results for the studied southbound 25th St approach at the Canal St site are shown in Table 6.4. Capacity results ranged from the mid 500 vph from Kreisel and HCS to over 1300 vph from Girabase, resulting in a wide range of other performance measure results.

Table 6.4. Canal St Site: Southbound 25th St Approach - Uncalibrated

	Capacity (veh/h)	v/c Ratio	Delay (s/veh)	LOS	Queue (veh)
RODEL 1.9.7	832	0.67	14.4	B	3.3*
ARCADY 7.1	784	0.78	20.47	C	3.34*
RCAT 1.4	824	0.67	14.94	B	3.5*
KREISEL 7	547	1.08	227	F	49
GIRABASE 4	971	0.61	5	A	1 to 5*
HCS 2010 6.1	569	1.04	74.2	F	16.2
SIDRA 5.1	680	0.866	18.7	C	8.5

*queue length low based on video evidence

Packages implementing the U.K. model conservatively showed v/c ratios of 0.67 to 0.78, corresponding to delays of about 15 to 20 s, respectively. Interestingly, RCAT reports delay of 14.94 s as LOS B, while 15.0 s would be classified as C despite the negligible difference in operations. Queue lengths of about three vehicles were considered low based on video evidence.

Kreisel and Girabase showed opposite results. While Kreisel predicted slightly over saturated conditions with a 1.08 v/c ratio and long delay of 227 s, Girabase showed conditions as less than half saturated and negligible delay. A queue length of 49 vehicles from Kreisel seems long but cannot be confirmed or rejected from video data collection.

HCS results also showed slight oversaturation with a 1.04 v/c ratio, but less extreme delay and queuing than Kreisel. SIDRA results were in between the U.K.

model packages and HCS. A delay of 19 seconds was similar to U.K. packages but queue length was more reasonable at nearly nine vehicles.

Calibration was possible in ARCADY, HCS, and SIDRA with results shown in Table 6.5. In each case, capacity results were similar ranging from about 420 to 460 vph. All showed oversaturated conditions with long delays and queues. ARCADY seemed particularly sensitive to high v/c ratios by showing over 660 s of delay and a queue of 105 vehicles. Calibrated parameters based on the data collection were possibly too conservative in this case, as a v/c ratio near 1.0 was expected from the capacity conditions observed.

Table 6.5. Canal St Site: Southbound 25th St Approach - Calibrated

	Capacity (veh/h)	v/c Ratio	Delay (s/veh)	LOS	Queue (veh)
RODEL 1.9.7	—	—	—	—	—
ARCADY 7.1	416	1.47	661.32	F	105.13
RCAT 1.4	—	—	—	—	—
KREISEL 7	—	—	—	—	—
GIRABASE 4	—	—	—	—	—
HCS 2010 6.1	445	1.34	191.8	F	26.8
SIDRA 5.1	461	1.279	161.2	F	54.9

— software does not allow for calibration

6.2 De Pere Site Software Results

Software results from the studied eastbound Main Ave approach at the De Pere site are shown for the uncalibrated scenario in Table 6.6. All software packages, except Girabase, showed LOS F and corresponding high v/c ratios, delays, and queues. Video data collection was not able to confirm the maximum back of queue, but anecdotal evidence from the Northeast Region DOT suggested about 70 vehicles for the right lane and 35 vehicles for the left lane as reasonable estimates. Of the two lane-based software packages, only HCS hinted at some lane imbalance with a queue of 44 vehicles in the right lane and 32 vehicles in left lane. Lane imbalance can result in significant differences in performance measures for different turning movements on the same approach, which could make lane-by-lane models more useful in such situations. Delay from Kreisel was extreme at over 500 seconds, ARCADY and HCS showed the next highest delay at over 100 seconds, and both RODEL and SIDRA showed about 60 seconds of delay.

Table 6.6. De Pere Site: Eastbound Main Ave Approach - Uncalibrated

	Capacity (veh/h)	v/c Ratio	Delay (s/veh)	LOS	Queue (veh)
RODEL 1.9.7	2206	0.95	58.3	F	80.1
ARCADY 7.1	2182	1.06	110.72	F	80.07
RCAT 1.4	2222	0.95	52.74	F	71.7
KREISEL 7	1897	1.15	530	F	167
GIRABASE 4	2609	0.84	2	A	0 to 2*
HCS 2010 6.1	L: 871 R: 855	L: 1.18 R: 1.31	L: 112.0 R: 164.1	L: F R: F	L: 31.8 R: 44.1
SIDRA 5.1	L: 1027 R: 1069	L: 1.044 R: 1.044	L: 60.1 R: 59.1	L: F R: F	L: 42.5 R: 43.5

*queue length low based on video evidence

Calibration available in ARCADY, HCS, and SIDRA also showed LOS F as can be seen in Table 6.7. Queue length from ARCADY nearly tripled to over 200 vehicles queued on the approach corresponding to over 400 s of delay, which are likely too large of estimates. Queue and delay results from HCS decreased by about one third. Lane imbalance was still present, although not to the extent estimated in the field. SIDRA showed reasonable queuing for the right lane, but did not show smaller queues in the left lane to reflect any lane imbalance.

Table 6.7. De Pere Site: Eastbound Main Ave Approach - Calibrated

	Capacity (veh/h)	v/c Ratio	Delay (s/veh)	LOS	Queue (veh)
RODEL 1.9.7	—	—	—	—	—
ARCADY 7.1	1891	1.22	411.17	F	227.25
RCAT 1.4	—	—	—	—	—
KREISEL 7	—	—	—	—	—
GIRABASE 4	—	—	—	—	—
HCS 2010 6.1	L: 963 R: 972	L: 1.07 R: 1.19	L: 69.2 R: 114.3	L: F R: F	L: 24.2* R: 35.6
SIDRA 5.1	L: 899 R: 913	L: 1.207 R: 1.207	L: 121.5 R: 121.2	L: F R: F	L: 81.1 R: 82.0

*queue length low based on video evidence

— software does not allow for calibration

Table 6.8 contains results from the Northbound Broadway St Approach in the uncalibrated scenario. Results for capacity were mixed, with approach capacity ranging from about 780 vph from Kreisel to about 1500 vph from RODEL, ARCADY, and RCAT. All software packages showed low values for queuing, contrary to what was observed in the field. Extent of the video recording showed at least 10 vehicles consistently in queue in the left lane and likely the back of queue extended another 10 to 20 vehicles. Right lane queues were more sporadic and did not appear to exceed 10 vehicles which showed the significant variability in performance measures that can occur within lanes on the same approach. Both the lane based modeling packages, HCS and SIDRA, identified lane imbalance skewed toward higher queuing in the left lane, a similar trend to field observations.

Table 6.8. De Pere Site: Northbound Broadway St Approach - Uncalibrated

	Capacity (veh/h)	v/c Ratio	Delay (s/veh)	LOS	Queue (veh)
RODEL 1.9.7	1512	0.43	4.1	A	0.9*
ARCADY 7.1	1476	0.48	4.71	A	0.93*
RCAT 1.4	1497	0.43	4.31	A	1.0*
KREISEL 7	772	0.87	32	D	16*
GIRABASE 4	1186	0.57	3	A	0 to 3*
HCS 2010 6.1	L: 421 R: 450	L: 0.91 R: 0.65	L: 55.4 R: 24.7	L: F R: C	L: 9.9* R: 4.5
SIDRA 5.1	L: 468 R: 395	L: 0.819 R: 0.735	L: 38.1 R: 34.2	L: E R: D	L: 8.4* R: 5.9

*queue length low based on video evidence

Table 6.9 shows calibrated results where available. ARCADY capacity was lowered by about 38 percent after calibration. For the lane based software, SIDRA capacity was lowered by about 25 percent for the left lane and about six percent for the right lane. HCS results were increased by about nine percent for the left lane and 36 percent for the right lane. Queue length estimates still remained low from ARCADY and HCS. SIDRA, however, showed more reasonable queuing and better reflected the lane imbalance with 22 vehicles queued in the left lane versus five in the right lane.

Table 6.9. De Pere Site: Northbound Broadway St Approach - Calibrated

	Capacity (veh/h)	v/c Ratio	Delay (s/veh)	LOS	Queue (veh)
RODEL 1.9.7	—	—	—	—	—
ARCADY 7.1	934	0.76	16.12	C	3.09*
RCAT 1.4	—	—	—	—	—
KREISEL 7	—	—	—	—	—
GIRABASE 4	—	—	—	—	—
HCS 2010 6.1	L: 458 R: 614	L: 0.85 R: 0.48	L: 42.5 R: 13.6	L: E R: B	L: 8.4* R: 2.6
SIDRA 5.1	L: 350 R: 417	L: 1.095 R: 0.697	L: 110.0 R: 29.8	L: F R: D	L: 22.4 R: 4.8

*queue length low based on video evidence

— software does not allow for calibration

6.3 Technical Accuracy Summary

In light of the model comparisons to the field data and RMSE calculations as well as the software output, the relative technical accuracy of each model and software could be compared based on capacity output. Due to the complex and numerous amount of data involved a graphical rating scale was developed to allow quick comparisons of the relative technical accuracy shown in Table 6.10. Table 6.11 shows the resulting comparisons.

Table 6.10. Graphical Rating Scale for Technical Accuracy

○	**Poor -** Model and software did not match field data
◔	**Fair -** Model and software match field data reasonably when used with some caution
◑	**Good -** Model and software match field data with some exceptions
◕	**Very Good -** Model and software consistently matched field data
●	**Excellent** - Model and software results clearly matched field data in all cases

Table 6.11. Software and Model Technical Accuracy Summary

Software	Technical Accuracy (Model prediction vs Field Data) Ratings are Based on Consistency of Capacity Prediction		
	'WisDOT Adjusted' U.K. Model	**Default Model** (using field measured geometry)	**Calibrated Model** (using field collected data)
RODEL 1.9.7	'WisDOT Calibrated' U.K. Model ◔	U.K. Model ○	U.K. Model *RODEL did not feature capacity calibration
ARCADY 7.1	'WisDOT Calibrated' U.K. Model ◔	U.K. Model ○	U.K. Model ◕
RCAT 1.4	'WisDOT Calibrated' U.K. Model ◔	U.K. Model ○	U.K. Model *RCAT did not feature capacity calibration
KREISEL 7	-	German HBS 2001 Model ◕	German HBS 2001 Model *KREISEL did not feature capacity calibration for the HBS 2001 Model
GIRABASE 4	-	French Model ○	French Model *GIRABSE did not feature capacity calibration
HCS 2010 6.1	-	HCM 2010 Model ◕	HCM 2010 Model ◕
SIDRA 5.1	-	ARR 321* ◑	ARR 321 ◕

* Uncalibrated ARR 321 approximates the SIDRA Standard Model with an environment factor of 1.0

6.4 Limitations

Several limitations in this research warrant discussion, but even with these limitations valuable insights can still be gained. First, only three approaches from two roundabouts were considered. Even with observing a small number of locations, the total sample size from each site was relatively large. For instance, the 268 queued minute observations from the PM peak of the left lane on the northbound Broadway St approach alone was about two-thirds the size of the entire multi-lane data set, 414 observations, in the NCHRP 572 research [14]. Having a large sample from one site allows for a good representation of a specific scenario, useful for calibration for one site, but lacks the between-site variation needed for broad capacity model development to minimize sampling error. Second, software analysis was limited to the turning movement data collected which was representative of the traffic volume serviced and not necessarily the traffic volume demand. If the traffic volume serviced is used and it is less than the true demand, queues and delays will be underrepresented. Software packages need accurate demand traffic volumes for queue and delay prediction. However, queue and delay models use the volume to capacity ratio and are thus also dependent on capacity estimates. Therefore, identifying the best queuing and delay models may not be possible but trends may still be identified. Models that tend to overpredict capacity would potentially have lower v/c ratios leading to the possibility of underpredicted queuing and delay, and vice versa for models that underpredict capacity.

6.5 Interface Usability

Each software package was evaluated in general terms of how user-friendly the program operates, recalling from Chapter 3, that usability was to be evaluated by initial learning curve, ease of data input, feedback and error prevention, and long-term memory load for infrequent users. Because of the subjective nature of these criteria, the comments reflected here represent the best consensus of the researchers and steering committee. Further, as software continually changes, these comments are based on the versions of the software provided at the onset of this research.

6.5.1 RODEL 1.9.7

RODEL 1.9.7 is a Microsoft-DOS application that uses a single window to display all input and output information at the same time as shown in Figure 6.1. Presenting all input and output information at once was seen as both a positive and negative aspect of the software. Seeing everything at once provides a concise overview while too much information can be distracting when trying to focus on one specific task.

Benefits of the interface include:

- Easy to learn;
- Simple input of parameters;
- Inputs can be quickly changed to see the potential effects on performance measures; and
- Scenarios can be easily be copied between files to create different sets of scenarios, although these cannot be compared side-by-side.

Considerations for the interface include:

- A younger generation of users may not be comfortable with DOS interface. Control of the program is by keyboard only;
- Red text on a black background can be straining on the eyes;
- Lack of formatted output creates the need to use screenshots (or retyping all output) as the common reporting mechanism.
- The color scheme is not conducive to efficient use of ink during printing of screenshots; The lack of an in-context help system makes abbreviations and other terms potentially difficult to remember;
- Some commands are hidden or difficult to remember, such as Ctrl+F2 to view slope and intercept parameters; and
- Lack of labeling input and output columns forces the user to mentally rotate information, which can lead to data entry or reporting errors.

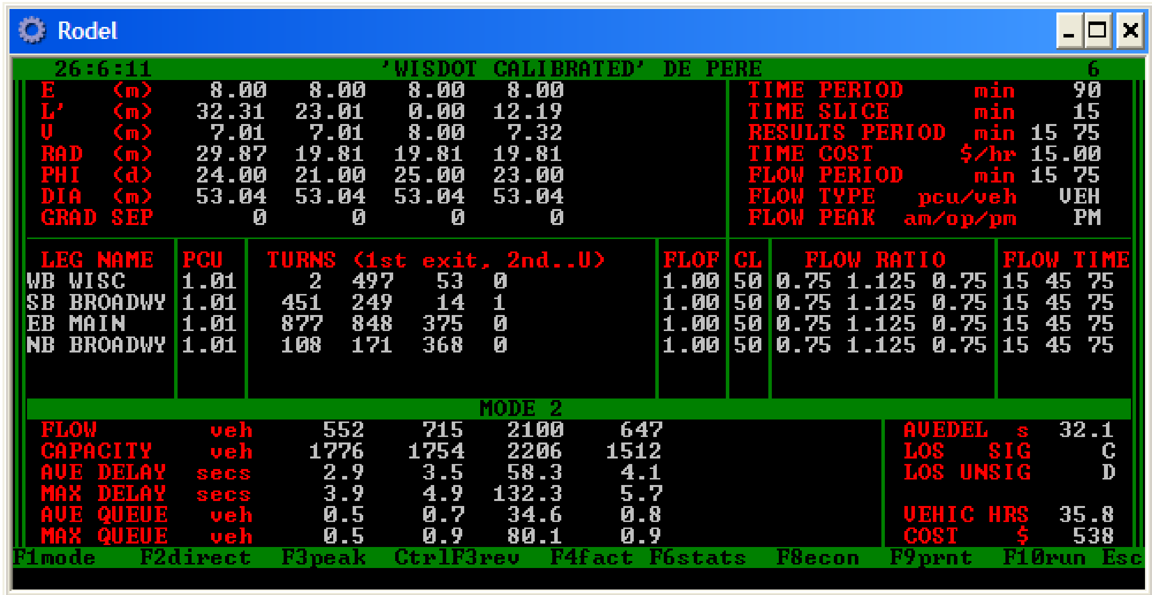


Figure 6.1. RODEL 1.9.7 Interface

6.5.2 ARCADY 7.1

ARCADY 7.1 uses a multiple document interface style, shown in Figure 6.2. While the screenshot looks cluttered, users have full control over what information display at any given time; this is an extreme example to show many different types of features. Toolbars across the top and left side of the main window organize the analysis workflow. Four major types of dialogs are commonly used in ARCADY and are labeled in the figure. Labeled dialog "1" shows a tree interface that contains the different scenarios and sites, as well as the geometry and capacity information for each approach. Dialog "2" shows a list style interface for entering data or viewing results. These style dialogs can also be viewed in a grid format to show relevant information from multiple approaches. Dialog "3" shows a schematic of the roundabout, which can be used to overlay information and highlight the approach to which selected data applies. Finally dialog "4" shows an example graphs that can be used to analyze, compare, and apply different scenarios.

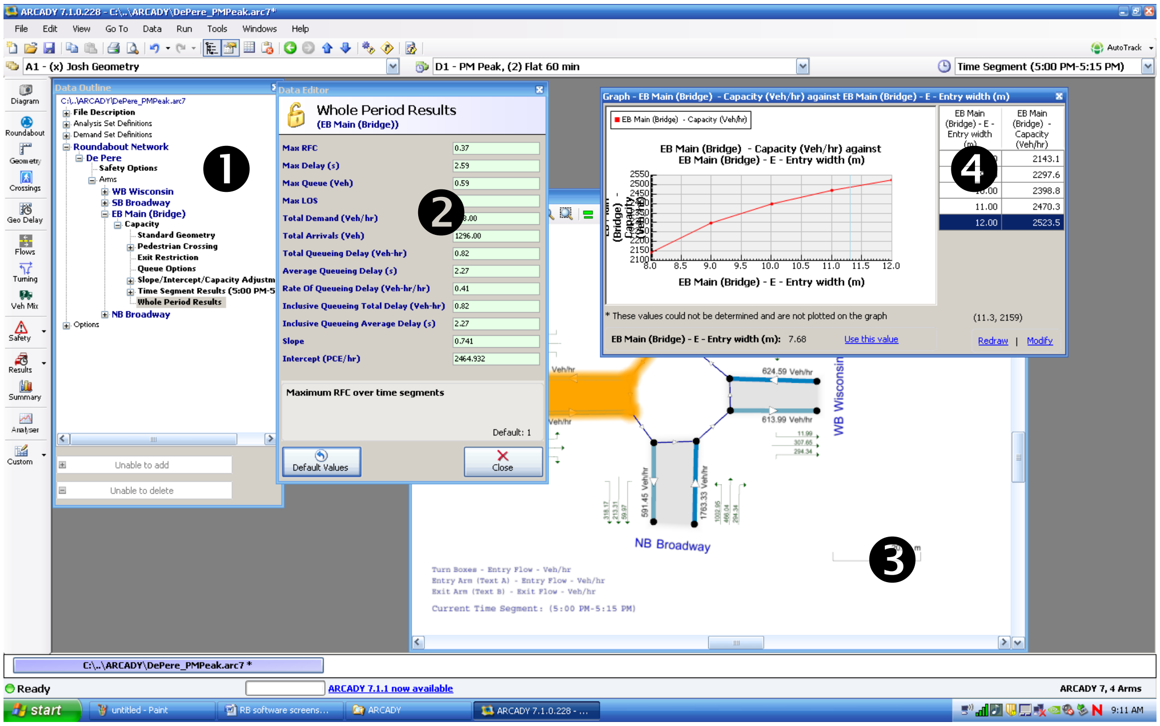


Figure 6.2. ARCADY 7.1 Interface

Benefits of the interface include:

- Information is organized into discrete areas allowing the user to view only the most relevant information at any given time;
- A dialog can be displayed that informs the user of any errors or warnings; Built-in glossary to quickly define any terms or acronyms;
- Easy side-by-side comparisons through customizable tables;
- Formatted output reports; and Data entry in tables can be copied and pasted to or from other applications (Excel).

Considerations for the interface include:

- Initially difficult to learn;
- Overwhelming number of options can be intimidating especially if the analyst is only interested in a subset of the available features and needs to filter out unwanted choices;
- Lack of strict step-by-step workflow can lead to data entry error, although the warnings dialog helps (if it is open);
- Hard to remember where options or inputs are located within the program because of the deep tree structure and not always intuitive location;
- The above points lead to a large long term memory demand, which is not as desirable for casual users; and
- Can be difficult for someone to quickly double-check all inputs.

6.5.3 RCAT 1.4

Microsoft Excel provides the basic interface for RCAT 1.4 and the spreadsheet is organized into four areas, 3 for input and one for output. All areas have similar design, and an example of the output area is shown in Figure 6.3. The four areas are: traffic demand turning movement counts, traffic flow profile, geometry, performance measure output. Navigation buttons in the upper right corner of each area allow quickly switching between the different input and output areas.

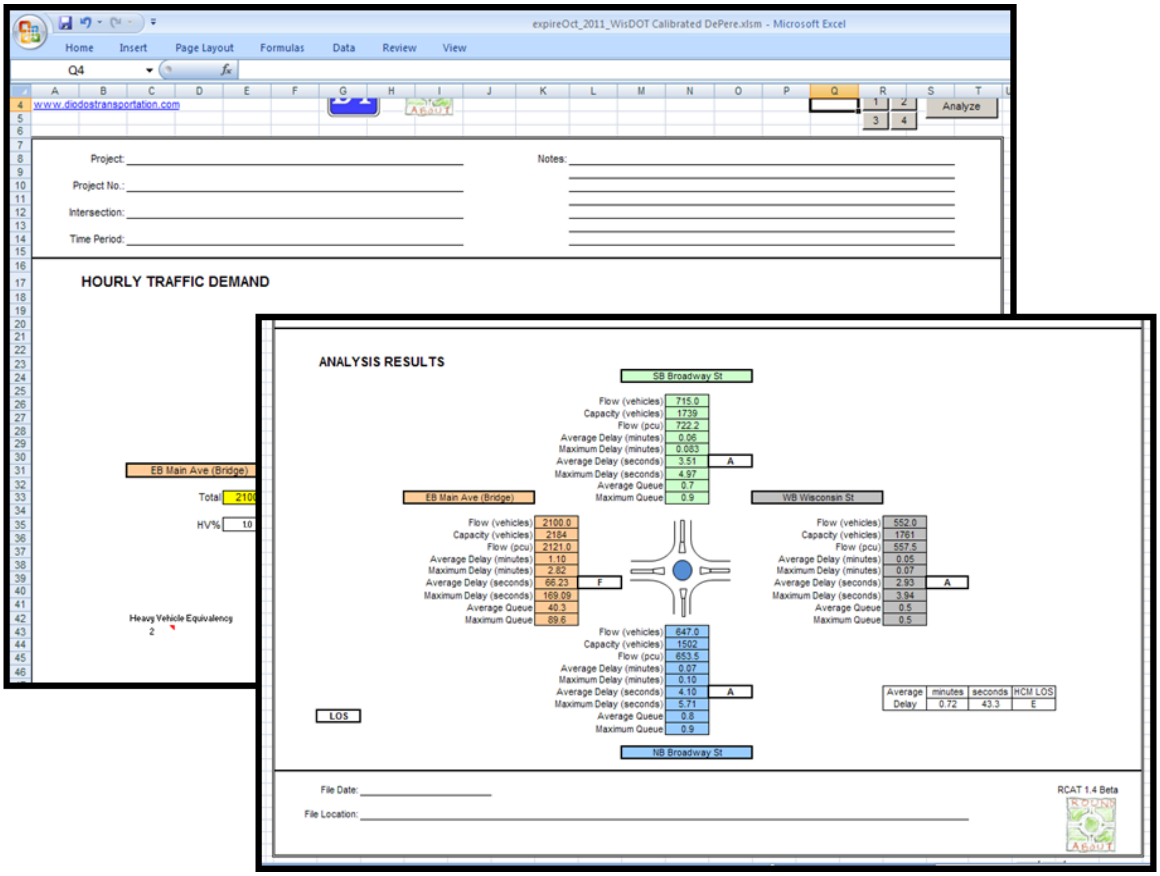


Figure 6.3. RCAT 1.4 Interface

Benefits of the interface include:

- Familiar tools for users already comfortable with Excel; and
- Highly organized workflow for efficient data entry and performance measure output.

Considerations for the interface include:

- Lack of error or warning messages other than the standard Excel errors within cells; and

- Worksheet format is rigid and locked by a 3rd party application, making customization not possible within RCAT. Other spreadsheets could potentially be developed to link to RCAT input and output.

6.5.4 KREISEL 7.0

Kreisel 7.0 uses a multiple document interface to display input and output information as shown in Figure 6.4. Typically only one dialog is open at a time at the users' discretion. A toolbar across the top of the main window guides users through the analysis workflow.

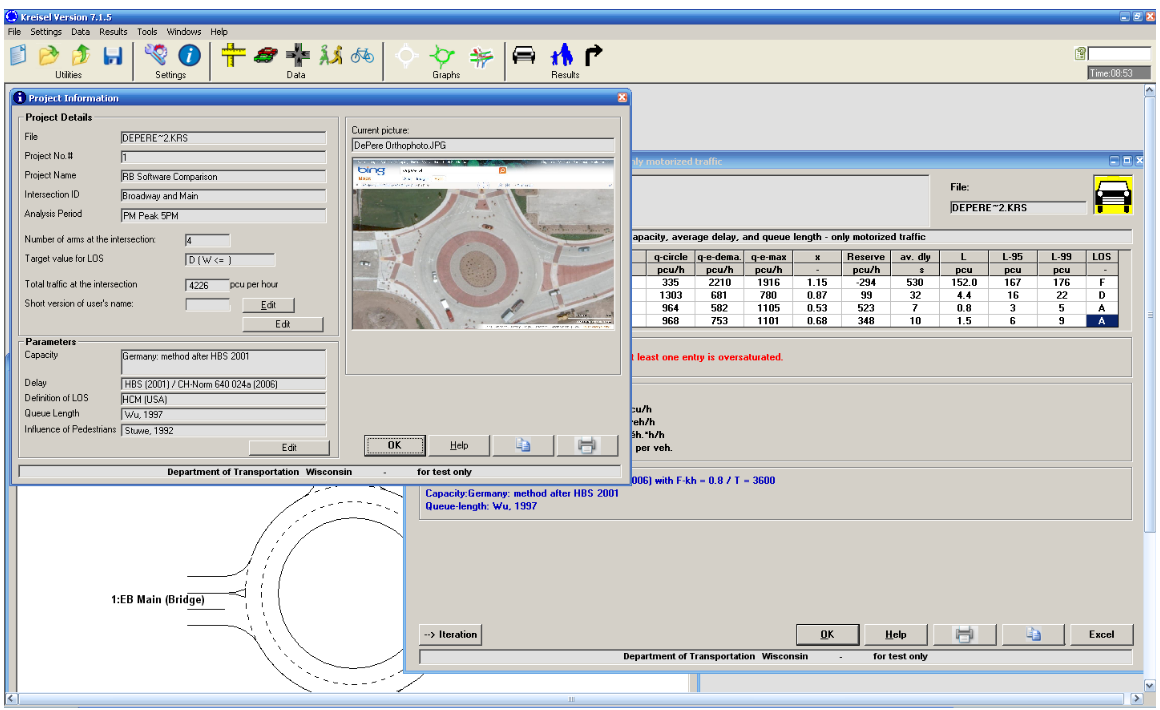


Figure 6.4. Kreisel 7.0 Interface

Benefits of the interface include:

- Moderate learning curve;

- Familiar tools for users already comfortable with Excel;
- Highly organized workflow for efficient data entry and performance measure output; and
- A schematic, while primitive, does help visually reinforce the general roundabout shape.

Considerations for the interface include:

- Many modeling options exist for each type of performance measure (capacity models, delay models, etc) and the user must be careful to choose the correct options; and
- Data entry is performed through a grid interface where most input options are labeled by abbreviations. Having the user guide handy helps to reassure term definitions.

6.5.5 GIRABASE 4.0

Simple and effective best define the interface for GIRABASE 4.0 which is shown in Figure 6.5. A version with a French interface was used for this research, but an English interface is available based on information from the vendor.

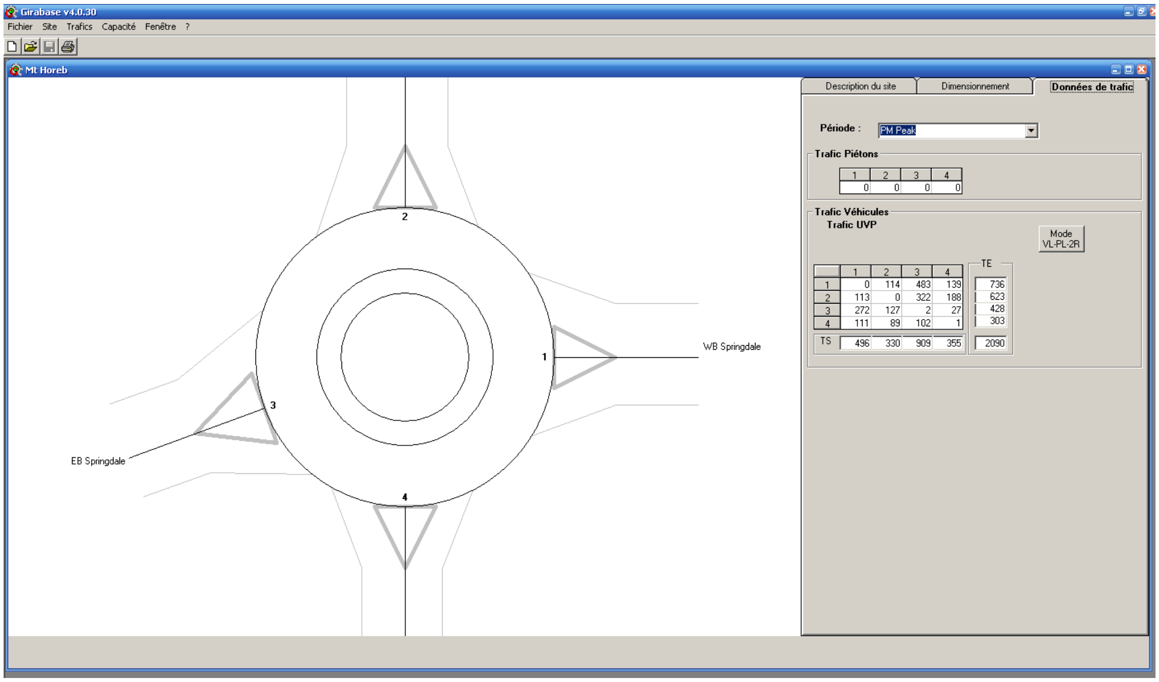


Figure 6.5. GIRABASE 4.0 Interface

Benefits of the interface include:

- Quick learning curve;
- Simple tabs guide user through the analysis workflow and is easy to remember; and
- Errors and warnings are displayed through highlighting bad input values, status bar messages, or pop-up dialogs.

Considerations for the interface include:

- Input and output cannot be easily displayed in a format for checking and reporting, although an option exists for printing all output; and
- Performance measures are atypical of other software. For example, reserve capacity is reported instead of capacity directly and level of service is not

reported. These limitations require the user to post-process output in order to make comparisons to other software.

6.5.6 HCS 2010 6.1

HCS 2010 uses a form-like interface for data entry and output display as shown in Figure 6.6.

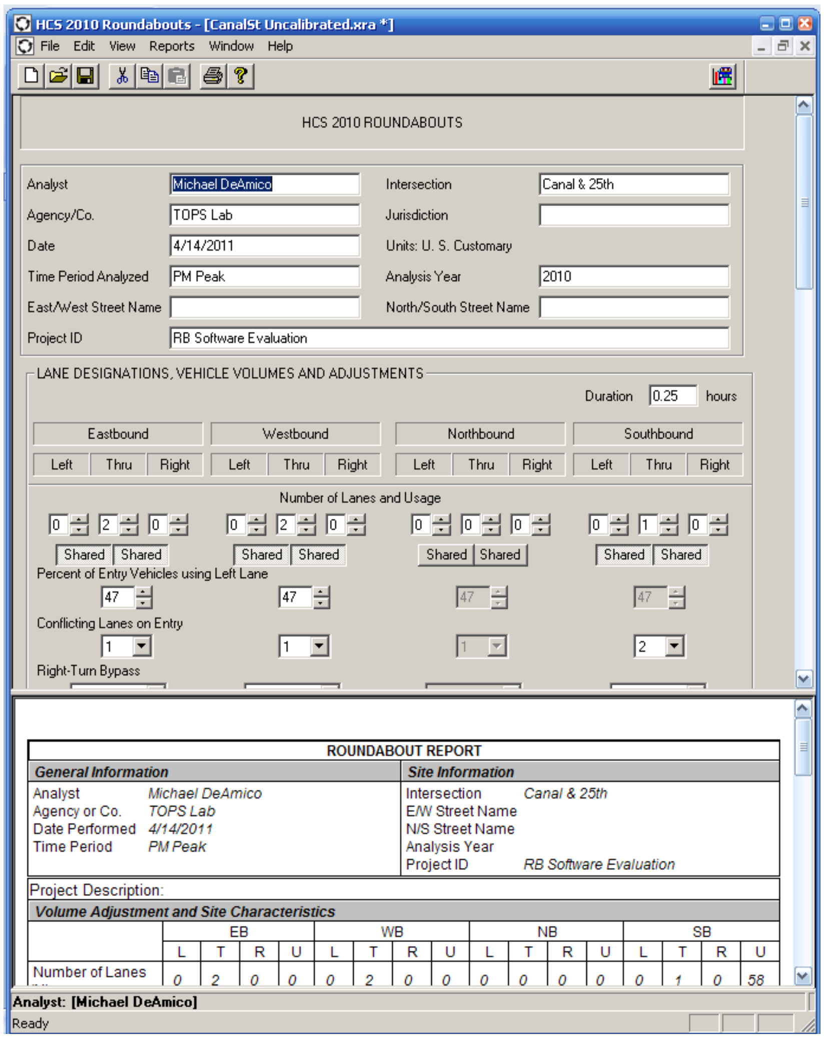


Figure 6.6. HCS 2010 6.1 Interface

Benefits of the interface include:

- Quick learning curve;
- Simple scrolling interface provides logical workflow;
- A single page formatted report provides quick access for checking and reporting analysis; and
- The interface is familiar to users of other HCS modules (stop controlled, freeways, etc).

Considerations for the interface include:

- Column labels are not always visible when scrolling, so data could mistakenly be entered into the wrong column; and
- Entering lane configurations for each approach can be confusing.

6.5.7 SIDRA 5.1

Figure 6.7 shows SIDRA 5.1 which uses a tabbed interface with a tree structure on the right side to organize different scenarios.

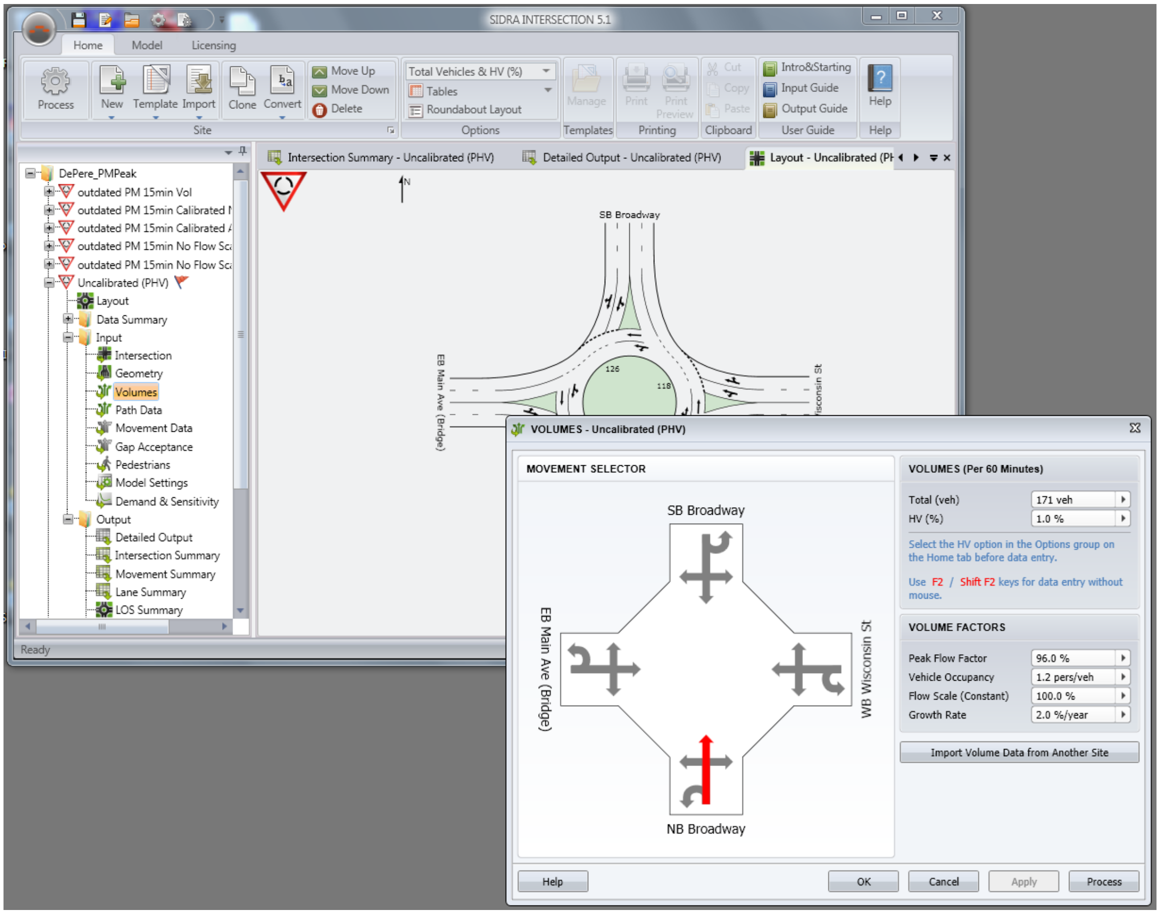


Figure 6.7. SIDRA 5.1 Interface

Benefits of the interface include:

- Moderately easy to learn, with an extensive help available from the user guide;
- Highly organized workflow with logical tree hierarchy for input and output which is easy to remember;
- Dialogs are supplemented with graphics to help visualize changes and data input;

- Formatted reports and summaries allow for reporting and analysis checks throughout the process; and
- Scenarios are easily cloned to analyze different geometries, volumes, etc.

Considerations for the interface include:

- Some options can be applied per approach or for the entire intersection; the user must be careful to apply changes to the appropriate scope; and
- Multiple scenarios can only be compared by toggling between separate tabs, which is not as easy as a side-by-side table.

6.6 Feature and Interface Comparisons

A graphical rating scale, explained in Table 6.12 was developed to allow quick comparisons to summarize the usability and features evaluated in each software.

Table 6.12. Graphical Rating Scale

○	**Poor -** Feature did not perform well or was absent
◔	**Fair -** Feature performed reasonably when used with some caution
◑	**Good -** Feature performed well but showed some limitations
◕	**Very Good -** Feature performed consistently and accurately
●	**Excellent** - Feature completely implemented, no issues discovered

Usability was holistically evaluated as summarized in Table 6.13. Again, these are qualitative, subjective results that were from a perspective that emphasized usage for DOT staff that may be more infrequent, rather than specialist, roundabout analysts and are based on the version of the software listed.

Table 6.13. Software Interface Evaluation

Software	Ease of User Interface	
RODEL 1.9.7	MS-DOS command line may be uncomfortable for younger generation users. No copy/paste or printing functions exist, so taking screen shots to demonstrate results is less than ideal.	◑
ARCADY 7.1	Uses a multiple document interface with tree outline of inputs and scenarios. Can be overwhelming with knowing where to start data entry due to large number of options. Easy to compare multiple scenarios side-by-side and explore relationships with graphing. Can be hard to remember where certain inputs are located in the long term making the software less usable for infrequent users.	◔
RCAT 1.4	Uses an Excel interface that is easy to use for those familiar with Microsoft Office. The interface is cleanly organized into three areas for input and one area for output.	●
KREISEL 7	A logical toolbar layout with separate windows for each input type provides an orderly workflow. Need to exercise caution when choosing from the multitude of model options. A grid-like interface for data input makes most data entry simple.	◑
GIRABASE 4	Tabbed interface with logical ordering of input. Easy to remember how to use the software. Output screen shows entering versus circulating flow graphs to aid in understanding capacity relationship.	●
HCS 2010 6.1	Single window interface with inputs organized in a large grid of rows and columns. Column headings are not always visible when scrolling through the long grid, leading to potential data entry errors.	◕
SIDRA 5.1	Tabbed interface with tree outline of inputs and outputs. Logical ordering of data input is easy to remember. Graphical output and a variety of formatted reports can easily be printed or transferred to other documents. User needs to check frequently to assure inputs apply to a specific leg or the entire intersection.	◕

6.6.1 Input requirements

Input data needs were compared in order to quantify the data input intensity of each software package as shown in Table 6.14.

Table 6.14. Software Data Input Needs

Software	List of Inputs for Basic Roundabout Analysis		
	Traffic Data	Geometry Data	Other Data
RODEL 1.9.7	• Traffic Volumes • % Trucks • Traffic Demand Profile	• Entry Width • Half Width • Flare Length • Entry Radius • Phi, Entry Angle • Inscribed Diameter	-
ARCADY 7.1			-
RCAT 1.4			-
KREISEL 7.0	• Traffic Volume converted to pcu/h or Traffic Volume by vehicle type	• Number of Lanes Entering • Number of Lanes Conflicting per approach • Inscribed Diameter	• Approximate Exit Capacity
GIRABASE 4.0	• Traffic Volume converted to pcu/h or Traffic Volume by vehicle type	• Central Island Diameter • Truck Apron Width • Circulating Width • Approach Angle • Approach Grade • Entry Width at 4 and 15 m • Splitter Island Width • Exit Width	• Environment: Urban, Rural, Suburban
HCS 2010 6.1	• Traffic Volumes • Peak Hour Factor • % Trucks	• Number of Lanes Entering • Number of Lanes Conflicting per approach • Bypass lanes, if any	-
SIDRA 5.1	• Traffic Volumes • Peak Hour Factor • % Trucks	• Number of Lanes Entering and exiting • Lane Disciplines/Configuration • Number of Lanes Conflicting per Approach • Approach and Exit Short Lane Lengths • Lane widths and lengths • Central Island Diameter • Circulating Width • Entry Angle • Approach Grade	• Approach and Exit Cruise Speeds

- : no other data was required for the scenarios evaluated

6.6.2 Feature Comparison

Major features that were of primary importance for the software analysis are summarized in Table 6.15. Where analyzing multiple models within one software is possible, Kreisel 7.0 can return results from about 30 different roundabout capacity models, and SIDRA 5.1 was found to have implementations of the HCM 2010 and limited results from the German model.

Table 6.15. Major Features for Software Comparison

Software	Can the software return results from multiple models?	Analysis by approach or by-lane	Maximum number of approaches	Allow calibration of model parameters	Allow analyzing multiple scenarios within the same file, side-by-side
RODEL 1.9.7	No	Approach	6	No	No
ARCADY 7.1	No	Approach	20	Yes	Yes
RCAT 1.4	No	Approach	4	No	No
KREISEL 7	Yes	Approach Based (HBS 2001)	8	No	No
GIRABASE 4	No	Approach Based	8	No	No
HCS 2010 6.1	No	Lane Based, up to 2 lanes	4	Yes	No
SIDRA 5.1	Yes	Lane Based, can do more than 2	8	Yes	Yes

Because software is continually changing, some secondary and desirable features were identified, but not formally evaluated, and are shown in Table 6.16.

Several points explaining the fractional ratings (partial circles) of the versions of the software evaluated were worth noting:

- Bypass lanes are modeled by removing right turns in the U.K. model packages;
- HCS modeling of other intersection types (signals, stop controlled, etc) requires the data to be re-entered by hand, whereas SIDRA allows scenarios to be copied and pasted; ARCADY corridor modeling is for roundabouts only;
- HCS allows for modeling other intersection types besides roundabouts, but requires the user to retype common information, such as traffic volumes;
- Formatted reports in Girabase are available by printing only;
- Kreisel and Girabase schematics are more limited than other software packages; HCS requires CORSIM for visualization;
- ARCADY safety analysis is based on U.K. research;
- Girabase graphing is limited to showing only entering versus circulating flow relationships; and
- SIDRA includes graphical sensitivity analysis for major inputs and outputs, but cannot graph any variable like ARCADY.

Table 6.16. Comparison of Advanced Secondary Features

Software	Allow bypass lanes	Allow modeling linked sites (corridors)	Allow modeling other intersection types	Includes formatted report output	Includes schematic or other visualization	Includes safety analysis	Includes graphing analysis capabilities
RODEL 1.9.7	◑	○	○	○	○	○	○
ARCADY 7.1	◑	◑	○	●	●	◑	●
RCAT 1.4	◑	○	○	●	○	○	○
KREISEL 7	○	○	○	●	◑	○	○
GIRABASE 4	●	○	○	◑	◑	○	◔
HCS 6.1	●	○	◕	●	◔	○	○
SIDRA 5.1	●	●	●	●	●	○	◕

6.6.3 Installation and License Requirements

Installation and licensing requirements for the version of each software evaluated were identified and are summarized in Table 6.17.

Table 6.17. Installation And Licensing Requirements Comparison

Software	Installation Requirements	Licensing Type & Cost
RODEL 1.9.7	Windows XP or Older (not Windows 7). Must be able to run DOS command line programs. No specific hardware requirements.	Response from vendor was based on a future version of the software.
ARCADY 7.1	Windows (XP, Vista, 7) Any modern PC will run ARCADY, for fast performance, recommended parameters are:2+ GHz Processor, 1 GB RAM, 50 MB hard drive space, hardware accelerated OpenGL capability.	Network ($9000 for 4 concurrent users) or Standalone ($2500). Additional seats available with discounted prices.
RCAT 1.4	Requires Microsoft Excel. Has been tested in Excel 2007 on Windows XP and 7. (RCAT was successfully used in Excel 2010 for this project as well).	Cost for one standalone license is $195. For 5 or more licenses, a quote will be determined.
KREISEL 7	Windows (XP, 7). No specific RAM, CPU, or hard drive requirements; it runs on old PCs/Laptops as well as modern ones. Installation directory uses 23 MB of hard drive space.	Cost is on case-by-case basis for large state agencies. Future versions will have licensing authorization over the internet. Upgrades come at 7% of the purchase price. A single user can purchase the program for 1285 Euro. (about $1900 U.S.)
GIRABASE 4	Windows 95,98,NT,2000,XP. Software will run on Windows 7 but has not been tested extensively. No specific RAM, CPU, or hard drive requirements. Installation directory uses 2 MB of hard drive space.	Single Workstation Licenses Only at 990 Euro (about $1420)
HCS 2010 6.1	Windows (2000,XP,Vista,7-32 bit, 7-64 bit). Some modules require .NET Framework (roundabout module does not) 512 MB RAM, 750 MB Hard Drive Space	An agency license is $12,000+, does not use a network based license server
SIDRA 5.1	Windows XP (SP2), Vista, 7, 32 bit and 64 bit. Internet Explorer 7 or later. Requires .NET Framework 3.5 (SP 1) and Microsoft SQL Compact edition 3.5 (SP 1) 1 GB RAM, Installation directory uses 50 MB of hard drive space.	Standalone (2350 AUD, about $2500 U.S.) or Network Based License (16000 AUD, or about $16900 U.S., for 10 Network Seats). Enterprise licensing available with case-by-case costs.

Exchange Rates Used (June 28th, 2011)
1 EUR = 1.43663 USD, 1 AUD = 1.05377 USD

6.6.4 Training Needs and Availability of Support

Training and support for the version of each software package evaluated are summarized in Table 6.18.

Table 6.18. Software Training and Support Availability

Software	Training Needs	Availability of Support
RODEL 1.9.7	Response from vendor was based on a future version of the software	Response from vendor was based on a future version of the software
ARCADY 7.1	Software and design training is available in the U.S. from TRL or authorized training centers. Costs are quoted based on class size and type.	Included for the 1st year, 15% of the initial purchase price each year thereafter
RCAT 1.4	No specific training required.	Email support and updates free 1 year.
KREISEL 7	No specific training required. Courses available in lengths of 1 or more days. Costs have been from 400 to 2000 Euros depending on the attendees and duration.	Telephone support (in German) at no cost.
GIRABASE 4	Training is available for an additional fee that is not included in the purchase price.	Software guaranteed stable for 12 months.
HCS 2010 6.1	1 to 3 day workshops and courses available. Flexible in teaching at various skill levels.	1st year included, $400/year thereafter
SIDRA 5.1	A U.S. representative is available for special training courses that can be arranged on demand. Fees range from $500 to $1000 for a 2-day course, depending on the number of trainees.	One year free tech support and upgrades included in purchase price.

6.6.5 Considerations for Future Software Versions

Like most technology, software versions can change at a rapid pace, making comparisons difficult when the user knows the latest-and-greatest features are coming soon. One emerging feature has been the integration of design and analysis software packages. Developers from ARCADY and SIDRA are working on incorporating real-time links between their analysis software and CAD design programs. ARCADY 7.1 currently interfaces with the CAD package AutoTrack 9 Junctions developed by Savoy Computing Services Ltd [44]. Future versions of SIDRA were demonstrated to link with the CAD software TORUS developed by Transoft Solutions [45]. RODEL has also been undergoing revisions with the introduction of RODEL V1-Win as an interim beta software before the release of RODEL V2.

7 Conclusions and Future Work

This research has analyzed current roundabout software in terms of a scientific perspective of technical accuracy, as well as from a managerial standpoint of usability and features. Certainly the choice about the future direction for roundabout analysis is a complex decision with widespread impacts that cannot be taken lightly. The following concluding comments summarize the major trends identified within this research.

7.1 Capacity Model Comparison

Within the scope of this research, all models were shown to perform well if properly calibrated as RMSE values were relatively similar ranging between 80 and 183 pcu/h/ln, depending on the scenario. However, calibration using field data is difficult for future, non-existent conditions when designing a proposed roundabout, which emphasizes the importance of proper use of uncalibrated models. Some uncalibrated models, specifically the NCHRP 572 and German models, showed consistently lower error than others, between 82 and 193 pcu/h/ln. Caution needs to be used in applying any model, especially when extrapolating foreign models to the U.S., because scenarios in the U.S. may differ from those used in the model development. Based on the scenarios evaluated, incorporating the

U.S. based capacity research into roundabout analysis would be desirable. Equally, situations beyond the scope of the NCHRP 572 research may require alternative analysis tools as recognized by the HCM 2010.

The U.K. model and ARR 321 method overpredicted capacity in the default scenarios, although only slightly in some cases, and SIDRA would show lower capacity from the ARR 321 method used. Specifically at the De Pere site, the U.K. model overpredicted capacity in cases of high circulating flows where capacity estimates are most critical for performance measures. This overprediction may be due to the more conservative driving observed compared to the aggressive behaviors that are reflected in the U.K. model. Combining data from the two approaches studied at the De Pere site showed that extending the approach based U.K. model to a lane-by-lane analysis needs careful consideration because each lane may not have equal capacity if lane utilization is not balanced. Importantly, models that overpredict capacity now may not overpredict capacity in the future as drivers gain more experience in the U.S.

7.2 Software Modeling Comparisons

Software modeling logically followed similar trends to the capacity modeling analysis. Where capacity models were shown to overpredict capacity, the software also showed high predictions of capacity, and thus less queuing than what was observed in the field. The French model implemented in Girabase did not seem to return results consistent with field observations. Calibration was only possible in three of the seven software packages: ARCADY, HCS and SIDRA. Calibration resulted in lower capacity predictions, which was consistent with the capacity data analysis. However software calibration had varied success, likely due to some of the limitations of the study and software analysis. In the case of the Canal St site, queues were longer than expected from all models. In the case of the U.K. model, this likely occurred because of the more sporadic congested time periods rather than the extended congestion that was observed at the De Pere site.

Lane-by-lane modeling was shown to be a more desirable method for capacity analysis because significant lane imbalance can result in variability in performance measures on the same approach, as was observed at the De Pere site. However, for eastbound De Pere, no software showed lane imbalance in queuing to the estimated extent observed in the field. This shows that the analyst still has responsibility for understanding how drivers will utilize the available lanes. On the northbound approach, queue estimates were low from all software packages in both the calibrated and uncalibrated scenarios, however, HCS and SIDRA correctly identified lane imbalance that is not otherwise detectable with an approach based method.

7.3 Software Usability Comparison

Experience in the U.S. appears to be at the cusp of change in terms of capacity model development as well as software packages. This research has come at the beginning of major capacity studies and certainly does not mark a definitive end as much remains to be learned about the future of roundabout operations. Ultimately software is constantly evolving and this research considered the most widespread versions of the popular analysis packages; new versions, or entire packages may emerge in the future. Therefore, the purpose of the software as well as the potential growth, evolution, and flexibility of any software and parent company must be considered to make a smart investment for the future. Likely there may not be one perfect solution, so a variety of the most useful software tools that fulfill specific roles should be considered. Realistically an analyst could become used to any software after a sufficient amount of experience, which makes comparing usability difficult. However, taking the perspective of an occasional user, usability varied from simple but less feature rich packages, like RCAT and GIRABASE, to complex packages and feature rich packages like ARCADY. Larger companies, such as those that produce ARCADY and SIDRA, seemed to offer more frequent updates, support, and features although at a greater cost.

7.4 Future Research

During this study, numerous questions and areas for future research were identified, further emphasizing that current practice is only at the beginning of fully understanding roundabout operations. Some potential future research areas are:

- More intensive research into delay and queue models. Even long queues tended to roll leading to questions regarding the definition of queuing and associated models during congestion;
- Study roundabout operational parameters and performance measures to test sensitivity to location specific factors, such as urban versus rural, regional differences, etc;
- Understanding how roundabouts operate within a corridor of other roundabouts or a corridor with mixed intersection types;
- Expand the analyses and comparisons to include microsimulation; and

- Use the lessons learned from this research toward future studies when more roundabouts approach capacity operations to refine calibration of model parameters.

7.5 Other Considerations for Discussion

Beyond specific future research ideas, many other pertinent questions, that are not easily answered, should be considered:

- What is the purpose of the model and software output? Is the purpose just to obtain LOS or is it needed to determine geometric design parameters? More than one type of software may be appropriate.

- How will driver behavior change in the future? Will gap acceptance parameters change or will more aggression be observed? Given the unpredictable nature of the future, should capacity estimates be based on a range of values rather than one average value?

- How appropriate is it to use foreign models in the U.S. when geometric design and driver behavior may differ on fundamental levels?

- Are there any concerns over choosing a model with proprietary, unpublished functions? Understandably there is need to protect intellectual property, but there is also a need for the analyst to be able to check and make sure the underlying research and models apply to site specific situations to avoid unsubstantiated software output.

- The relative merits between default models that work right "out-of-the box" versus models that require adjustment or calibration deserves careful consideration as development of proper adjustments for any model requires extensive data collection and reduction.

- How will the software fit into the workflow for roundabout design and analysis? Better understanding how the software is intended to be used within a larger roundabout design and analysis workflow could help refine the choices. The full impact of choosing an analysis tool should be investigated. Extensive "what-if" testing to see how past decisions may have changed with new analyses may be useful.

- Should the software be used as a compliment to established guidelines for good roundabout design? Enhanced guidelines may lead to more consistency between roundabouts which could reinforce driver expectation and understanding and may in turn increase safety as well as capacity.

Clearly, there are many aspects that require careful thought when evaluating roundabout, or any other type of, analysis software. Approaching problems from a scientific and open minded perspective helps in making informed decisions to provide the most value for investing in the transportation system.

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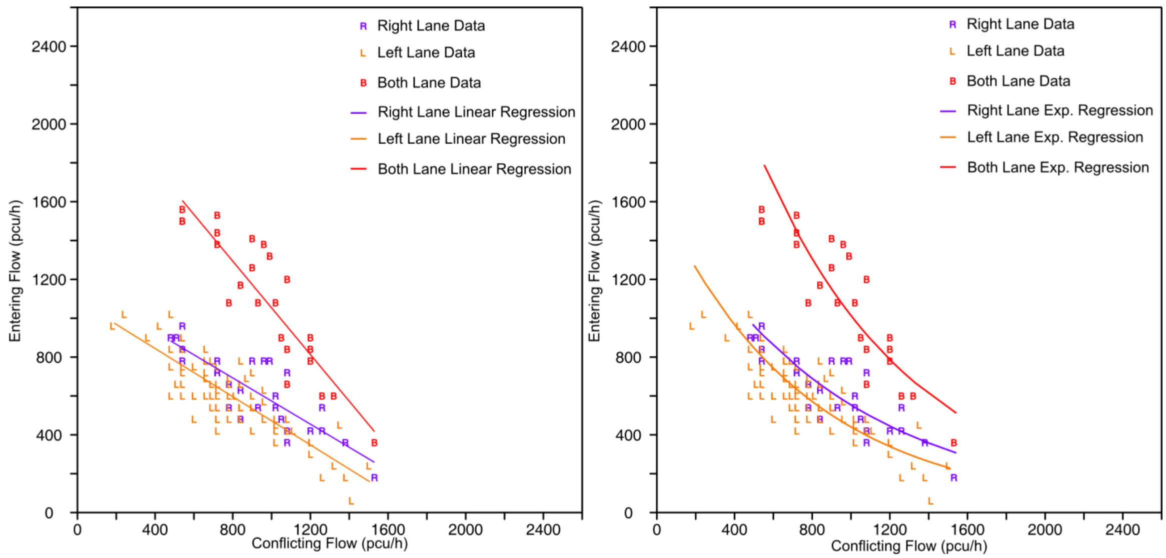
Appendix A

De Pere AM Capacity Data - Northbound Approach

De Pere Northbound AM Field Data



(a)
Field Data with Linear Regression

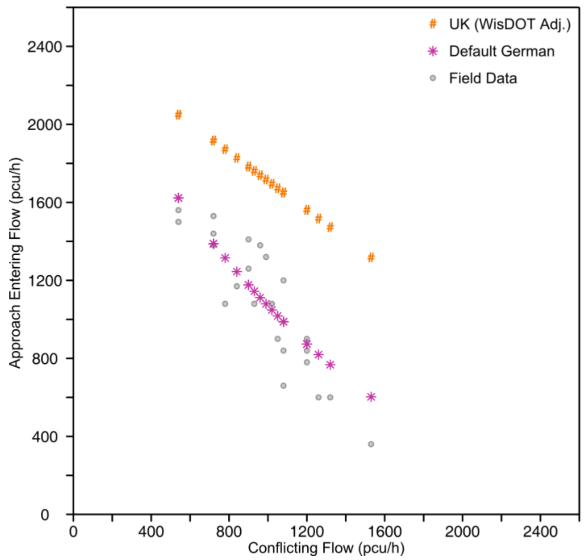
(b)
Field Data with Exponential Regression

Figure B-1. De Pere Northbound AM Field Capacity Data

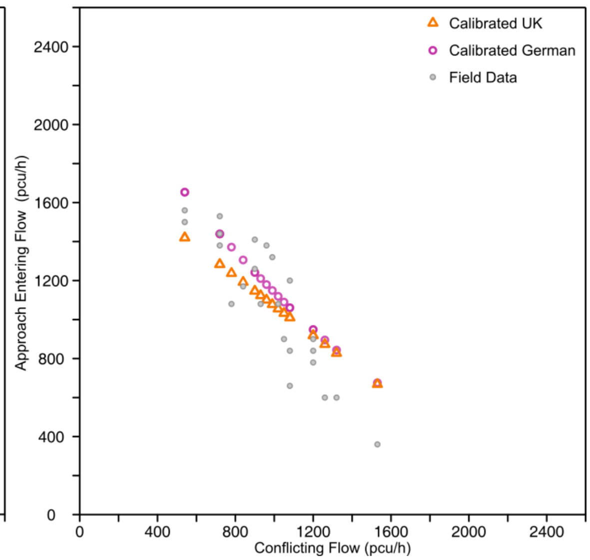
Table B-1. De Pere Northbound AM Field Data Regression Results

Lane	Regression	Intercept (pcu/h)	Slope	n	R^2	RMSE (pcu/h/ln)
Right	Linear	1169	0.595	27	0.706	104
	Exponential	1640	1.12×10^{-3}	27	0.688	110
Left	Linear	1091	0.622	84	0.707	102
	Exponential	1603	1.33×10^{-3}	84	0.656	114
Approach (Both Lanes)	Linear	2255	1.201	24	0.807	74
	Exponential	3550	1.28×10^{-3}	24	0.777	92

De Pere Northbound AM – Approach Based Model Comparison



(a)
Field Data with Linear Regression



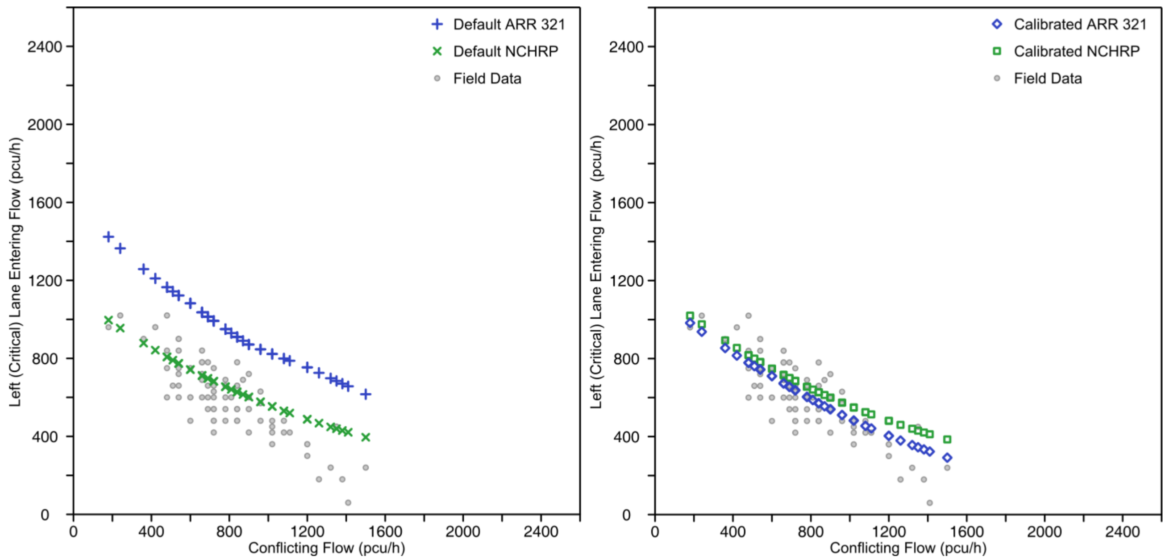
(b)
Field Data with Exponential Regression

Figure B-2. De Pere Northbound AM Approach Based Capacity Comparison

Table B-2. RMSE and Model Characteristics from the De Pere NB AM Approach Analysis

	Uncalibrated				Calibrated			
Model	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)
U.K.	2450	0.740	24	333	1829	0.759	24	93
German	2483	1.53×10^{-4}	24	82	2400	5.56×10^{-5}	24	94

De Pere Northbound AM – Lane Based Model Comparison



(a)
Uncalibrated Lane Based Models

(b)
Calibrated Lane Based Models

Figure B-3. De Pere Northbound AM Lane Based Capacity Comparison

Table B-3. RMSE and Model Characteristics from the De Pere NB AM Lane Based Analysis

	Uncalibrated				Calibrated			
Model	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**	**Intercept (pcu/h)**	**Slope**	**n**	**RMSE (pcu/h/ln)**
ARR 321	1633	N/A	84	381	1133	N/A	84	107
NCHRP	1130	7.00×10^{-4}	84	149	1165	7.38×10^{-4}	84	145

Appendix B

Software Output for all Approaches

Notes on Software Output

All software output was found to be comparable between the software packages, with a subtle differences between some of the definitions of capacity, delay, and queue length. The following table briefly summarizes some basic definitions used in each software.

Software	Model Aggregation	Model Used For Evaluation	Capacity (predicted maximum entry flow)	v/c Ratio	Delay	Queue Length
RODEL 1.9.7	Approach Based	UK Model	Based on the sum of capacity results from the 15-minute intervals within the analysis period	No output by software; calculation was done by hand	Average delay based on time in queue – does not include geometric delay or accel/decel delay	Maximum queue during analysis period
ARCADY 7.1			Based on the capacity from the peak 15-minute interval within the analysis period	Based on the demand flow and capacity during the peak 15-minute period	Maximum of average delay per time slice, based on time in queue – does not include geometric delay or accel/decel delay	Maximum queue during analysis period
RCAT 1.4			Based on the sum of capacity results from the 15-minute intervals within the analysis period		Average delay based on time in queue – does not include geometric delay or accel/decel delay	Maximum queue during analysis period
KREISEL 7.0		German (HBS 2001)[1]	Based on the capacity from the peak 15-minute period	Based on the demand flow and capacity during the peak 15-minute period	Uses definition from German Highway Capacity Manual – “queuing delay” with no accel/decel component	95th Percentile
GIRABAS E 4.0		French	No output by software; software returns “reserve capacity” from which capacity can be calculated for the peak period	No output by software; calculation was done by hand	Level of service is not reported by the software	Software returns an average and maximum queue length, no percentile queues given
					Delay and queue tends to be lower due to the software allowing "maximums to be exceed 5% of the time"	
HCS 2010 6.1	Lane Based	HCM 2010	Based on the capacity from the peak 15-minute period	Based on the demand flow and capacity during the peak 15-minute period	Uses “control delay” similar to two-way stop definition in HCM 2010. Has a term for accel/decel and move-up in queue time	95th Percentile
SIDRA 5.1		SIDRA Standard[2]			Delay output option was chosen to be compatible with HCM definition	

(1) Kreisel software can be used to evaluate over 30 different capacity models
(2) SIDRA software can use capacity models based on the HCM 2010 and the German HBS 2001.

Units for Software Output

Kreisel, Girabase, and HCS output capacity in pcu/hr. The following tables show these capacity values converted to veh/hr to allow equal comparison between all software packages based on the following:

- Passenger car equivalents were 2.0 for trucks and 0.5 for motorcycles and bicycles.
- Percent heavy vehicles was 1% for all approaches on all sites, except 2% on eastbound Canal St.

Resulting units for the software output tables are:

<table>
<tr><th></th><th>Capacity</th><th>v/c Ratio</th><th>Delay</th><th>LOS</th><th>Queue Length</th></tr>
<tr><td>RODEL</td><td rowspan="7">veh/hr</td><td rowspan="7">Unitless</td><td rowspan="7">sec/veh</td><td rowspan="7">All levels of service used the HCM 2010 unsignalized definition:

A: 0 – 10 s
B: >10 – 15 s
C: >15 – 25 s
D: >25 – 35 s
E: >35 – 50 s
F: > 50 s or v/c > 1.0</td><td rowspan="7">Number of vehicles</td></tr>
<tr><td>ARCADY</td></tr>
<tr><td>RCAT</td></tr>
<tr><td>KREISEL</td></tr>
<tr><td>GIRABASE</td></tr>
<tr><td>HCS</td></tr>
<tr><td>SIDRA</td></tr>
</table>

Lane Based Models

Results are given per lane, where:
L = left lane
R = Right Lane

Queuing Results

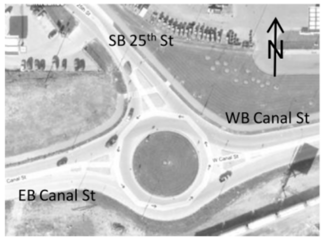
Queue lengths with an asterisk (*) denote results that appear unreasonable based upon reviews of video data collection. Only the studied approaches were analyzed for reasonableness of queue length.

Blank Result Rows

The software versions of RCAT, Kreisel, Girabase did not allow for calibration of the capacity model used during the evaluation.

Uncalibrated Canal St Site Results Canal St & 25th St, Milwaukee, WI – PM Peak

Results from RODEL, ARCADY, and RCAT reflect WisDOT adjusted Scenario



SB 25th St

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL	832	0.67	14.4	B	3.3*
ARCADY	784	0.78	20.47	C	3.34*
RCAT	824	0.67	14.94	B	3.5*
KREISEL	547	1.08	227	F	49
GIRABASE	971	0.61	5	A	1 to 5*
HCS	569	1.04	74.2	F	16.2
SIDRA	680	0.866	18.7	C	8.5

EB Canal St

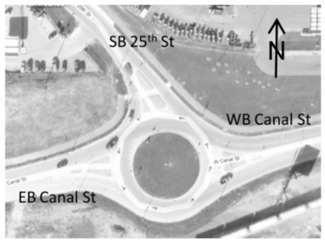
	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL	2038	0.15	2.0	A	0.2
ARCADY	2010	0.17	2.16	A	0.21
RCAT	2021	0.15	2.06	A	0.2
KREISEL	1747	0.19	2	A	1
GIRABASE	2808	0.11	0	A	0 to 2
HCS	L: 725 R: 725	L: 0.22 R: 0.24	L: 7.4 R: 7.8	L: A R: A	L: 0.8 R: 0.9
SIDRA	L: 888 R: 993	L: 0.176 R: 0.176	L: 6.3 R: 3.6	L: A L: A	L: 1.1 R: 1.1

WB Canal St

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL	2520	0.53	3.0	A	1.4
ARCADY	2516	0.58	3.44	A	1.40
RCAT	2498	0.53	3.08	A	1.4
KREISEL	2350	0.61	4	A	7
GIRABASE	3751	0.38	0	A	0 to 3
HCS	L: 1054 R: 1054	L: 0.63 R: 0.71	L: 12.3 R: 15.0	L: B R: C	L: 4.7 R: 6.4
SIDRA	L: 1411 R: 1627	L: 0.468 R: 0.468	L: 2.0 R: 2.8	L: A L: A	L: 3.8 R: 3.8

* Queuing result low based on video review

Calibrated Canal St Site Results Canal St & 25th St, Milwaukee, WI – PM Peak



SB 25th St

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL					
ARCADY	416	1.47	661.32	F	105.13
RCAT					
KREISEL					
GIRABASE					
HCS	445	1.32	186.6	F	26.4
SIDRA	461	1.279	161.2	F	54.9

EB Canal St

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL					
ARCADY	2221	0.15	1.91	A	0.18
RCAT					
KREISEL					
GIRABASE					
HCS	L: 725 R: 725	L: 0.22 R: 0.24	L: 7.4 R: 7.8	A A	L: 0.8 R: 0.9
SIDRA	L: 970 R: 1067	L: 0.162 R: 0.162	L: 5.7 R: 3.1	A A	L: 1.0 R: 1.0

WB Canal St

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL					
ARCADY	2662	0.55	3.02	A	1.23
RCAT					
KREISEL					
GIRABASE					
HCS	L: 1054 R: 1054	L: 0.63 R: 0.71	L: 12.3 R: 15.0	B C	L: 4.7 R: 6.4
SIDRA	L: 1412 R: 1629	L: 0.467 R: 0.467	L: 2.0 R: 2.8	A A	L: 3.7 R: 3.8

* Queuing result low based on video review

Uncalibrated De Pere Site Results Broadway St & Main Ave, De Pere, WI – PM Peak

Results from RODEL, ARCADY, and RCAT reflect WisDOT adjusted Scenario

SB Broadway St

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL	1754	0.41	3.5	A	0.9
ARCADY	1685	0.47	4.01	A	0.87
RCAT	1777	0.40	3.38	A	0.8
KREISEL	1090	0.68	10	A	6
GIRABASE	1565	0.48	1	A	1 to 4
HCS	L: 543 R: 569	L: 0.51 R: 0.82	L: 15.8 R: 33.5	L: C R: D	L: 2.8 R: 8.4
SIDRA	L: 595 R: 734	L: 0.462 R: 0.640	L: 13.5 R: 16.4	L: B R: C	L: 2.6 R: 4.9

EB Main Ave (Bridge)

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL	2206	0.95	58.3	F	80.1*
ARCADY	2182	1.06	110.72	F	80.07*
RCAT	2222	0.95	52.74	F	71.7*
KREISEL	1897	1.15	530	F	167
GIRABASE	2609	0.84	2	A	0 to 2*
HCS	L: 871 R: 885	L: 1.18 R: 1.31	L: 112.0 R: 164.1	L: F R: F	L: 31.8 R: 44.1
SIDRA	L: 1027 R: 1069	L: 1.044 R: 1.044	L: 60.1 R: 59.1	L: F R: F	L: 42.5 R: 43.5

WB Wisconsin St

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL	1776	0.31	2.9	A	0.5
ARCADY	1724	0.35	3.22	A	0.54
RCAT	1759	0.31	2.96	A	0.6
KREISEL	1094	0.53	7	A	3
GIRABASE	1749	0.33	1	A	1 to 5
HCS	L: 544 R: 570	L: 0.50 R: 0.54	L: 15.5 R: 16.0	L: C R: C	L: 2.7 R: 3.2
SIDRA	L: 651 R: 716	L: 0.421 R: 0.421	L: 11.6 R: 10.7	L: B R: B	L: 2.4 R: 2.5

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL	1512	0.43	4.1	A	0.9*
ARCADY	1476	0.48	4.71	A	0.93*
RCAT	1497	0.43	4.31	A	1.0*
KREISEL	772	0.87	32	D	16*
GIRABASE	1186	0.57	3	A	0 to 3*
HCS	L: 421 R: 450	L: 0.91 R: 0.65	L: 55.4 R: 24.7	L: F R: C	L: 9.9* R: 4.5
SIDRA	L: 468 R: 395	L: 0.819 R: 0.735	L: 38.1 R: 34.2	L: E R: D	L: 8.4* R: 5.9

NB Broadway St

* Queuing result low based on video review

Calibrated De Pere Site Results Broadway St & Main Ave, De Pere, WI – PM Peak

Results from RODEL, ARCADY, and RCAT reflect WisDOT adjusted Scenario

SB Broadway St

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL					
ARCADY	1783	0.44	3.62	A	0.79
RCAT					
KREISEL					
GIRABASE					
HCS	L: 543 R: 569	L: 0.51 R: 0.82	L: 15.8 R: 33.5	L: C R: D	L: 2.8 R: 8.4
SIDRA	L: 614 R: 757	L: 0.448 R: 0.621	L: 12.8 R: 15.3	L: B R: C	L: 2.4 R: 4.6

EB Main Ave (Bridge)

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL					
ARCADY	1891	1.22	411.17	F	227.25
RCAT					
KREISEL					
GIRABASE					
HCS	L: 963 R: 972	L: 1.07 R: 1.19	L: 69.2 R: 114.3	L: F R: F	L: 24.2* R: 35.6
SIDRA	L: 899 R: 913	L: 1.207 R: 1.207	L: 121.5 R: 121.2	L: F R: F	L: 81.1 R: 82.0

WB Wisconsin St

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL					
ARCADY	1983	0.31	2.62	A	0.44
RCAT					
KREISEL					
GIRABASE					
HCS	L: 544 R: 570	L: 0.50 R: 0.54	L: 15.5 R: R: 16.0	L: C R: C	L: 2.7 R: 3.2
SIDRA	L: 703 R: 765	L: 0.392 R: 0.392	L: 10.3 R: 9.7	L: B R: A	L: 2.1 L: 2.2

	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL					
ARCADY	934	0.76	16.12	C	3.09*
RCAT					
KREISEL					
GIRABASE					
HCS	L: 456 R: 597	L: 0.84 R: 0.49	L: 41.6 R: 14.1	L: E R: B	L: 8.3* R: 2.7
SIDRA	L: 350 R: 417	L: 1.095 R: 0.697	L: 110.0 R: 29.8	L: F R: D	L: 22.4 R: 4.8

NB Broadway St

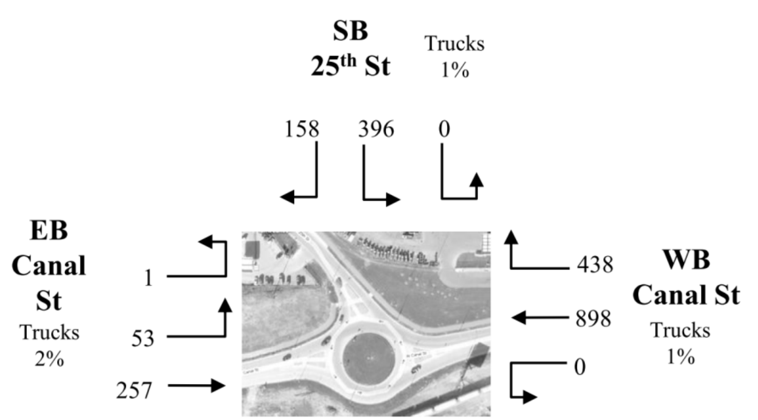
* Queuing result low based on video review

Traffic Volumes

PM peak hour turning movement counts (veh/hr) were used for the software analysis as shown. Because turning movement counts represent the actual volume serviced and not the true demand, performance measures of v/c, delay, and queue may not field conditions where demand exceeded capacity.

Canal St Site: ***Thr. April 15, 2010 3:30 PM – 4:30 PM***

Volumes shown are shown before adjustment for a peak hour factor of 0.94



De Pere Site: ***Wed. May 19, 2010 5:00 PM – 6:00 PM***

Volumes shown are shown before adjustment for a peak hour factor of 0.96