Roundabout Software Evaluation

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University of Wisconsin-Madison

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16. 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 compared to each other; 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. 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 model parameters that meet agency needs.

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Executive Summary

Just as signals have undergone historical transformations from the early red and green semaphore that was turned manually to the modern signal with full-actuation and other capabilities, roundabouts too have an ongoing history. However, the form of roundabouts seen today is a relatively recent evolution in the U.S. compared to their signal cousins. Large rotary intersections used in the early U.S. transportation system, where circulating traffic yields, were shown to be problematic and have paved the way for compact modern roundabouts, where entering traffic yields to circulating traffic, to provide safer and more efficient operations. Understanding traffic operations, such as capacity, has been an active area of research in order to better understand how roundabouts fit into the transportation system.

Using the right software can increase accuracy and productivity. However, a growing number of choices and evolving features leave many questions about what is the best option, providing the motivation for this research. In order to select a software package, specific needs and goals must be identified in regards to what value the software should provide. The scope of this research includes analyzing software in terms of technical accuracy compared to field data, features and usability, hardware requirements, training, and costs. Beyond this scope, many other considerations, unique to each agency, are required in order to arrive at a recommendation for a software package.

This research has analyzed recent observations from two roundabouts in Wisconsin in regards to estimating capacity and making comparisons to worldwide experience where roundabouts have been historically more prevalent. In addition, seven popular software packages from around the world were compared in the analysis.

The two sites examined during peak hour operations in the summer of 2010 were:

- The "Canal St" site (25th St and Canal St) in Milwaukee, WI, and
- The "De Pere" site, in De Pere, WI, at the east end of the Claude Allouez Bridge.

For the Canal St site, the single lane entry approach of southbound 25th St was studied during the PM peak hours. This analysis represented data from a single lane roundabout, although two conflicting lanes were present on the studied approach. The De Pere site represented a multilane roundabout, with each approach having two entering lanes conflicted by two circulating lanes. Studied approaches included the northbound Broadway St approach and the eastbound Main Ave approach from the Claude Allouez Bridge during AM and PM peak periods.

Field data was compared against default capacity models, as well as calibrated models based on the data collected. Some capacity models, like the United Kingdom (U.K.),

French, and German model, aggregate the capacity prediction for the entire approach, others aggregate capacity lane-by-lane, such as the NCHRP 572 (now implemented in the HCM 2010) model and SIDRA models. A summary of the models and software used is shown in Table 1. The exact capacity model for Girabase and SIDRA could not be obtained due to these models including proprietary parameters not published in research. Consequently, an adequate representation for the French model was not obtained. For the SIDRA model, an approximation was made by using equations from the Australian Road Research Board Report 321 (ARR 321). The current version of SIDRA has since expanded on ARR 321 with several functions, including an "environment factor" used for calibrating capacity to local conditions. Capacity graphs shown within this report using ARR 321 approximate using an uncalibrated environment factor of 1.0 in SIDRA

Table 1. Summary of Capacity Models and Software

<table>
<tr><th>Name</th><th>Software Used</th><th>Capacity Aggregation</th><th>Model Parameters</th><th>Calibration Needs</th></tr>
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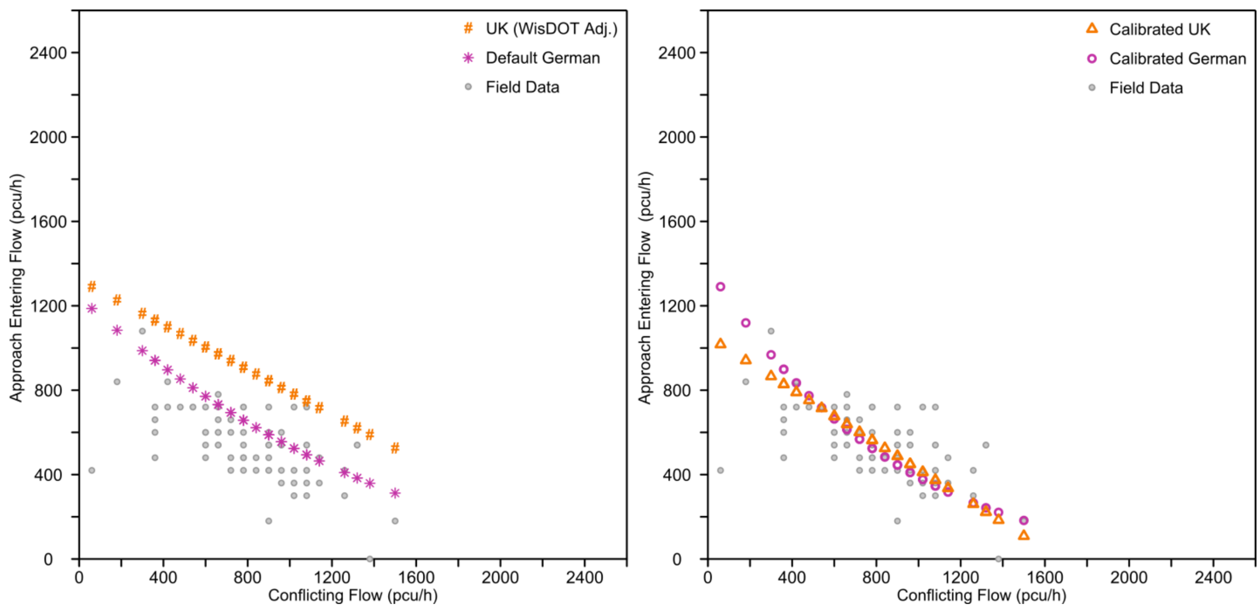
* For capacity graphing, ARR 321 was used to approximate the SIDRA Standard Model with an environment factor of 1.0

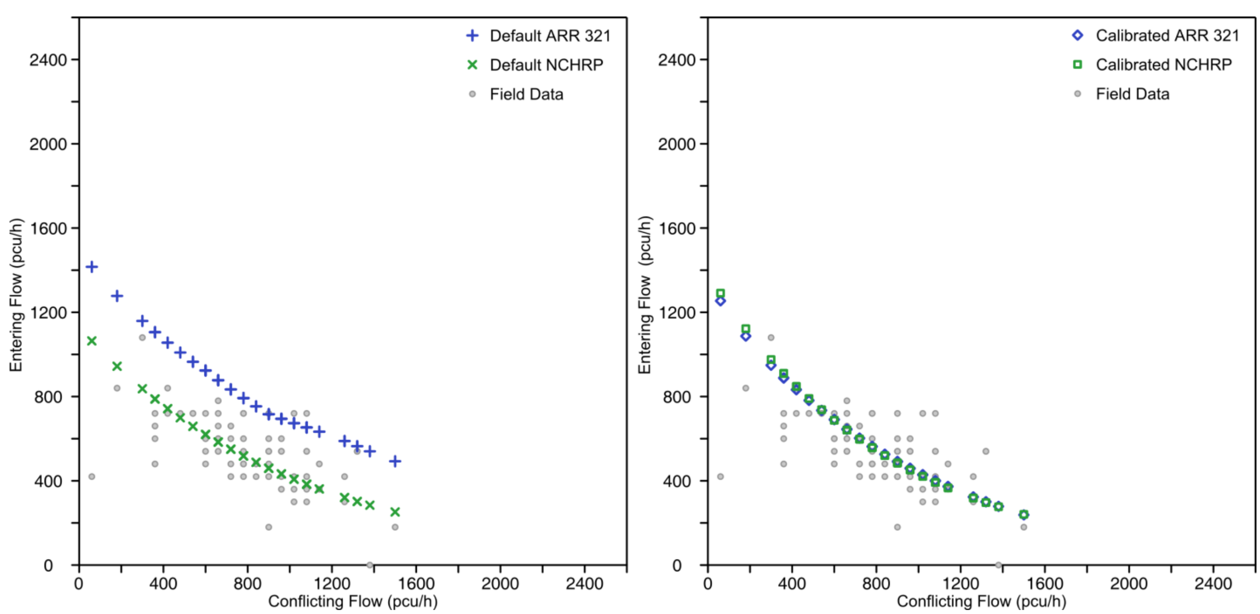
For the Canal St site, uncalibrated and calibrated approach based models can be seen in Figure 1, and lane based models can be seen in Figure 2. Notably, the default U.K. and ARR 321 models overpredict capacity, while the NCHRP model and German model provide a closer fit to the data. Calibration improved the fit for all models. Congestion was more sporadic at this location, limiting the total number, and magnitude, of capacity observations.



(a) Uncalibrated Approach Based Models

(b) Calibrated Approach Based Models

Figure 1. Canal St Approach Based Capacity Comparison

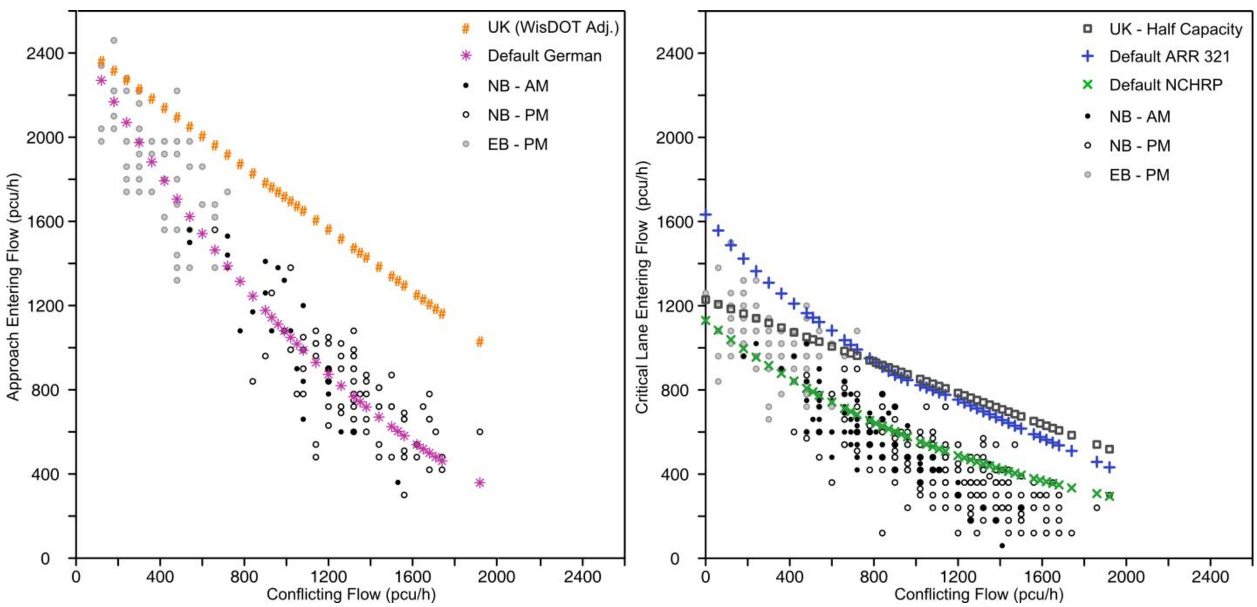


(a) Uncalibrated Lane Based Models

(b) Calibrated Lane Based Models

Figure 2. Canal St Lane Based Capacity Comparison

Field data from the De Pere site was analyzed from each approach separately, but the overall trends can be summarized if assumptions are made that data from all approaches, differing critical lanes, and time periods are combinable. Figure 3 shows the combined data only for uncalibrated scenarios. Calibration improved the fit for all models, just the same as the Canal St site analysis. In Figure 3, the U.K. model provided similar capacity predictions at low circulating flows, but quickly diverged to overpredict capacity at high circulating flows. Under high circulating flows, capacity prediction is increasingly important because delays and queues tend to be longer under these conditions. Default NCHRP 572 and German models provided a good fit throughout the range of capacity data. The ARR 321 model showed overprediction, but visually followed the same trend as the data. A "half-U.K." model is shown under the assumption that 50% of the approach capacity could be assigned to each lane, and shows a similar trend to the U.K. approach based scenario.

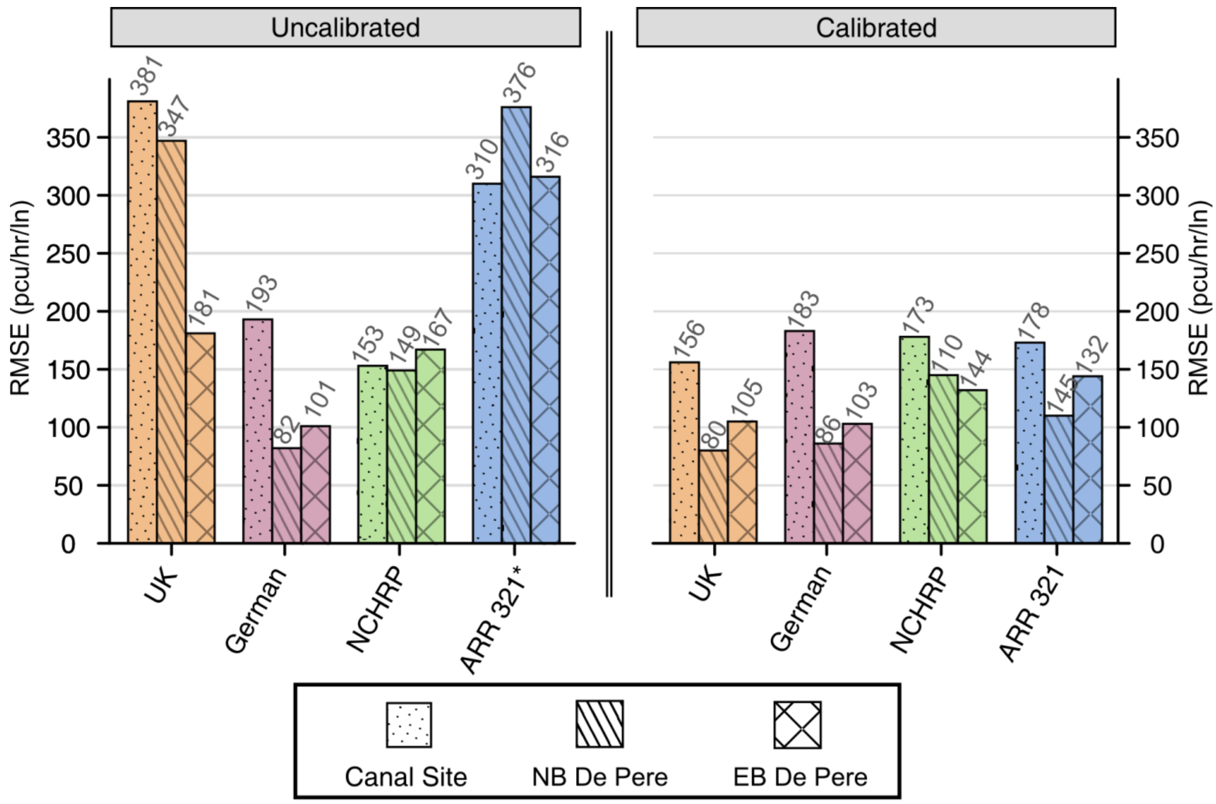


(a) Uncalibrated Approach Based Models

(b) Uncalibrated Lane Based Models

Figure 3. Combined De Pere Capacity Data Comparison

As a summary of the field data capacity analysis, root mean squared error (RMSE) values (pcu/h/ln) were computed on a per lane basis shown in Figure 4. These values represent the average difference between the model prediction and the observed field data. Importantly, calibration made differences between models indistinguishable, which showed that many models can be applied to a situation with careful consideration. Because of the intensive data needs for calibration, and the fact that calibration can only be performed on existing roundabouts, uncalibrated models play an important role in design and analysis. The error measurements showed the default German and NCHRP 572 models had lower error than either of the default U.K. or ARR 321 models which reflect higher average capacity observations in those countries. Consideration of slope and intercept adjustment for the U.K. model, or environment factors for SIDRA in uncalibrated situations would be advisable



* 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 4. Root Mean Square Error Summary

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 appear 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.

Ultimately, software is constantly evolving and this research has come at the beginning of understanding roundabouts in the U.S. The most widespread versions of the popular analysis packages were considered; 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 software package, and a variety of the most useful software tools that fulfill specific roles should be considered to achieve the best design. Usability can be difficult to compare because an analyst could become accustomed to any software with enough experience. However, taking the prospective 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, appeared to offer more frequent updates, support, and features although at a greater cost.

Certainly capacity is not the only criterion when considering a roundabout. Safety, speed, operating costs, environmental, and other benefits play an important role in considering a roundabout as a desired intersection type. Transportation engineers have the roundabout as an essential tool in a diverse set of intersection control types and experience in the U.S. is at the beginning of fully understanding roundabouts. In terms of technical accuracy, a software package that has the capability of performing capacity analysis using U.S. based models is desirable based upon the findings of this research. Beyond this scope, many other considerations, unique to each agency, are required in order to arrive at a recommendation for a software package. Issues include: how do advanced features fit into existing workflows (e.g. signal analysis, or integration with CAD design software), what are the relative benefits versus costs of each feature, and what are future needs and will the software be adaptive. Such concerns leave the ultimate conclusion open ended with the resulting evaluation matrix forming a guide to aid decision making. Capacity and other benefits may improve over time. Continuing research as traffic volumes and driving experience grow will be vital to the next evolution of roundabouts.

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Chapter 1 Introduction

Roundabouts have been used worldwide due to their contribution to safety and operational efficiency, as well as other side benefits. 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 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 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 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 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 U.K. capacity model for design and analysis. 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 to identify which analysis tools best fit their needs. In design, a desirable solution needs to balance constraints and should not be over or under designed. Inappropriate 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

The objective of this research 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 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.

The resulting evaluation matrix forms a guide for decision makers as to how to proceed in making any changes, if necessary, to the roundabout design workflow. Software changes quickly and as such, specific packages and the most widely used versions were identified at the beginning of the study in order to remain consistent and fair throughout the research.

1.3 Document Organization

This document 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.

Chapter 2 Literature Review

This literature review is divided into sections discussing capacity models as well as background for each software used in capacity modeling. 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, bicycles), proportions of turning vehicles, driver population characteristics, weather conditions, etc. 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 1. The general trend is that fewer vehicles can enter the roundabout as the number of circulating vehicles increases.

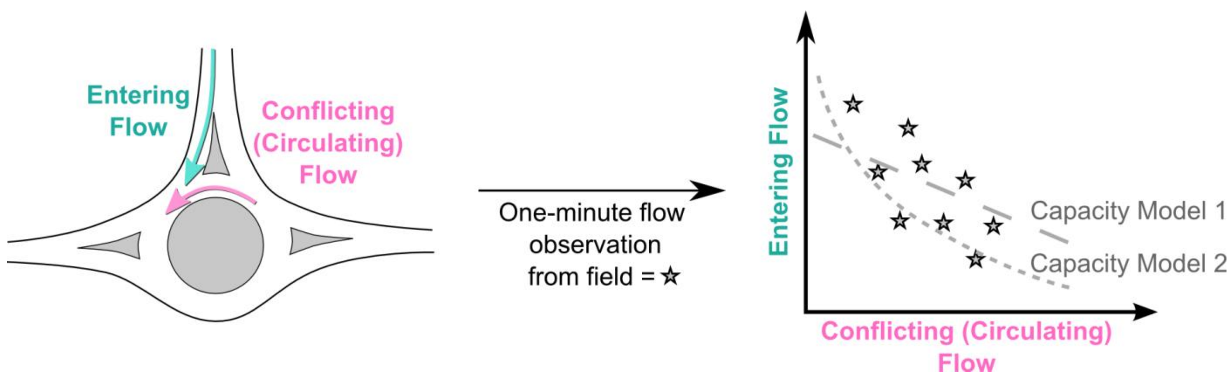

Figure 1. Example Entering-Circulating Capacity Graph Development

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.

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 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.

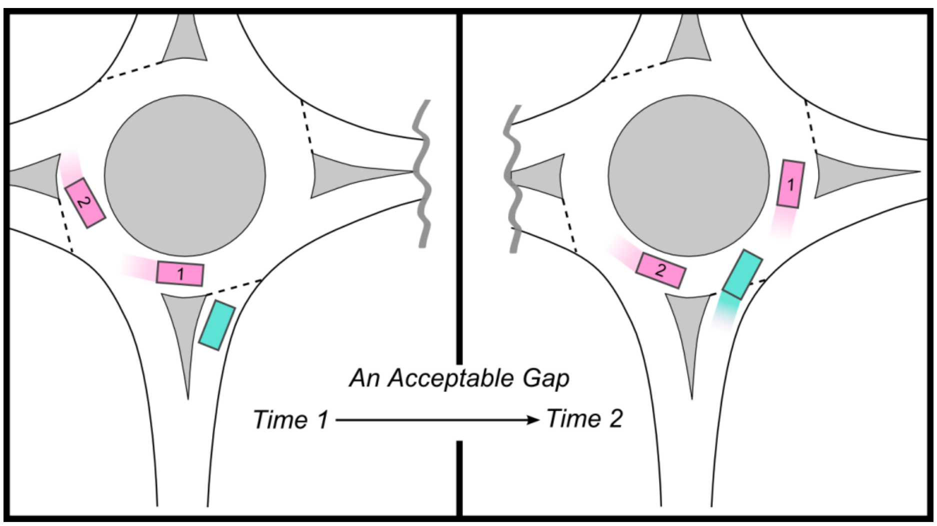

Figure 2. Critical Gap Depiction

Follow-up headway is the amount of time between entering vehicles that are utilizing the same gap in circulating traffic *(1)*. Figure 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.

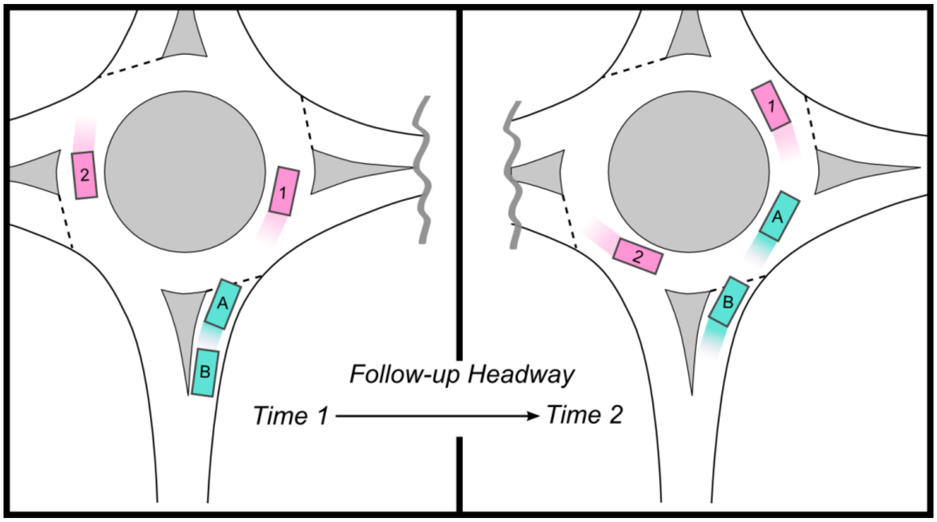

Figure 3. Follow-up Headway Depiction

In general, as critical gap decreases, capacity increases because drivers are taking less time to make their decision and enter the roundabout. The same is true for follow-up headway because more than one driver will use the same gap, which increases efficiency.

2.4 Capacity Models

Understanding and modeling roundabout capacity has been studied 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 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) *(3)*. 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 *(3)*. Essentially, this restriction is in the spirit of calibrating the model to what Wisconsin drivers are expected to use as effective entry width.

Table 1. Summary of Capacity Models

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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 *(9)* which has been applied to roundabout capacity models worldwide *(1-8)*. Much debate has occurred about the two primary techniques for developing capacity models: *gap acceptance* or *empirical regression* *(10-16)*, 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" *(10)*. 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 *(5, 10, 17)*, as well as France *(10)*, and the U.K. has changed through estimates based on weaving, gap acceptance, and linear regression *(12)*. Certainly roundabout capacity modeling has changed in the U.S. as well, from linear form *(18)*, to early gap acceptance techniques *(19)* which continue to be refined as more is learned in the U.S. *(2)*.

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 *(4)*:

- 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 4 *(3)*.

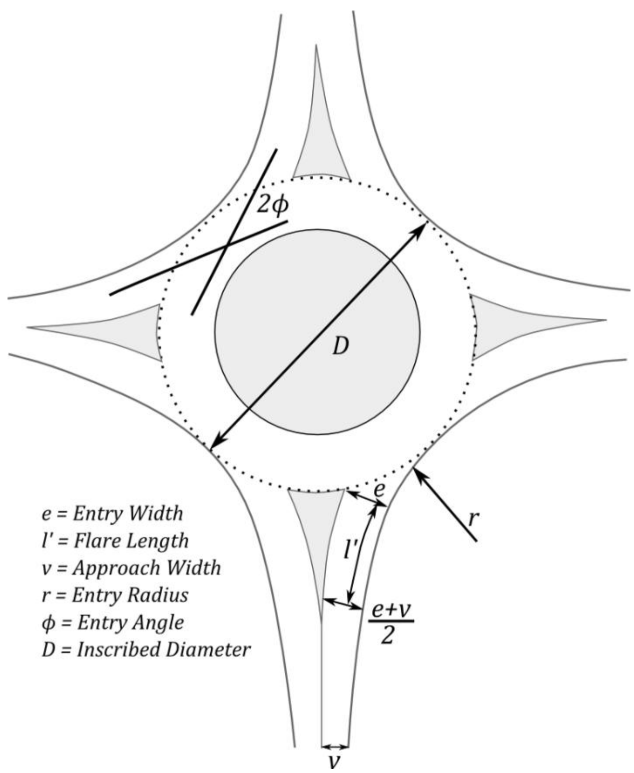


Figure 4. U.K. Model Geometric Parameters *(Based on WisDOT FDM 11-26-20 Attachment 20.1)*

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. 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. 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 *(*4*)*. During these periods, the amount of entering and circulating flow is gathered on a minute-by-minute basis. Then only the intercept of the linear capacity equation is adjusted proportionately to the average entering and circulating flow observations.

2.4.2 German Model

The model presented in the German Highway Capacity Manual (HBS 2001) was used for this research *(*5*,* 6*)*. 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 is specifically identified, but this research used critical gap and follow-up headway values derived from the study sites 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 *(11)*.

2.4.3 French Model

Original research from France obtained for this study was only published in the French language *(7)*, which presented some difficulties. Other literature *(11,21)* 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 *(22)*. Additionally, the model is sensitive to the environment: urban, rural, or suburban, based on the inputs of Girabase. 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)*. 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 *(23)*. 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

$$c = 1130e^{-1.0 \cdot 10^{-3} q_c}$$

for the critical lane of a multilane roundabout

$$c = 1130e^{-0.7 \cdot 10^{-3} q_c}$$

where

$$c = \text{lane capacity (pcu/h)}$$
$$q_c = \text{circulating flow (pcu/h)}$$

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:

$$c_R = 1130e^{-0.7 \cdot 10^{-3} q_c}$$
$$c_L = 1130e^{-0.75 \cdot 10^{-3} q_c}$$

where

$$c_R = \text{capacity for the right entry lane (pcu/h)}$$
$$c_L = \text{capacity for the left entry lane (pcu/h)}$$

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

$$c = \text{capacity for an entry lane (pcu/h)}$$
$$A = \frac{3600}{t_f}$$
$$B = \frac{\left(t_c - \frac{t_f}{2}\right)}{3600}$$

q_c = conflicting flow (pcu/h)
t_f = follow-up headway (s)
t_c = critical gap (s)

Calibrating the A and B terms results in changing either or both the intercept and shape, or slope, of the capacity function as seen in the three cases demonstrated in Figure 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*.

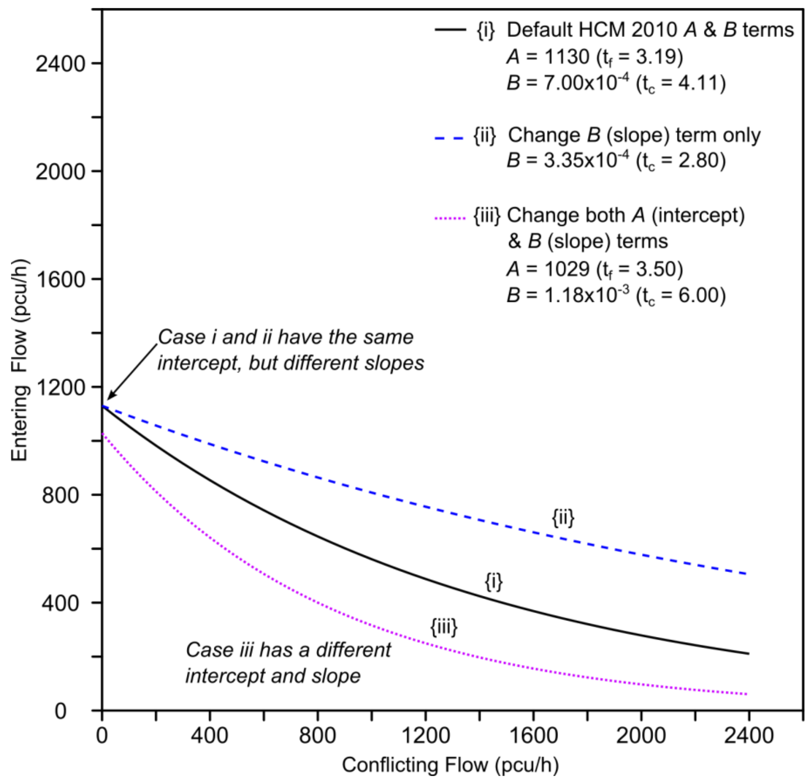


Figure 5. Effects of Calibration Parameters for the HCM 2010 Capacity Equations

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 *(*8*)*.

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

$$Q_m = \min[q_e, 60n_m]$$

$$Q_g = \frac{3600}{\beta}\left(1 - \Delta_c \frac{q_c}{3600} + 0.5\beta\varphi_c \frac{q_c}{3600}\right) e^{-\lambda(\alpha-\Delta_c)}$$

$$f_{od} = 1 - f_{qc}(p_{qd}p_{cd})$$

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 (≈ 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:

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

for the O-D adjustment calibration parameter:

with a single-lane circulating flow

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

with a multi-lane circulating flow

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

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

for the dominant lane, follow-up headway

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

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 flow (s)
β'_d	=	unadjusted dominant lane follow-up headway (s)
	=	$\beta'_o - 3.94 \cdot 10^{-4} q_c$ 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)
	=	$3.37 - 0.0208D_i + 0.889 \cdot 10^{-4} D_i^2 - 0.395n_e + 0.388n_c$ 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

$$\beta_s = 2.149 + (0.5135\beta_d - 0.8735)r_{ds}$$
$$subject\ to\ \beta_d \leq \beta_s \leq \beta_{max}$$

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

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

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

where

α	=	dominant or subdominant lane critical gap, α_d or α_s respectively (s)
β	=	dominant or subdominant lane follow-up β_d or β_s (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 *(24)*:

- 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 from ARR 321 to be notably different 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 *(24)*. Even though the exact capacity function for SIDRA could not be obtained, Figure 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.

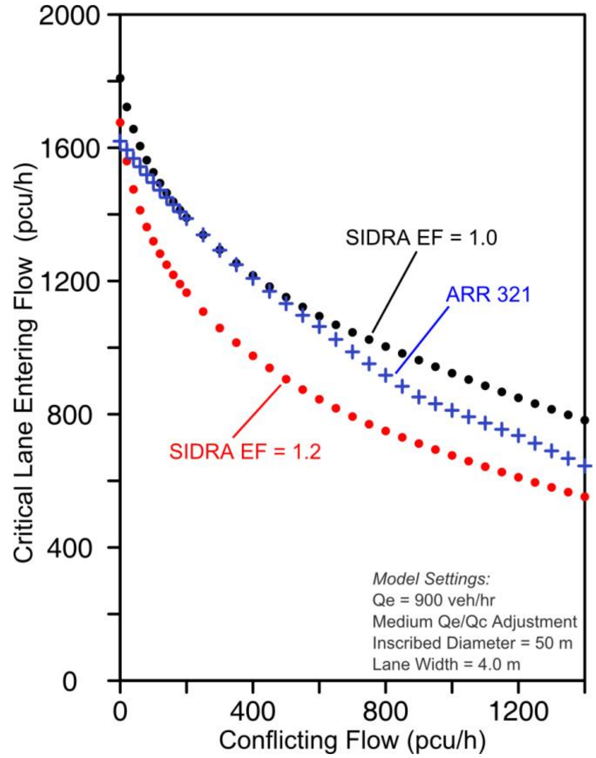


Figure 6. Comparison of SIDRA Capacity with Environment Factors and the ARR 321 Method
(Adapted from the SIDRA User Guide, Figure 19.4.2)

2.4.6 Summary and Notes on Capacity Model Parameters

Table 2 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 which has been omitted from the table. Parameters listed in Table 2 are not necessarily the same as what a user would need to enter in a software package implementing the models. Some parameters are automatically calculated from broader inputs, like traffic volumes, or have default values that only need to be changed for calibration purposes. Section 6.6.1 discusses actual software inputs for implementing each model.

Table 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 *(25, 26)*. 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 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 *(25)*.

Three single lane entry sites in Indiana were analyzed in terms of capacity in the second study. In summary, the analysis found considerably lower gap acceptance values from the default single-lane HCM 2010 values, resulting in the HCM model to underpredict capacity. Lower critical gap and follow-up headway were suggested to be a result from potential driver familiarity *(26)*.

2.6 Software Background

Other transportation software comparison studies have been completed *(27-31)*, 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 *(30)*. For roundabout analysis, this research is timely as other agencies have been investigating the various models and software packages available *(31)*.

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 *(32, 33)*. Many state DOTs, including Wisconsin, currently uses this program as the standard for roundabout analysis as outlined in the FDM *(3)*. 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) is also based on 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 *(34)*.

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 *(35)*.

Kreisel: Many capacity models 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 *(36)*.

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) *(37)*. 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 *(38, 24)*. 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.

Chapter 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 7 shows a high level overview of the methodology used for the evaluation, with each of the seven milestone steps further described in this section. Steps 2 and 3 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.

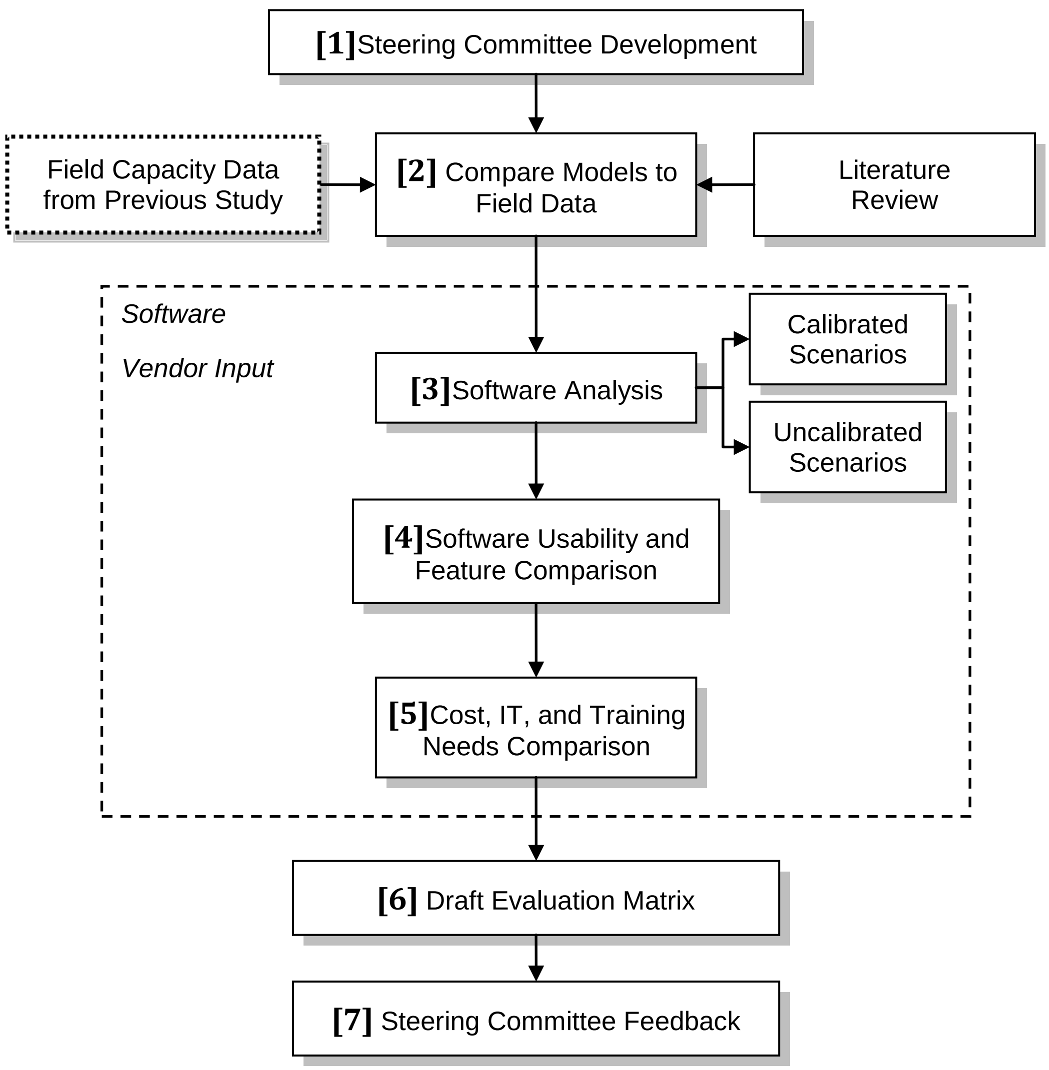


Figure 7. Software Evaluation Project Methodology

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. Meetings were held at intermediate milestones to discuss preliminary results and identify future investigations.

Table 3. 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 model. Graphing entering flow versus circulating flow allowed root-mean-square error (RMSE) computations to give a quantitative estimate for comparing the accuracy of each model. Section 5.4.2 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 comparison performed in *Step 2*. 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.

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.

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.

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

Chapter 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 *(39)*. 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 8. Within each site, the local street names will be used to reference each approach.

Figure 8. Study Locations

4.2 Canal St Site

Located in Milwaukee, WI the Canal St roundabout is in an urban, industrialized location. Figure 9 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. 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.

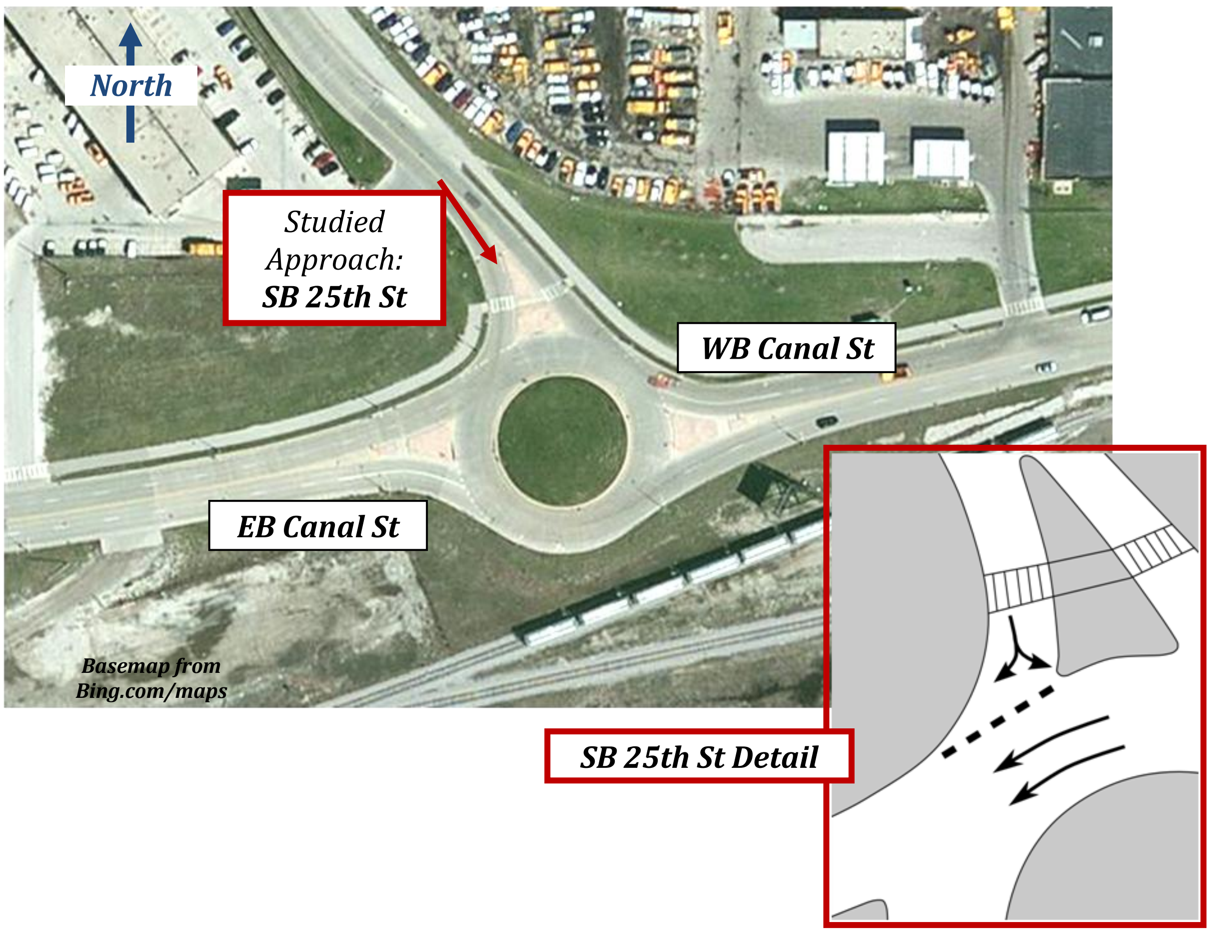


Figure 9. Canal St Site Configuration

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. 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 10. Studied approaches included northbound Broadway St and eastbound Main Ave (from the bridge). Complete intersection geometry details are presented in Section 5.3.

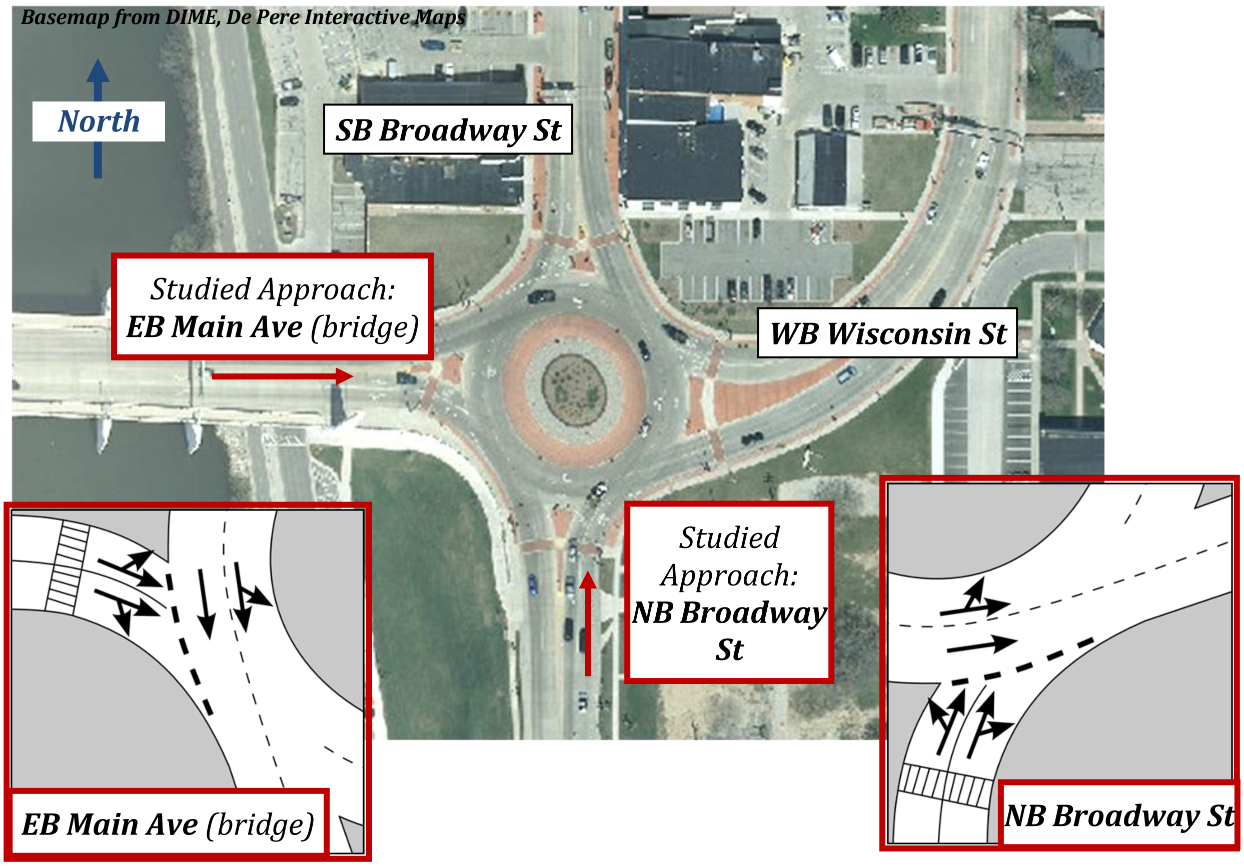


Figure 10. De Pere Site Configuration

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 operation typical of a weekday peak period.

At the chosen sites, only the approaches with the most queuing were further analyzed. Field operational data was obtained by means of video recordings. High definition cameras were set up to observe the studied approach and corresponding exit of the major movement. A Miovision™ proprietary 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. Videos from each camera were combined in post-processing to obtain a single synchronized video for data reduction as shown in Figure 11.

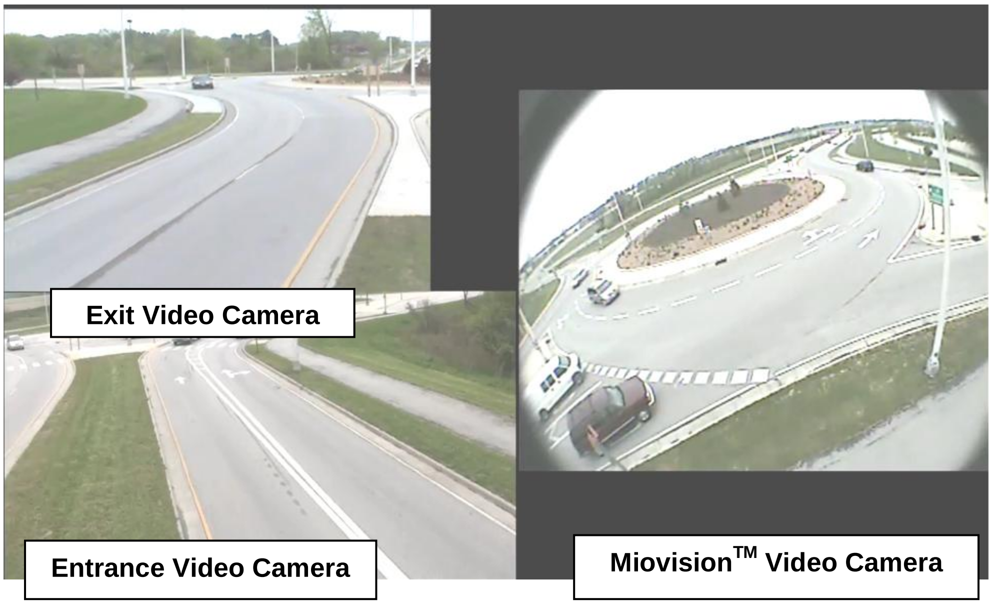


Figure 11. Sample Synchronized Video Screenshot used for Data Reduction

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.

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 *(40)*. Essentially, the software allows the user to manually record timestamps that correspond to specific events for each vehicle, such as time entering the roundabout, time conflicting with the subject approach, or time of exit. 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. Additionally, turning movement counts were obtained by means of the Miovision™ data reduction service.

Chapter 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.

Table 4 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:

1. A data set for whenever the left lane was queued (queuing may or may not have been present in the right lane);
2. A data set for whenever the right lane was queued (queuing may or may not have been present in the left lane); and
3. 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 Site. Especially the northbound Broadway approach with queues in the left lane for almost the entire study period.

Data collection for an AM peak period was only available for the De Pere site and is shown in Table 5. No queuing was observed on the eastbound (bridge) Main Ave approach. 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 B. An exploration of combining AM and PM peak data is presented in Section 5.5.2.

Table 4. Summary of Observed PM Peak Minutes of Queuing

Studied Approach	PM Peak Number of One-Minute Queuing Intervals
Canal St Site ***Thursday April 15, 2010*** *Between 1:30 pm to 6:00 pm*	
SB 25th St	71
[Out of approx. 250 min]	
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. Summary of Observed AM Peak Minutes of Queuing

Studied Approach	AM Peak 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 by means of the Miovision™ data reduction.

Figure 12 shows the resulting 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.

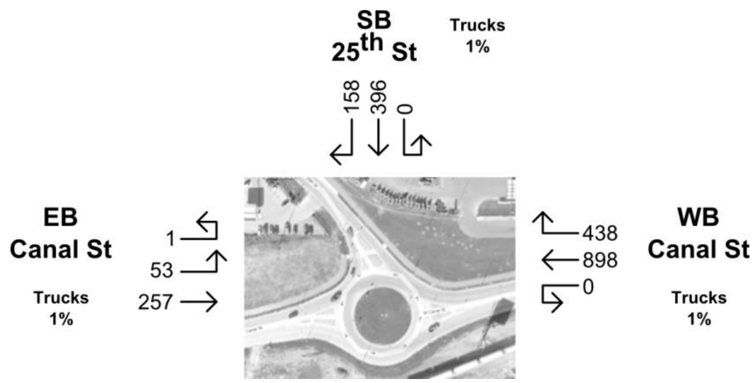


Figure 12. Canal St Site Peak Hour Volumes

Figure 13 shows the resulting 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.

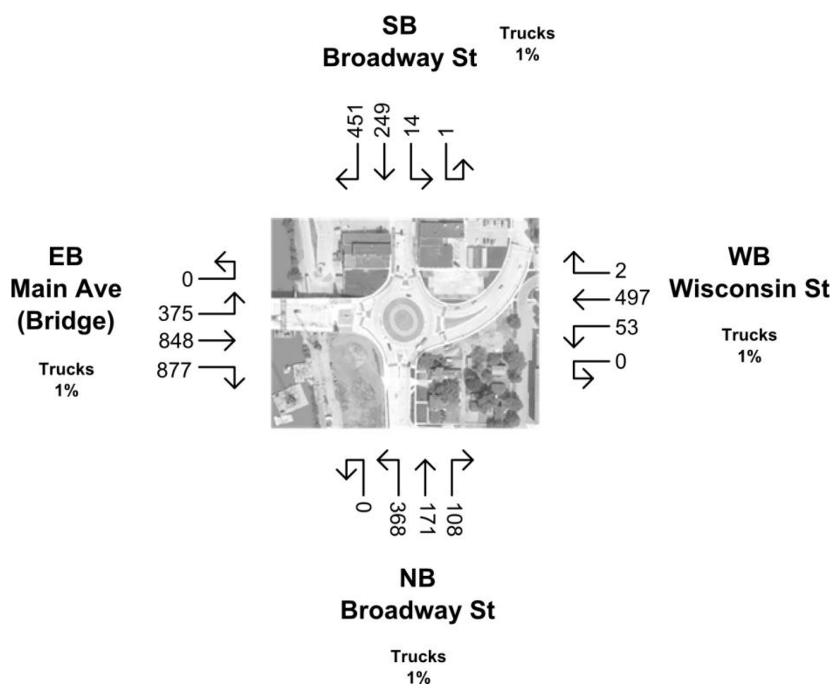


Figure 13. De Pere Site Peak Hour Volumes

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 6 and Table 7 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 6. 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 7. 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 *(26)*.

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 *(25)*.

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 8 for the Canal St site and Table 9 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 8. Canal St Site Geometry and Characteristics

	Approach		
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 9. 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. Three other important items related to the capacity spreadsheet analysis are:

1. A spreadsheet could not be adequately developed for the French model to replicate results compatible with the Girabase software and have therefore been omitted from all applicable capacity graphs.

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.

5.4.1 Calibration

Models were consequently calibrated based on the collected gap acceptance and entering-circulating field data. Gap acceptance models including the German, NCHRP, and ARR 321 methods were calibrated by adjusting only the critical gap and follow-up headway values to match the field data. While SIDRA can be calibrated by gap acceptance values or through an environment factor parameter, ARR 321 does not use this parameter and approximations were not made to establish a calibrated environment factor for SIDRA. Calibration of the linear U.K. model followed the procedure where only the intercept was changed based on entering-circulating field data *(4)*. As a starting point for calibration, field measured geometry was used to remain independent of any ‘WisDOT adjusted’ parameters not specified in the original 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 values of RMSE per lane. Formulaically, RMSE was determined by:

$$RMSE = \frac{\sqrt{(model\,prediction\; - field\;observation)^2/n}}{number\;of\;lanes}$$

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

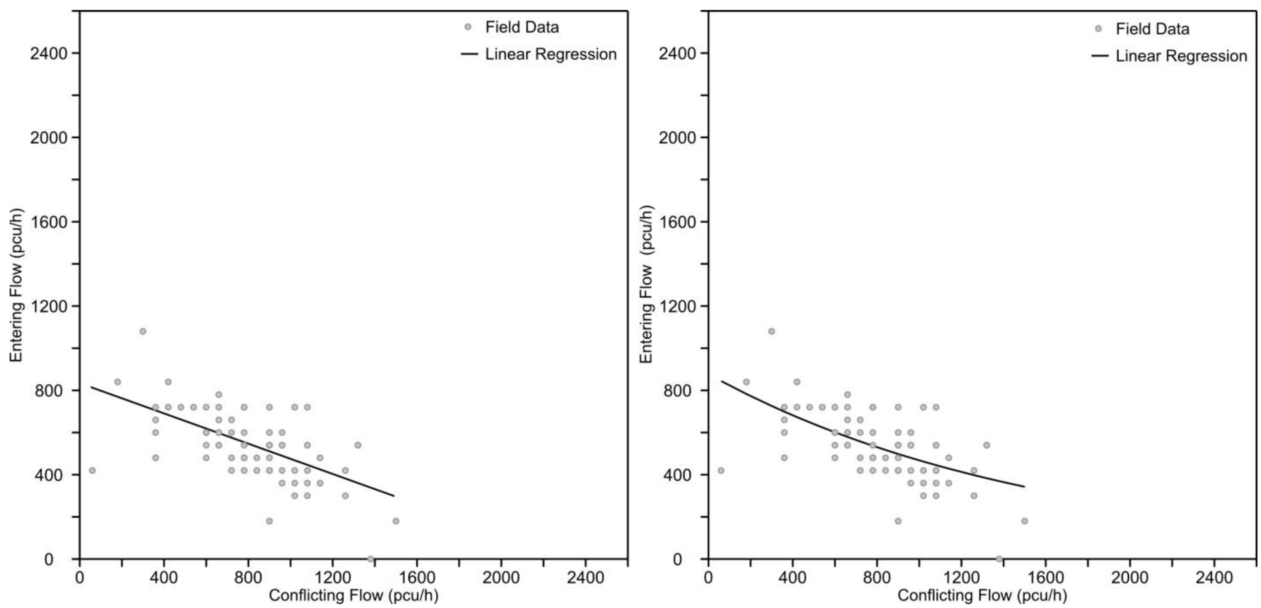
Lower errors indicate a better fit of the model to the data. There is no rule about what a "good" RMSE value is, goodness depends on how precise the model needs to be. Typically, a model with lower RMSE is chosen as the best model, but understanding why the model shows a fits to the data and any underlying 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

The general trend for capacity models is that capacity decreases with increasing conflicting flow. Linear models use a slope and intercept to describe the maximum capacity and rate of decrease toward minimum capacity. 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 Figure 14 and Table 10.



(a)
Field Data with Linear Regression

(b)
Field Data with Exponential Regression

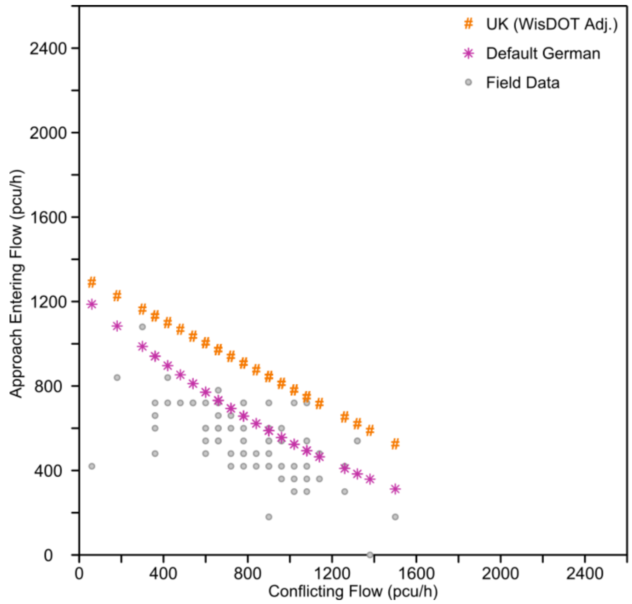
Figure 14. Canal St Field Capacity Data

Table 10. Canal St Field Data Regression Results

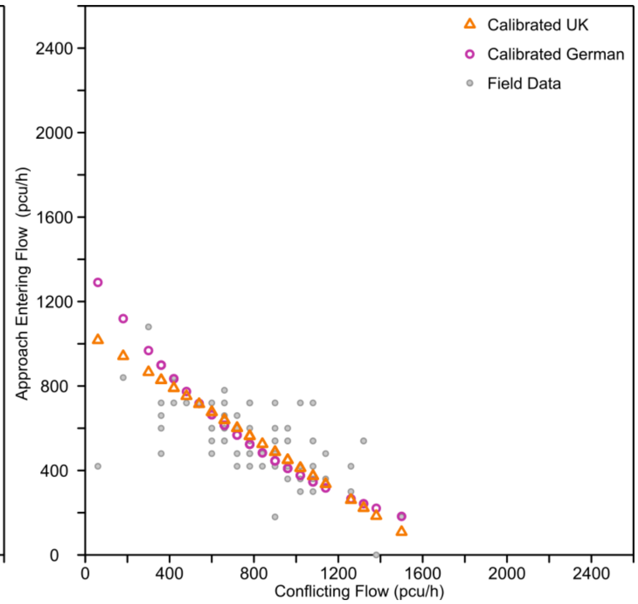
Regression	Intercept (pcu/h)	Slope	n	R^2	RMSE (pcu/h/ln)
Linear	829	0.359	71	0.367	67
Exponential	869	6.35×10^{-4}	71	0.314	69

Figure 15 and Table 11 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.

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



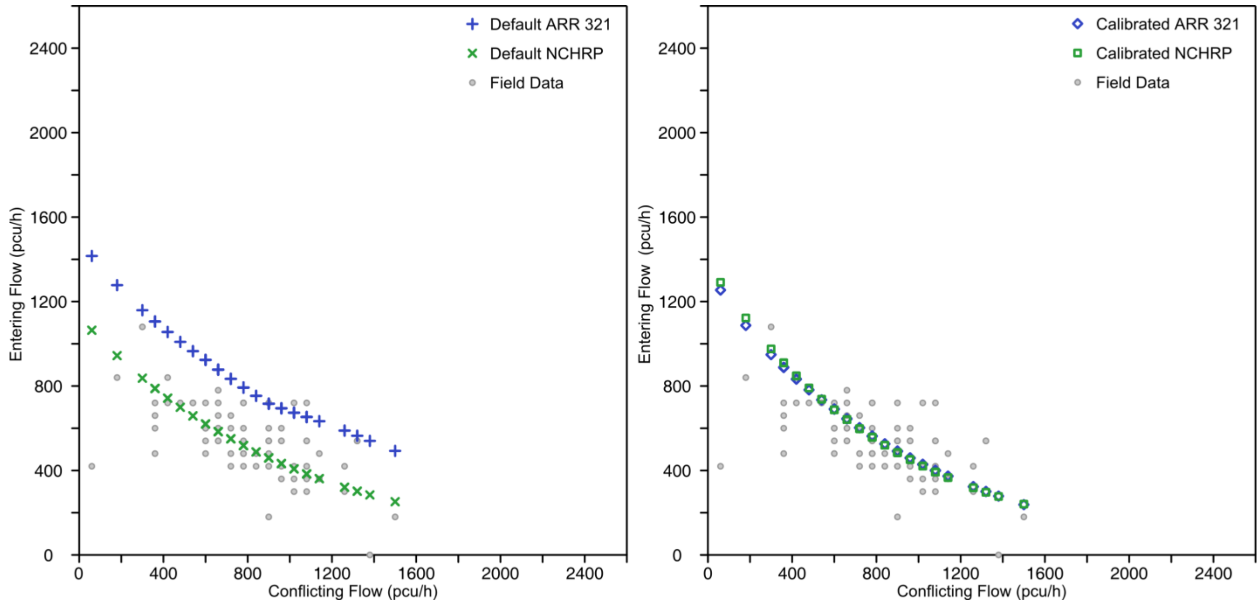
(b)
Calibrated Approach Based Models

Figure 15. Canal St Approach Based Capacity Comparison

Table 11. 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

Lane based models for the Canal St site are shown in Figure 16 and Table 12. 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.



(a) Uncalibrated Lane Based Models

(b) Calibrated Lane Based Models

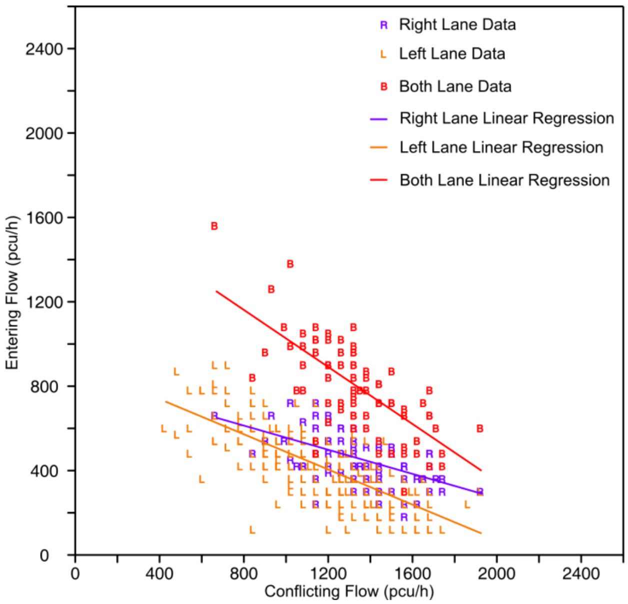
Figure 16. Canal St Lane Based Capacity Comparison

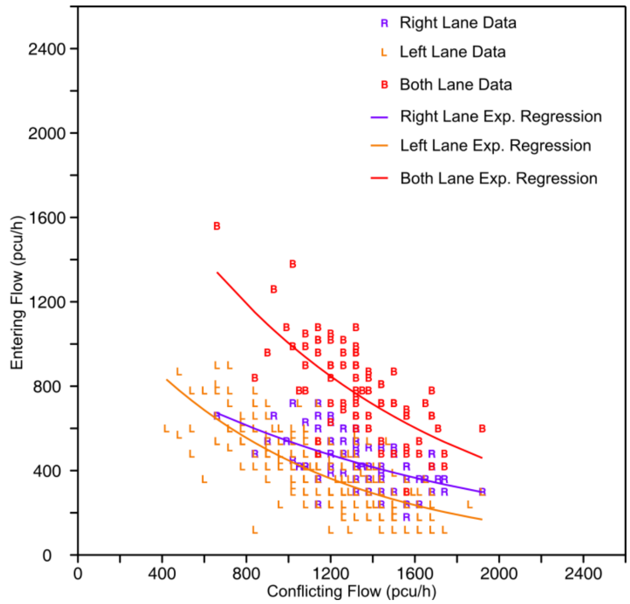
Table 12. RMSE and Model Characteristics from the Canal St Lane Based Analysis

	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

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 B. 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 17 and Table 13 show the field capacity data along with linear and exponential regressions of the data. Caution should be exercised when considering the intercepts of the regressions because no data was observed for low circulating flows indicative of the actual intercept.





(a) Field Data with Linear Regression

(b) Field Data with Exponential Regression

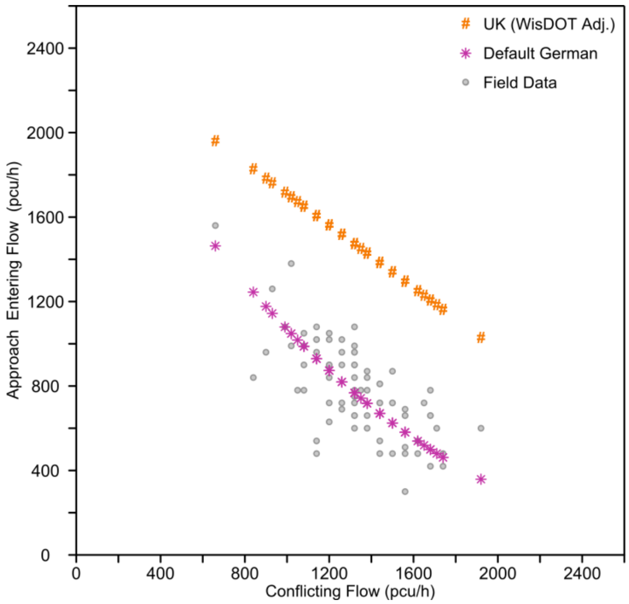
Figure 17. De Pere Northbound PM Field Capacity Data

Table 13. De Pere Northbound PM Field Data Regression Results

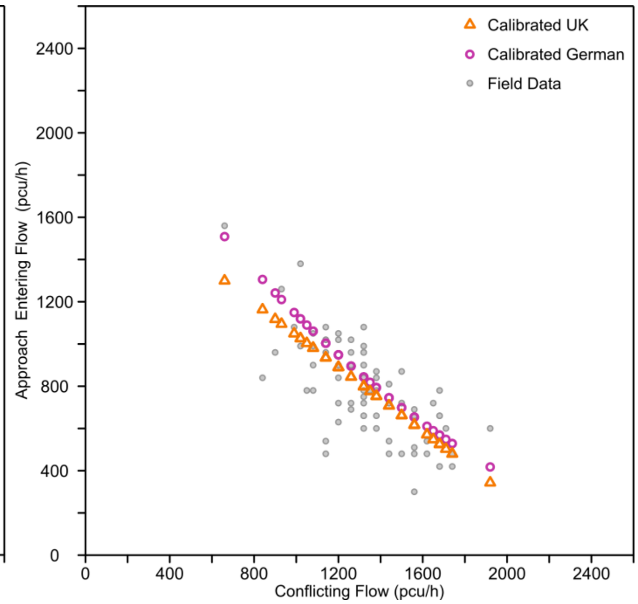
Lane	Regression	Intercept (pcu/h)	Slope	n	R^2	RMSE (pcu/h/ln)
Right	Linear	832	0.286	77	0.306	100
	Exponential	1031	6.47×10^{-4}	77	0.281	101
Left	Linear	895	0.471	268	0.530	109
	Exponential	1303	1.07×10^{-3}	268	0.475	111
Approach (Both Lanes)	Linear	1689	0.676	76	0.494	80
	Exponential	2349	8.50×10^{-4}	76	0.454	79

Approach models for northbound Broadway St are shown in Figure 18. Model error and characteristics and are shown in Table 14. 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.

A possible explanation for the overprediction in the U.K. model is that, under high circulating flows, the model reflects aggressive driver characteristics that contribute to capacity which were not observed during this research. Another possible explanation for the overprediction is that most of the traffic utilized the left lane, leaving the right lane underutilized. 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.



(a)
Field Data with Linear Regression



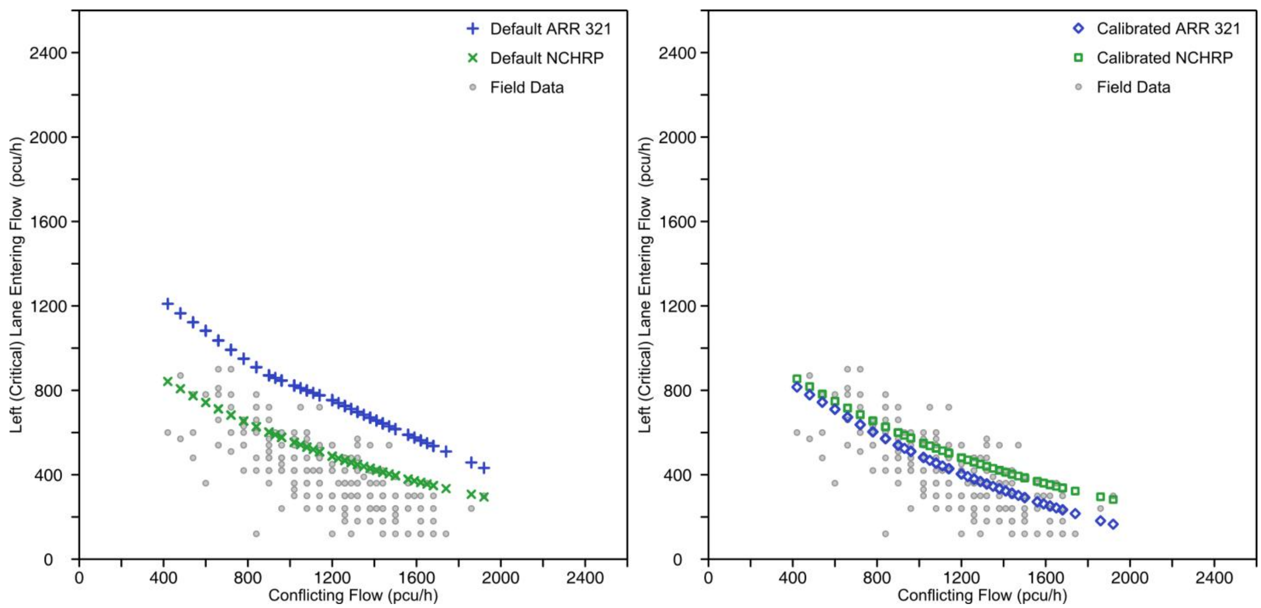
(b)
Field Data with Exponential Regression

Figure 18. De Pere Northbound Approach Based Capacity Comparison

Table 14. RMSE and Model Characteristics from the De Pere NB 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	76	347	1801	0.759	76	80
German	2483	$1.53{\times}10^{-4}$	76	82	2400	$5.56{\times}10^{-5}$	76	86

Figure 19 and Table 15 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.



(a)
Uncalibrated Lane Based Models

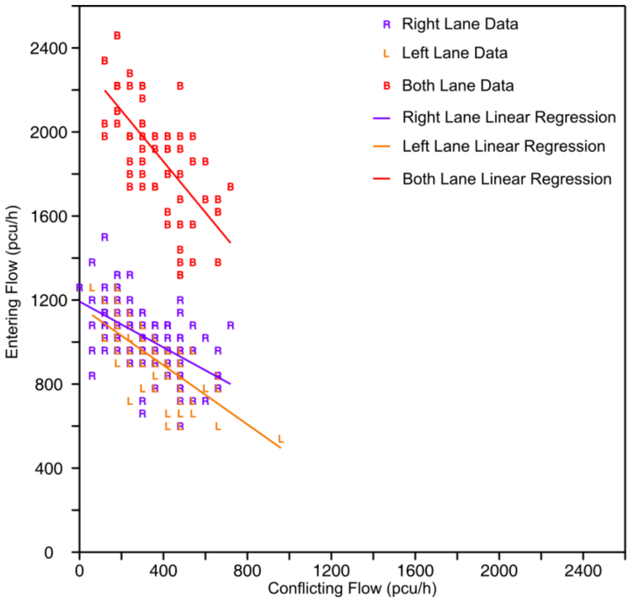
(b)
Calibrated Lane Based Models

Figure 19. De Pere Northbound Lane Based Capacity Comparison

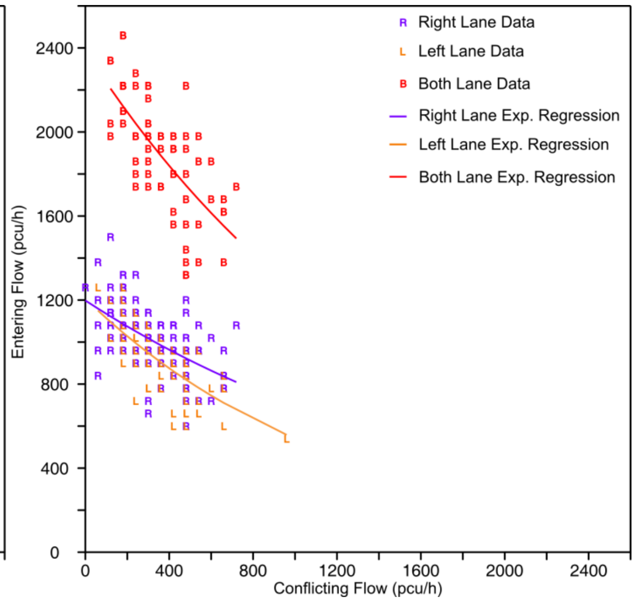
Table 15. RMSE and Model Characteristics from the De Pere NB Lane Based Analysis

	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

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 20 and Table 16 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.



(a)
Field Data with Linear Regression



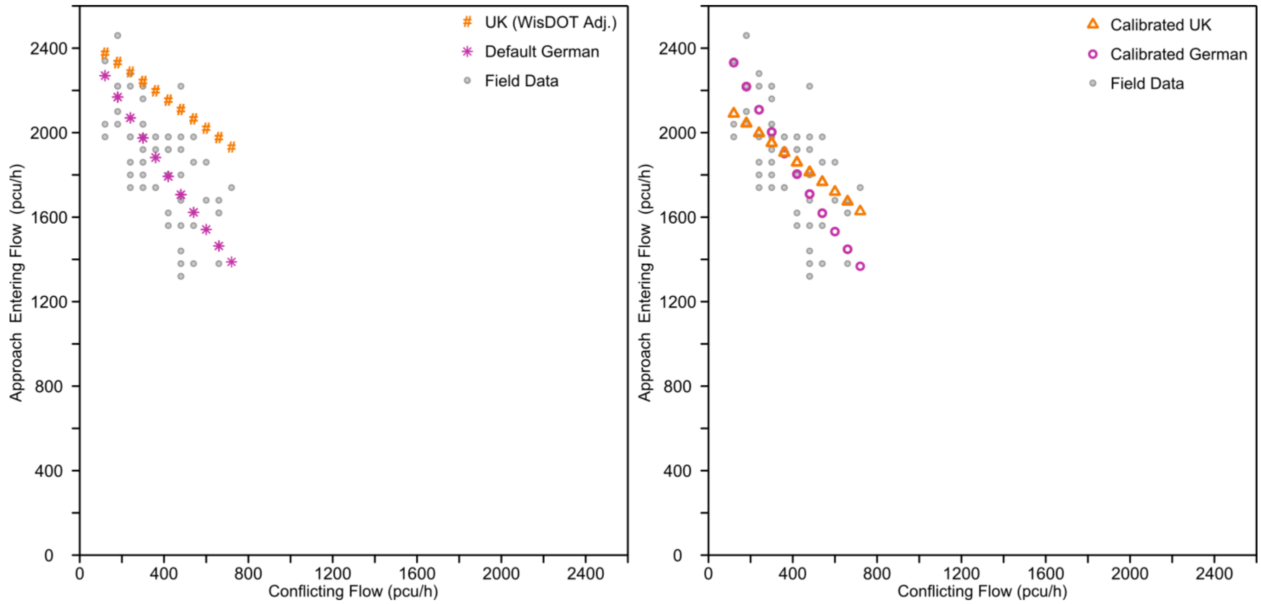
(b)
Field Data with Exponential Regression

Figure 20. De Pere Eastbound PM Field Capacity Data

Table 16. 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

Figure 21 and Table 17 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.



(a)
Uncalibrated Approach Based Models

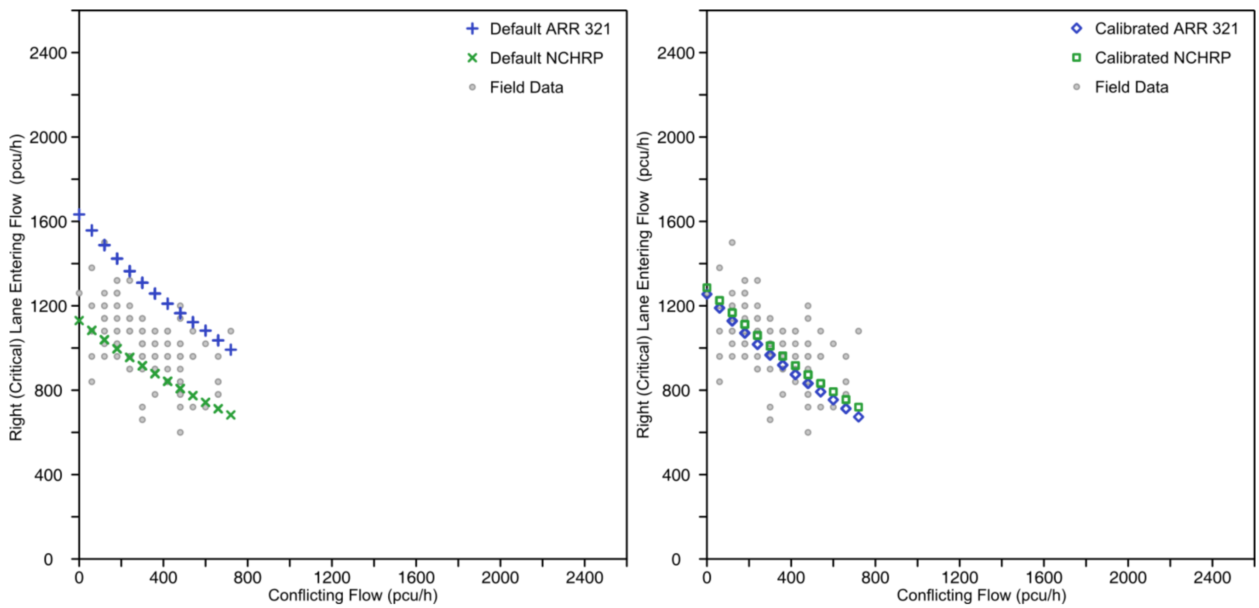
(b)
Calibrated Approach Based Models

Figure 21. De Pere Eastbound Approach Based Capacity Comparison

Table 17. 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	0.740	66	181	2182	0.771	66	105
German	2483	1.53×10^{-4}	66	101	2571	2.22×10^{-4}	66	103

Lane based model results for the eastbound approach are presented in Figure 22 with error and model characteristics in Table 18. 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.



(a) Uncalibrated Lane Based Models

(b) Calibrated Lane Based Models

Figure 22. De Pere Eastbound Lane Based Capacity Comparison

Table 18. 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

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 23. 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 it 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 be over-represent error from SIDRA. 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.

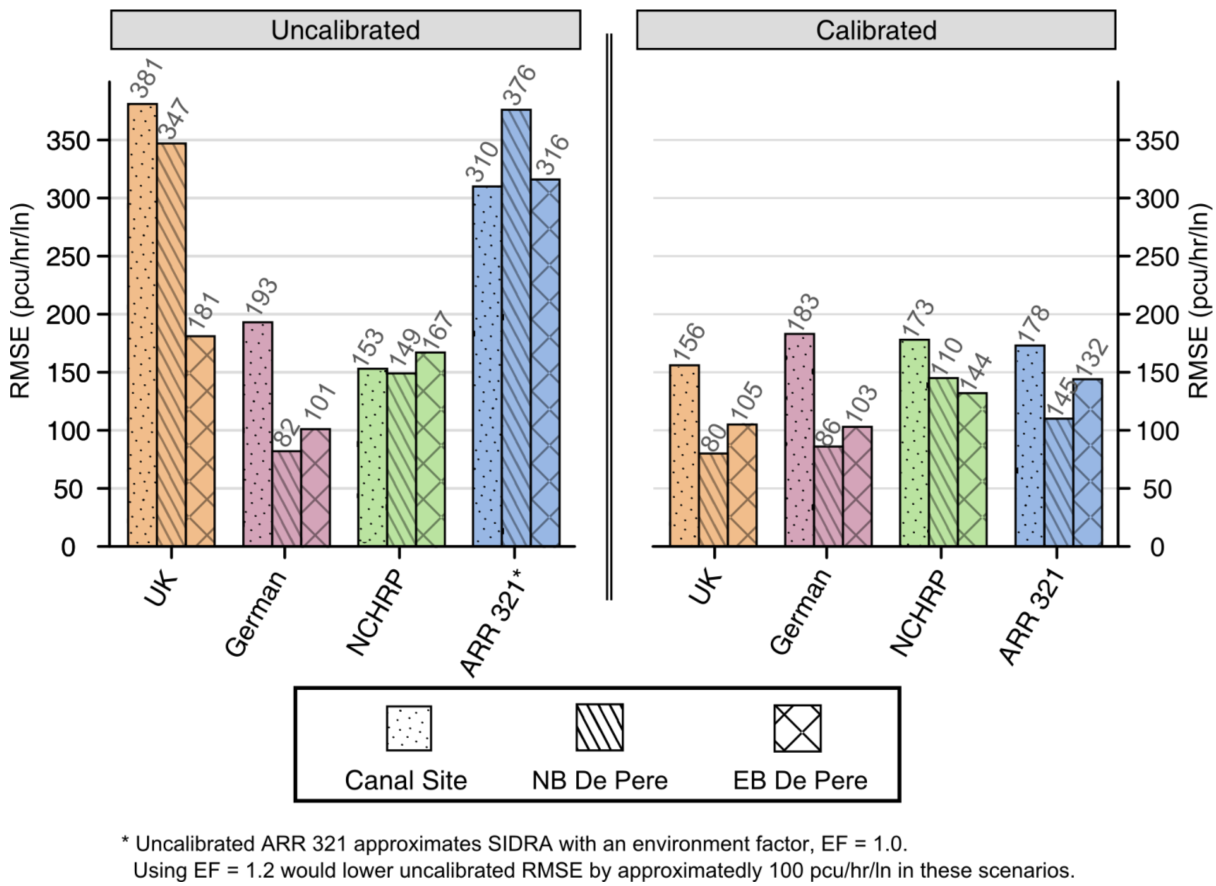


Figure 23. Root Mean Square Error Summary

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.

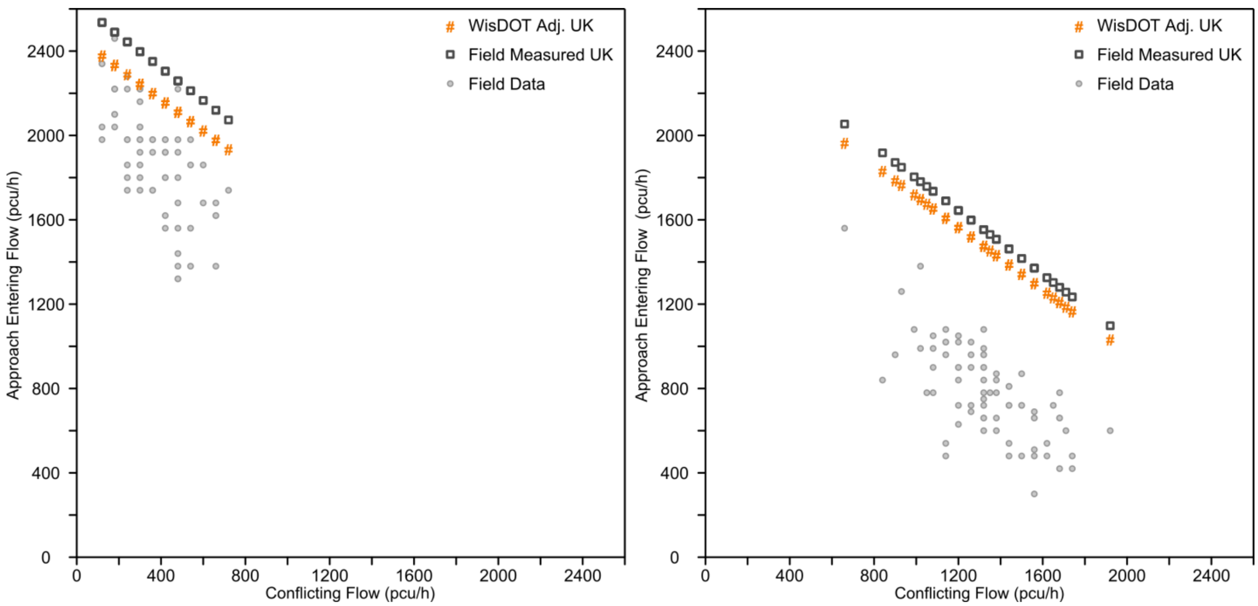
5.5 Capacity Modeling Extensions

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. Further, each geometric parameter is treated as a continuous variable allowing for minute changes to affect capacity. Figure 24 and Figure

25 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 19 and Table 20 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 24. U.K. Model Effective Geometry Comparison from the De Pere Site

Table 19. 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

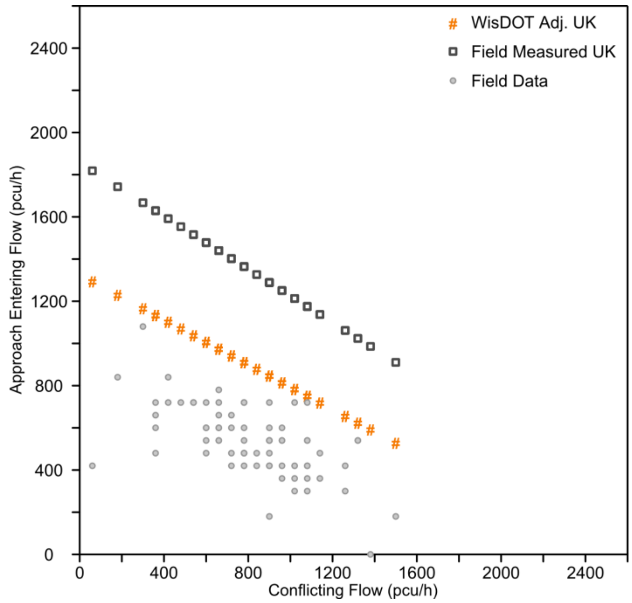


Figure 25. U.K. Model Effective Geometry Comparison from the Canal St Site

Table 20. RMSE and Model Characteristics from the Canal St Effective Geometry Comparison

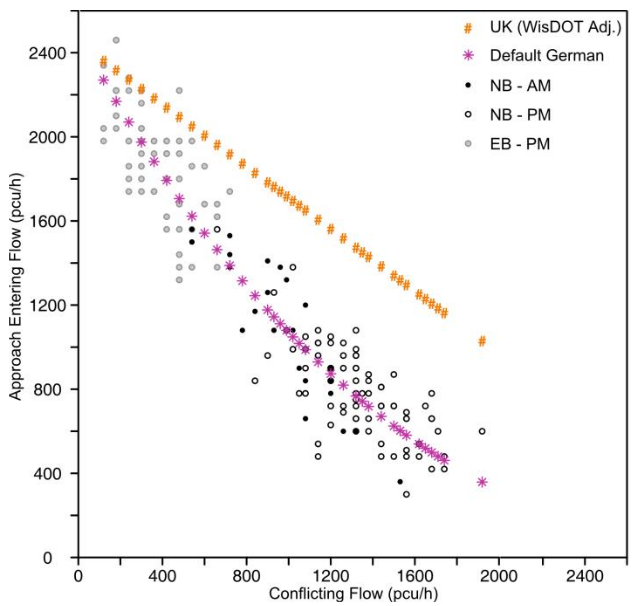
Model	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)
WisDOT Adj. U.K.	1323	0.532	71	381
Field Measured U.K.	1856	0.631	71	821
Calibrated U.K. (not depicted)	1055	0.631	71	156

5.5.2 Combined De Pere Eastbound and Northbound Data Analysis

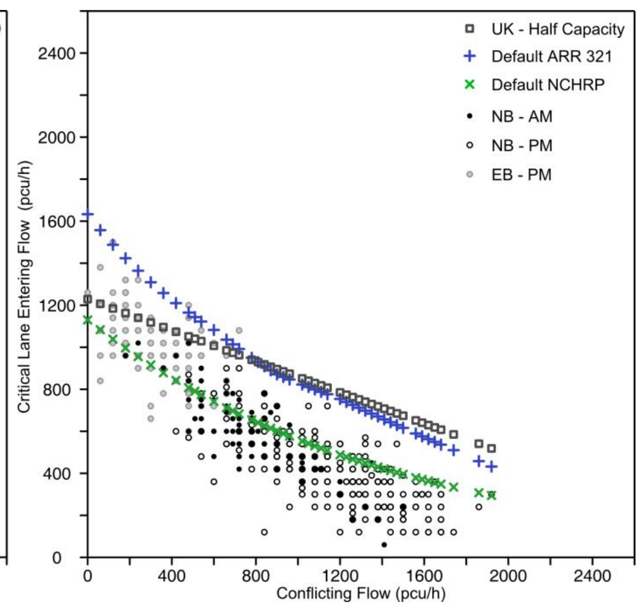
Both studied approaches from the De Pere site had similar geometric parameters for the U.K. model and therefore would have a similar capacities based on the model assumptions. The following assumptions were made when combining the data:

- 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 26, 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 26 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 26. Combined De Pere Capacity Data Comparison

Table 21 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 22 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 21. Model Characteristics from the Combined De Pere Capacity Data Comparison

Approach Based					Critical Lane Based				
Model	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)	Model	Intercept (pcu/h)	Slope	n	RMSE (pcu/h/ln)
U.K.	2458	0.740	166	292	U.K. - Half Cap.	1229	0.740	477	348
German	2483	1.53×10^{-4}	166	90	NCHRP	1130	7.00×10^{-4}	477	151
					ARR 321	1633	N/A	477	362

Table 22. 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.

Chapter 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.

Calibrated scenarios then expanded upon the default scenario by making the same model adjustments performed in the spreadsheet analysis 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.

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.

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. A full list of differences is presented with the software output from all approaches in Appendix C.

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 23. 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 23. 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 7.0	547	1.08	227	F	49
GIRABASE 4.0	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 about 15 to 20 seconds of delay, 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 24. 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 24. 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 7.0	—	—	—	—	—
GIRABASE 4.0	—	—	—	—	—
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 25. 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 25. 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 7.0	1897	1.15	530	F	167
GIRABASE 4.0	2609	0.84	2	A	0 to 2*
HCS 2010 6.1	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 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 26. 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 26. 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 7.0	—	—	—	—	—
GIRABASE 4.0	—	—	—	—	—
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 27 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 27. 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 7.0	772	0.87	32	D	16*
GIRABASE 4.0	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 28 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 28. 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 7.0	—	—	—	—	—
GIRABASE 4.0	—	—	—	—	—
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 29. Table 30 shows the resulting comparisons.

Table 29 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 30. 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 7.0	-	German HBS 2001 Model ◕	German HBS 2001 Model *KREISEL did not feature capacity calibration for the HBS 2001 Model
GIRABASE 4.0	-	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 study 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 number of observations from the northbound Broadway St approach alone was about two-thirds the size of the entire multi-lane data set in the NCHRP 572 research. 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 in terms of input and output. 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 27. 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.

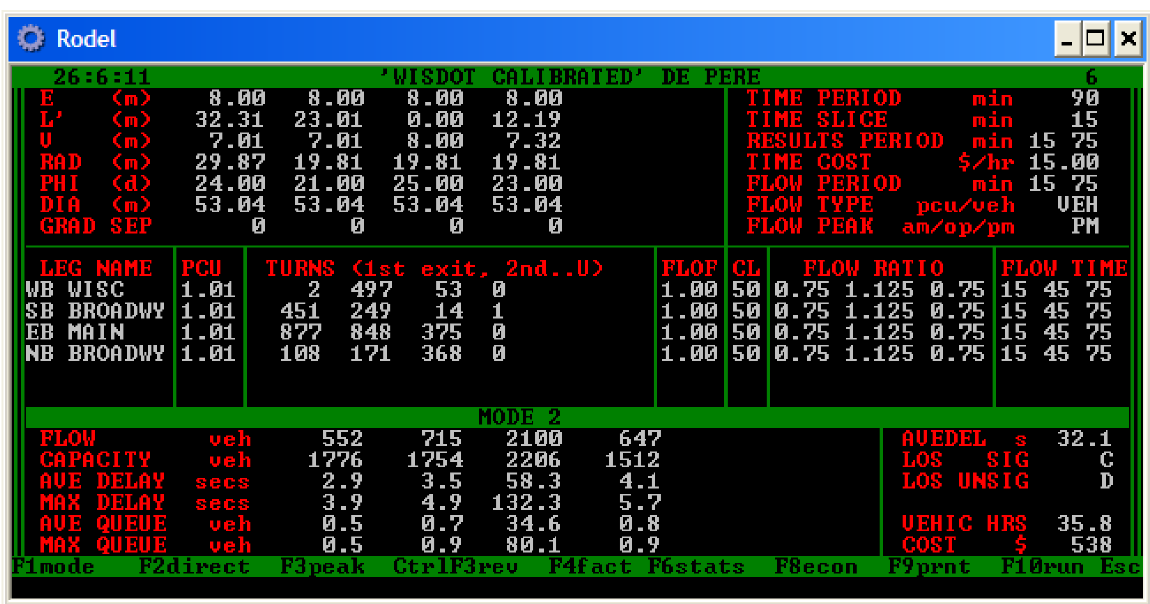


Figure 27. RODEL 1.9.7 Interface

6.5.2 ARCADY 7.1

ARCADY 7.1 uses a multiple document interface style, shown in Figure 28. 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.

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.

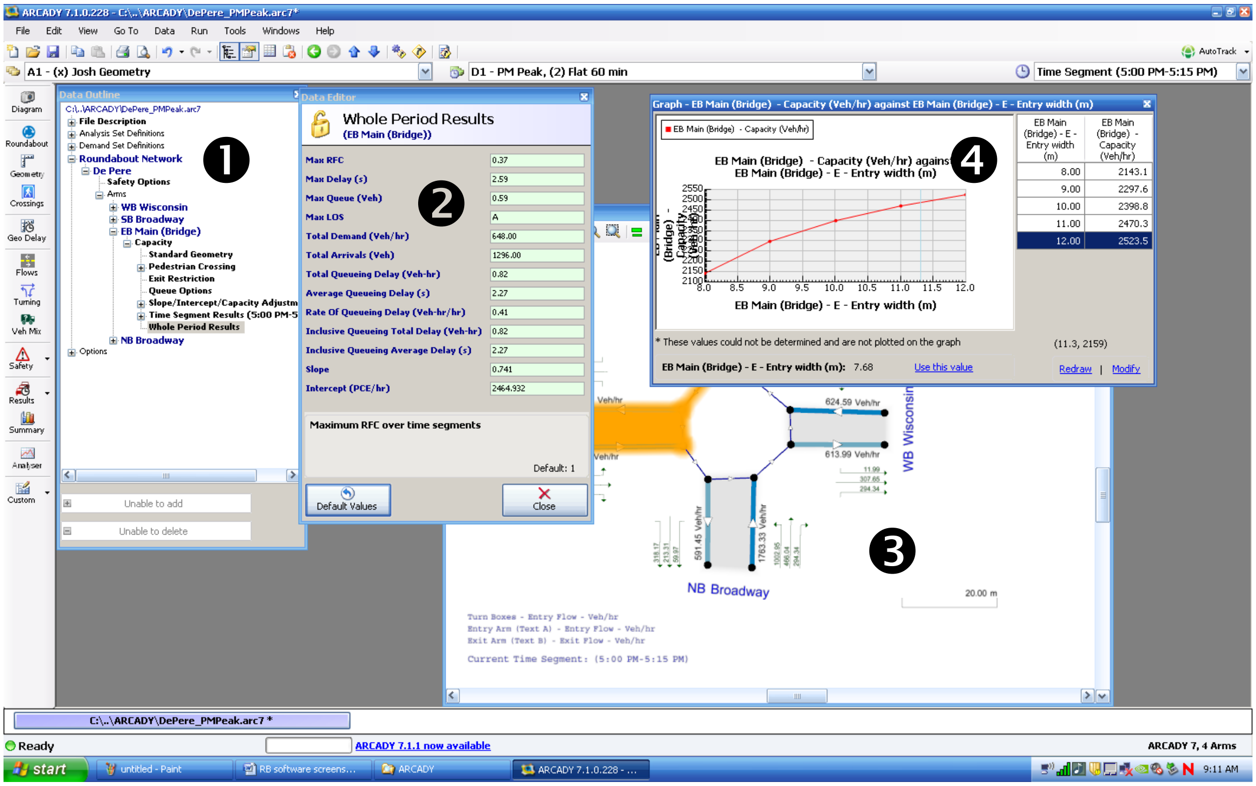


Figure 28. ARCADY 7.1 Interface

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 29. 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.

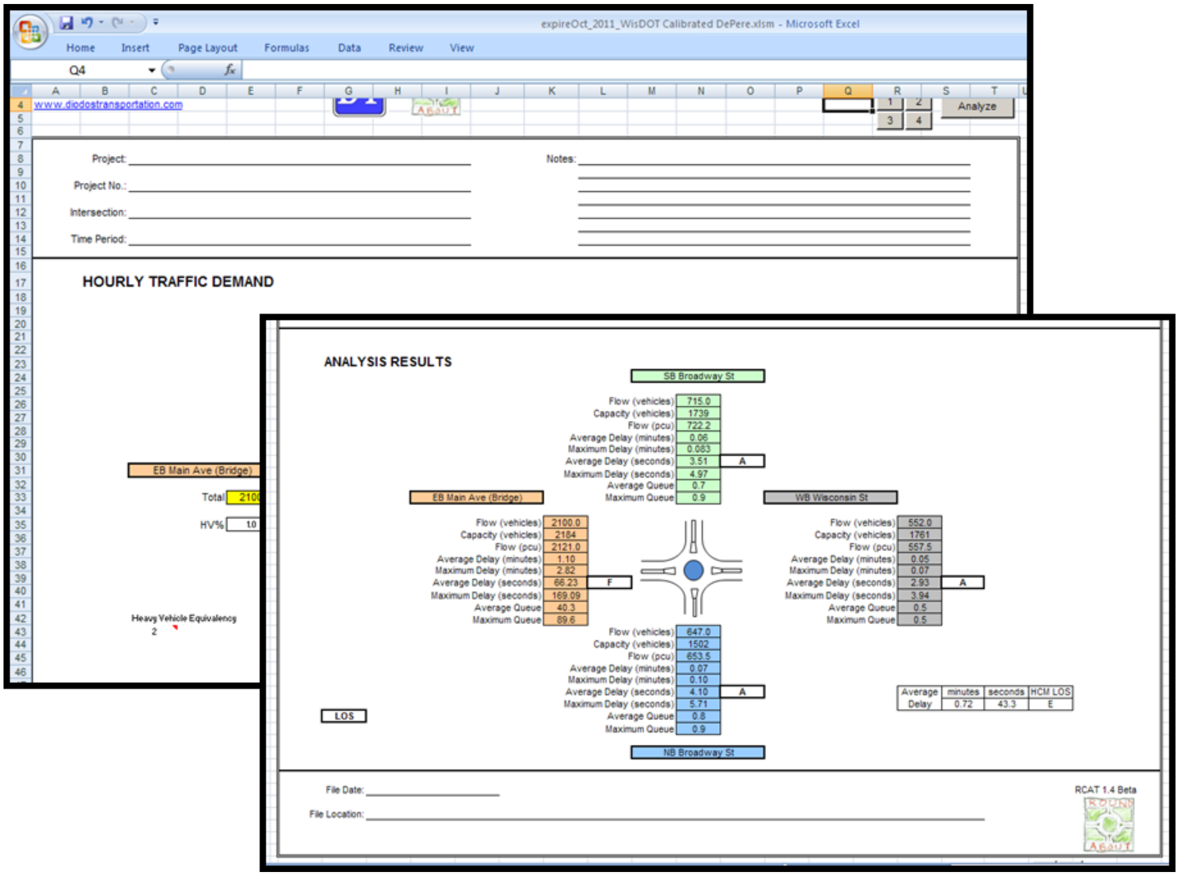


Figure 29. RCAT 1.4 Interface

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 30. 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.

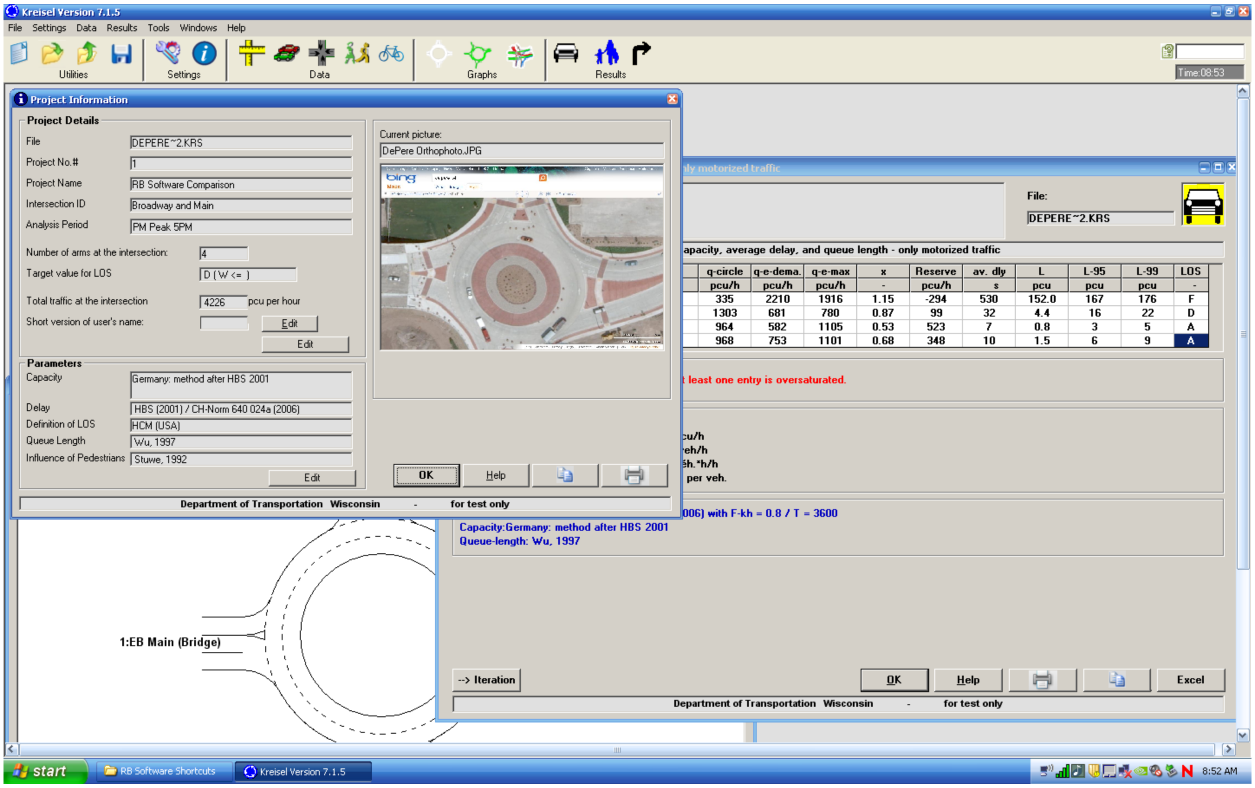


Figure 30. Kreisel 7.0 Interface

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 31. A version with a French interface was used for this research, but an English interface is available based on information from the vendor.

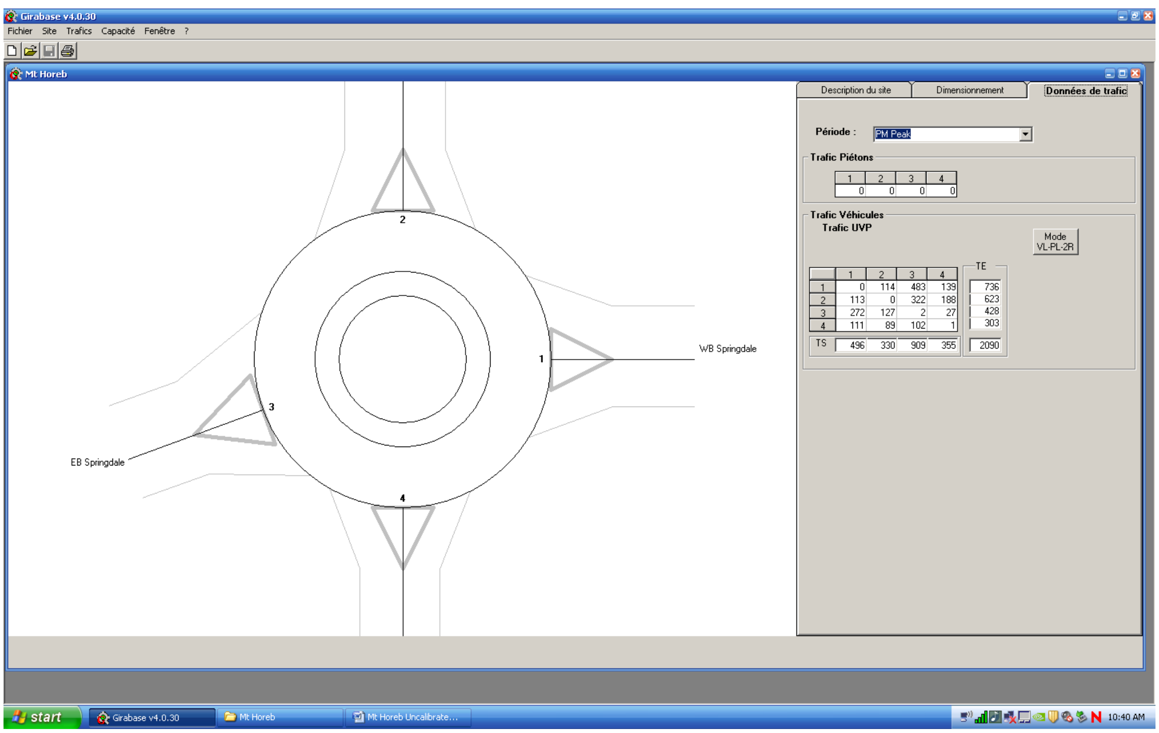


Figure 31. GIRABASE 4.0 Interface

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 32.

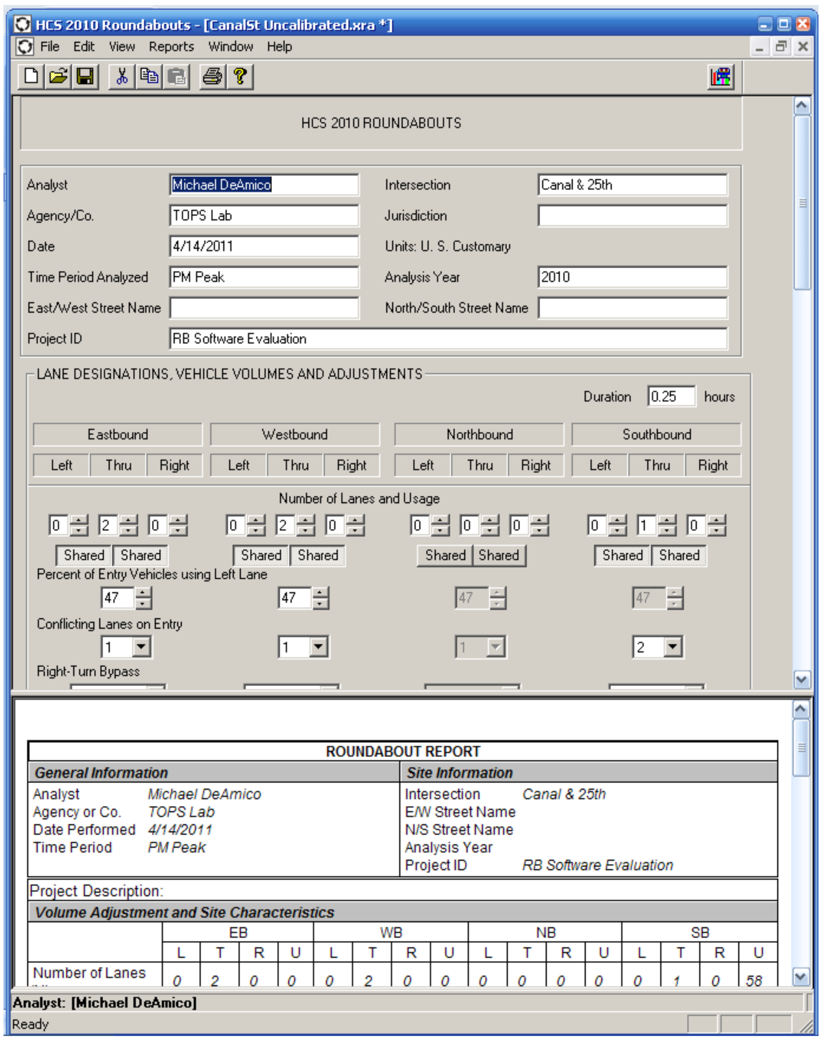


Figure 32. HCS 2010 6.1 Interface

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

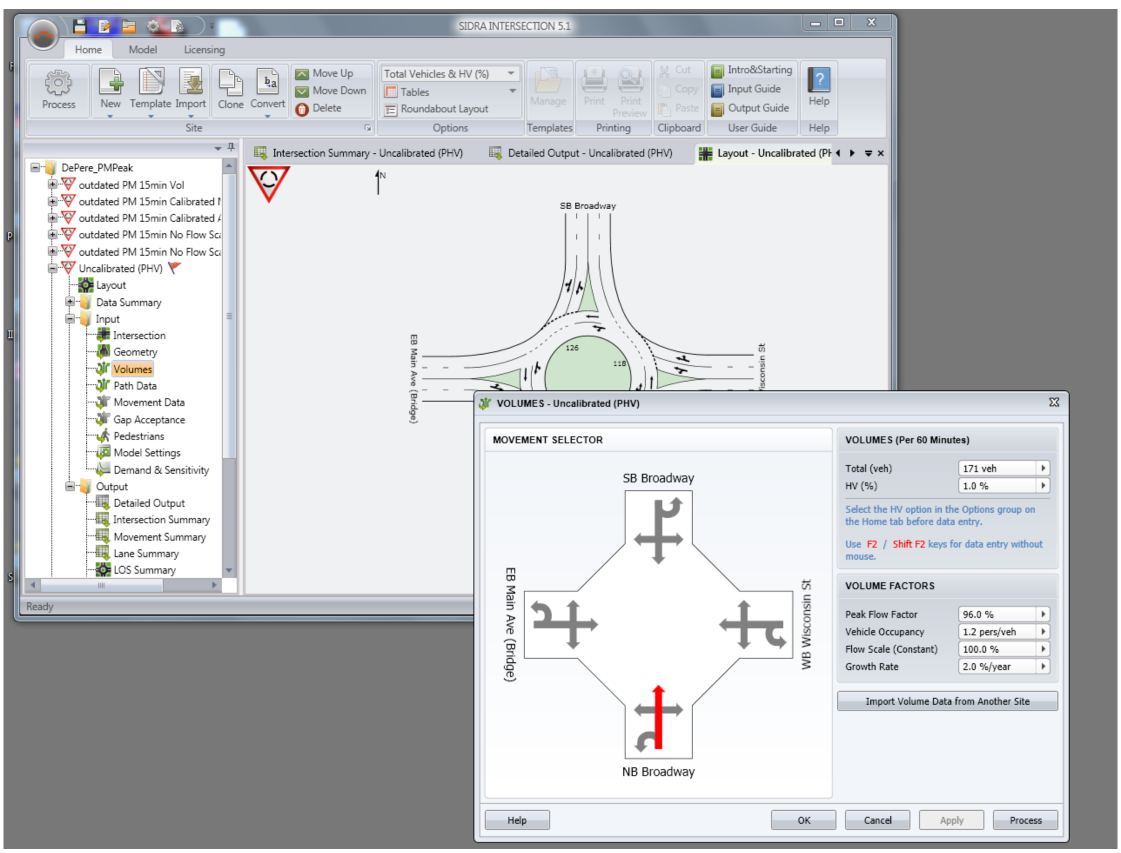


Figure 33. SIDRA 5.1 Interface

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 31 was developed to allow quick comparisons to summarize the usability and features evaluated in each software.

Table 31. 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 32. 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 32. 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 7.0	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 4.0	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 33.

Table 33. Software Data Input Needs

<table>
<tr><th rowspan="2">Software</th><th colspan="3">List of Inputs for Basic Roundabout Analysis</th></tr>
<tr><th>Traffic Data</th><th>Geometry Data</th><th>Other Data</th></tr>
<tr><td>RODEL 1.9.7</td><td rowspan="3">• Traffic Volumes
• % Trucks
• Traffic Demand Profile</td><td rowspan="3">• Entry Width
• Half Width
• Flare Length
• Entry Radius
• Phi, Entry Angle
• Inscribed Diameter</td><td>-</td></tr>
<tr><td>ARCADY 7.1</td><td>-</td></tr>
<tr><td>RCAT 1.4</td><td>-</td></tr>
<tr><td>KREISEL 7.0</td><td>• Traffic Volume converted to pcu/h or Traffic Volume by vehicle type</td><td>• Number of Lanes Entering
• Number of Lanes Conflicting per approach
• Inscribed Diameter</td><td>• Approximate Exit Capacity</td></tr>
<tr><td>GIRABASE 4.0</td><td>• Traffic Volume converted to pcu/h or Traffic Volume by vehicle type</td><td>• Central Island Diameter
• Truck Apron Width
• Circulating Width
• Approach Angle
• Approach Grade
• Entry Width at 4 and 15 m
• Splitter Island Width
• Exit Width</td><td>• Environment: Urban, Rural, Suburban</td></tr>
<tr><td>HCS 2010 6.1</td><td>• Traffic Volumes
• Peak Hour Factor
• % Trucks</td><td>• Number of Lanes Entering
• Number of Lanes Conflicting per approach
• Bypass lanes, if any</td><td>-</td></tr>
<tr><td>SIDRA 5.1</td><td>• Traffic Volumes
• Peak Hour Factor
• % Trucks</td><td>• 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</td><td>• Approach and Exit Cruise Speeds</td></tr>
</table>

- : 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 34. While Kreisel 7.0 can return results from about 30 different roundabout capacity models, SIDRA 5.1 was found to be able to return results from the German model as well as use HCM 2010 models. A discussion of the SIDRA HCM implementation can be found in Appendix E.

Table 34. 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 7.0	Yes	Approach Based (HBS 2001)	8	No	No
GIRABASE 4.0	No	Approach Based	8	No	No
HCS 6.1	No	Lane Based, up to 2 lanes	4	Yes	No
SIDRA 5.1	Yes	Lane Based, can do more than 2 lanes	8	Yes	Yes

Because software is continually changing, some secondary and desirable features were identified, but not formally evaluated, and are shown in Table 35. 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. Screenshots of graphical analysis capabilities are shown in Appendix D; and
- SIDRA includes graphical sensitivity analysis for major inputs and outputs, but cannot graph any variable like ARCADY.

Table 35. 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 7.0	○	○	○	●	◑	○	○
GIRABASE 4.0	●	○	○	◑	◑	○	◔
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 36.

Table 36 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 7.0	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 4.0	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 37.

Table 37. 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 7.0	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 4.0	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 *(41)*. Future versions of SIDRA were demonstrated to link with the CAD software *TORUS* developed by Transoft Solutions *(42)*. RODEL has also been undergoing revisions with the introduction of *RODEL V1-Win* as an interim beta software before the release of *RODEL V2*. Appendix F presents an overview of developments of the current RODEL developments.

Chapter 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. Tables representing the evaluation matrix have been consolidated into Appendix A.

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.

- If a software package is chosen, how applicable are the advanced analysis features?

- What are the future prospects of the software? Is it actively developing and adding useful features? Would multipurpose software, be subject to doing many things acceptably but struggle to do some things particularly well?

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
Evaluation Matrix Summary

Graphical Rating Scale

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

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 7.1.0	'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 7.0	-	German HBS 2001 Model ◕	German HBS 2001 Model *KREISEL did not feature capacity calibration for the HBS 2001 Model
GIRABASE 4.0	-	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

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

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 7.0	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 4.0	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.	◕

Feature Comparison

Software	Can the software return results from multiple models?	Approach or lane based	Allow for calibration of model parameters	Allow for analyzing multiple scenarios within the same file	Advanced/Other Features Not Evaluated							
					Allow for bypass lanes	**Maximum Number of Legs**	**Allow for modeling linked sites (corridors)**	**Can the Software Model Other Intersection Types?**	**Includes formatted report output**	**Visualization**	**Includes Safety Analysis**	**Includes graphing analysis capabilities**
RODEL 1.9.7	No	Approach	No	No	Remove right turns ◑	6	No ○	No ○	No ○	No ○	No ○	No ○
ARCADY 7.1	No	Approach*	Yes	Yes	Similar to RODEL ◑	20	Yes - RB only ◑	No ○	Yes ●	Yes, schematic ●	Yes – based on UK ◑	Yes ●
RCAT 1.4	No	Approach	No	No	Similar to RODEL ◑	4(4)	No ○	No ○	Yes ●	No ○	No ○	No ○
KREISEL 7.0	Yes (1)	Approach Based (HBS 2001)	Yes/No(3)	No	No ○	8	No ○	No ○	Yes ●	Yes, schematic ●	No ○	No ○
GIRABASE 4.0	No	Approach Based	No	No	Yes ●	8	No ○	No ○	Yes – via printing only ◑	Yes, schematic ●	No ○	Entering\circulating graph only ◔
HCS 6.1	No	Lane Based, up to 2 lanes	Yes	No	Yes ●	4	No ○	Yes – must retype input ◕	Yes ●	Yes, CORSIM ●	No ○	No ○
SIDRA 5.1	Yes (2)	Lane Based, can do more than 2 lanes	Yes	Yes	Yes ●	8	Yes(5) ●	Yes ●	Yes ●	Yes, schematic (6) ●	No ○	Yes (7) ◕

*applies to current version of software – future versions may change as discovered through the evaluation process

(1) Kreisel can evaluate roundabout with many (35) capacity models from multiple countries

(2) In addition to the SIDRA standard model, SIDRA can use the HCM 2010 model, as well as the German HBS 2010 model. When using the HCM model, gap acceptance parameters can be calibrated. The German model is limited to showing the capacity per movement using only default gap acceptance parameters.

(3) Calibration parameters become available depending upon the model chosen. The German HBS 2001 option does not allow for calibration, but Kreisel has indicated that they may be willing to customize the software to customer specifications.

(4) RCAT could be changed to allow for more legs, but the model should be verified to apply to more than 4 legs.

(5) SIDRA currently uses a manual iterative method for linking sites in a corridor. Future version are planned to automate the process.

(6) SIDRA is also working with VISSIM for visualization purposes

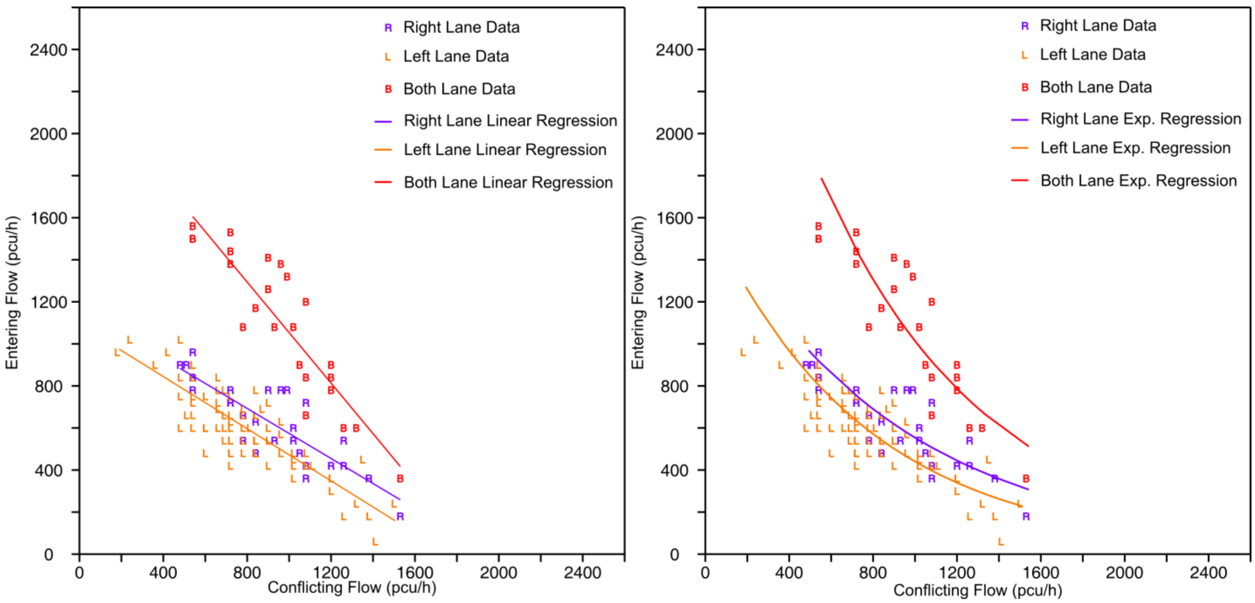
(7) SIDRA graphical analysis, while easy to use and robust in analyzing sensitivity to the most common parameters, does not allow for graphing relationships between any two variables like ARCADY.

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 7.0	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 4.0	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.

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 7.0	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 4.0	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 USA 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.

Appendix B
De Pere AM Capacity Data - Northbound Approach

De Pere Northbound AM Field Data



(a)
Field Data with Linear Regression

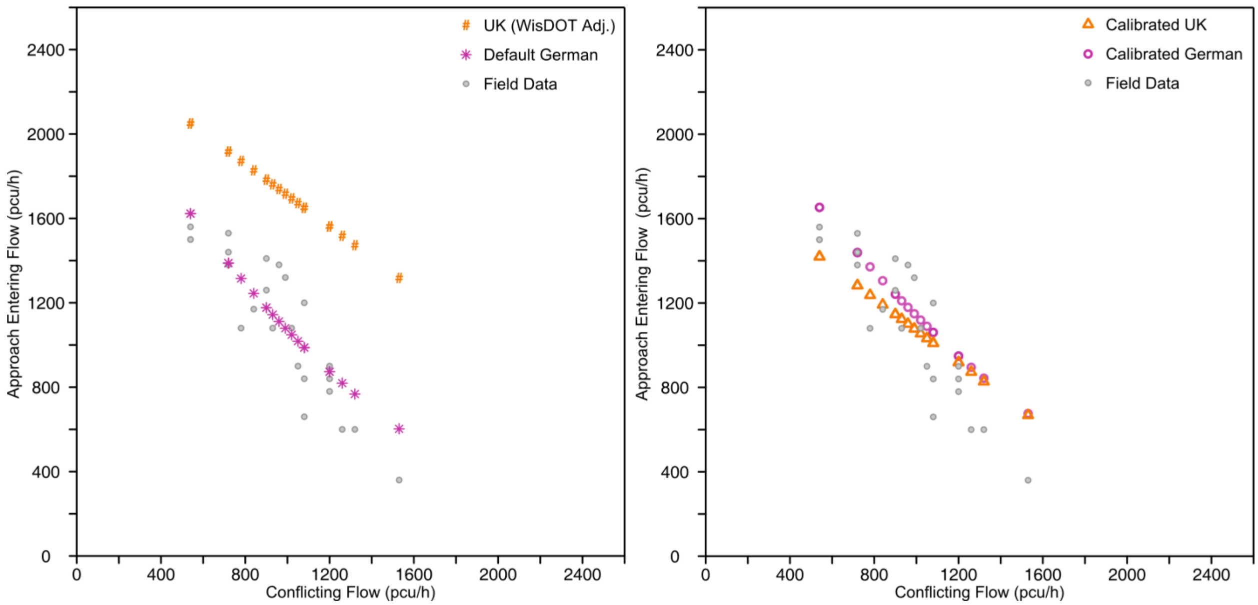
(b)
Field Data with Exponential Regression

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

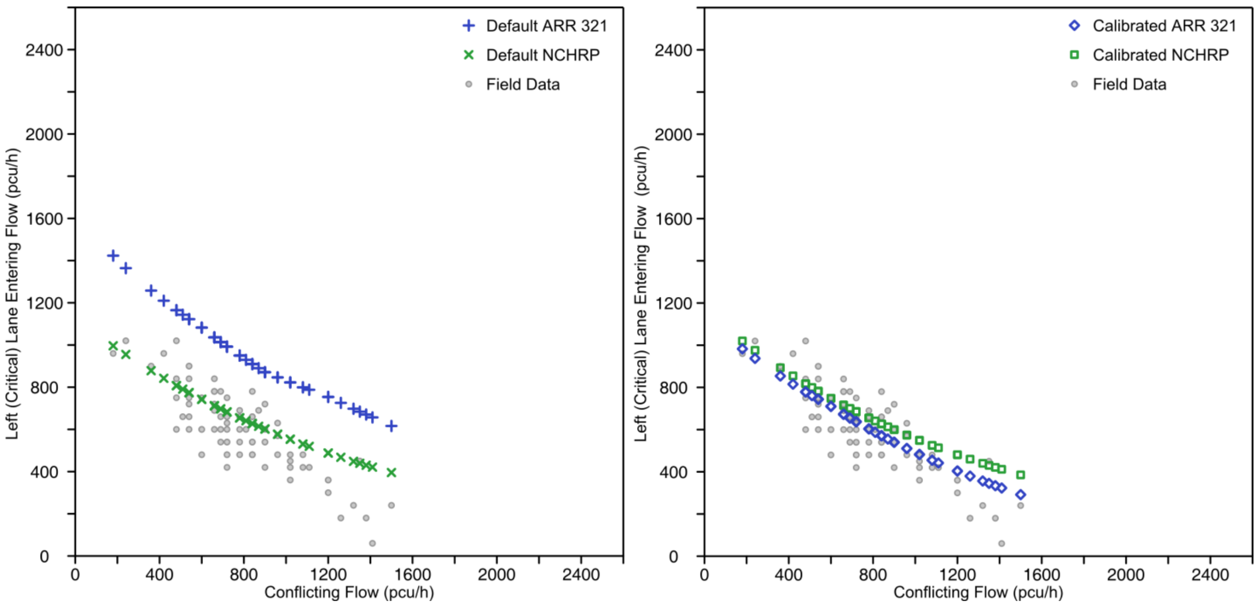
(b)
Field Data with Exponential Regression

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 C
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

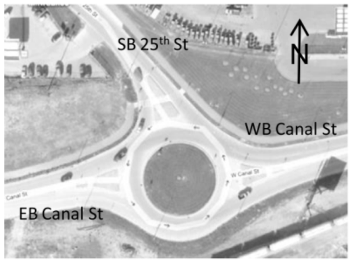
Queue lengths with an asterisk (*) denote results that appear unreasonable based upon reviews of video data collection. Only the studied approaches were analyzed for reasonableness of queue length.

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

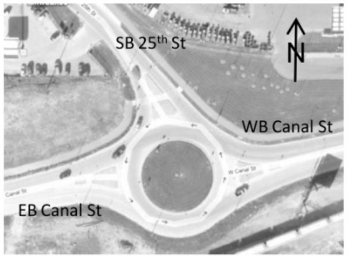
	Capacity	v/c Ratio	Delay	LOS	Queue
RODEL	2038	0.15	2.0	A	0.2
ARCADY	2010	0.17	2.16	A	0.21
RCAT	2021	0.15	2.06	A	0.2
KREISEL	1747	0.19	2	A	1
GIRABASE	2808	0.11	0	A	0 to 2
HCS	L: 725 R: 725	L: 0.22 R: 0.24	L: 7.4 R: 7.8	L: A R: A	L: 0.8 R: 0.9
SIDRA	L: 888 R: 993	L: 0.176 R: 0.176	L: 6.3 R: 3.6	L: A L: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

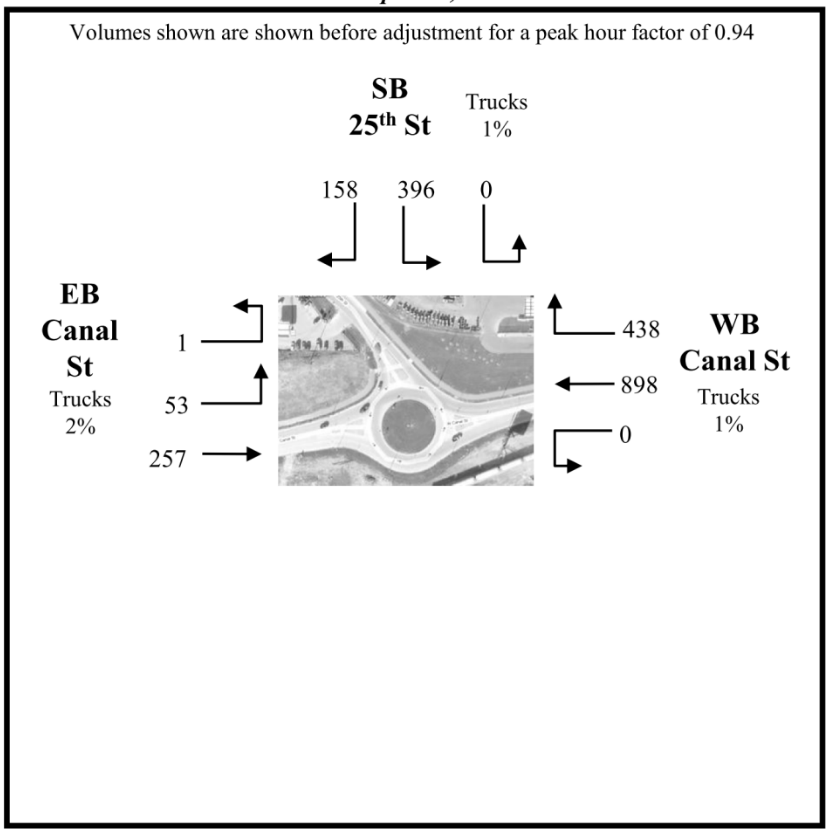
NB Broadway St

* Queuing result low based on video review

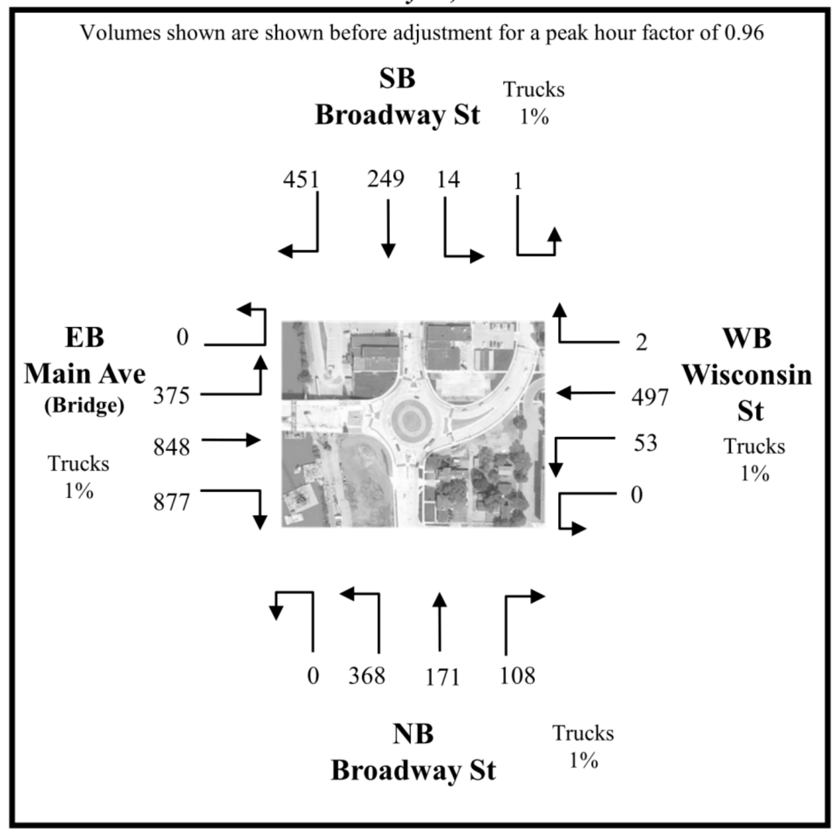
Traffic Volumes

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***



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



Appendix D
Software Graphical Analysis Screenshots

ARCADY, SIDRA, and to some extent, Girabase offered features to explore scenarios through graphing input and output variables. Such tools are useful for quickly exploring a range of situations or discovering relationships in sensitivity analysis. A brief overview of screenshots from each of these three software packages is provided here.

ARCADY 7.1

ARCADY 7.1 allows graphical analysis of virtually any variable against any other variable in x-y or other types of graphs. A sample interface is shown in Figure D-1.

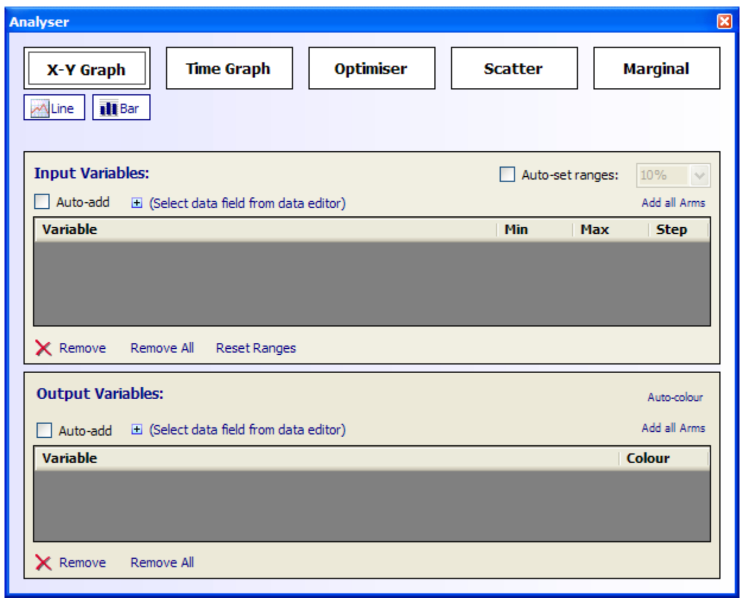


Figure D-1 ARCADY Graph Creation Dialog

As one example, Figure D-2 shows how capacity is predicted to vary with different inscribed diameters. Another possible graph could be how volume-to-capacity (v/c) ratios on each approach change with varying traffic levels. An optimizer function is also available to find parameters that meet specific goals, e.g. at what traffic volume does the critical approach reach v/c = 1.0.

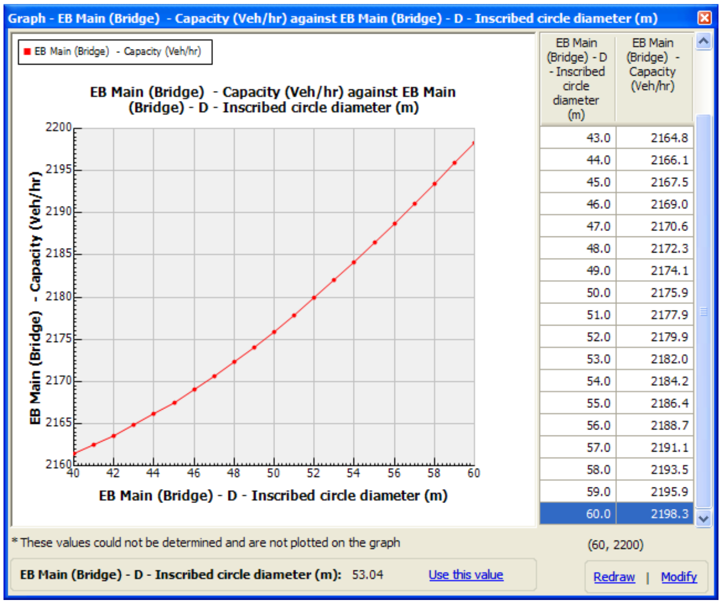


Figure D-2 Example ARCADY X-Y Graph

SIDRA 5.1

SIDRA allows for graphical sensitivity analysis of several pre-defined independent variables such as critical gap and follow-up headway, saturation flow, maximum green times, etc. The full list is shown in Figure D-3 which is a screenshot from the sensitivity analysis setup.

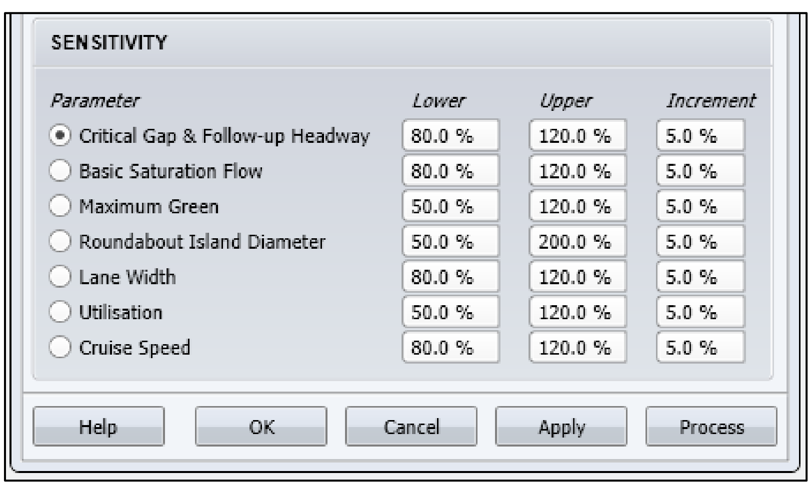


Figure D-2 SIDRA Graphical Sensitivity Analysis Options

Once the sensitivity options are processed, several pre-defined dependent variables can be displayed on an x-y graph. Figure D-3 shows an example where the influence of critical gap and follow-up headway is shown to affect delay and degree of saturation. Other combinations are possible by checking the variables shown to the right of the graph.

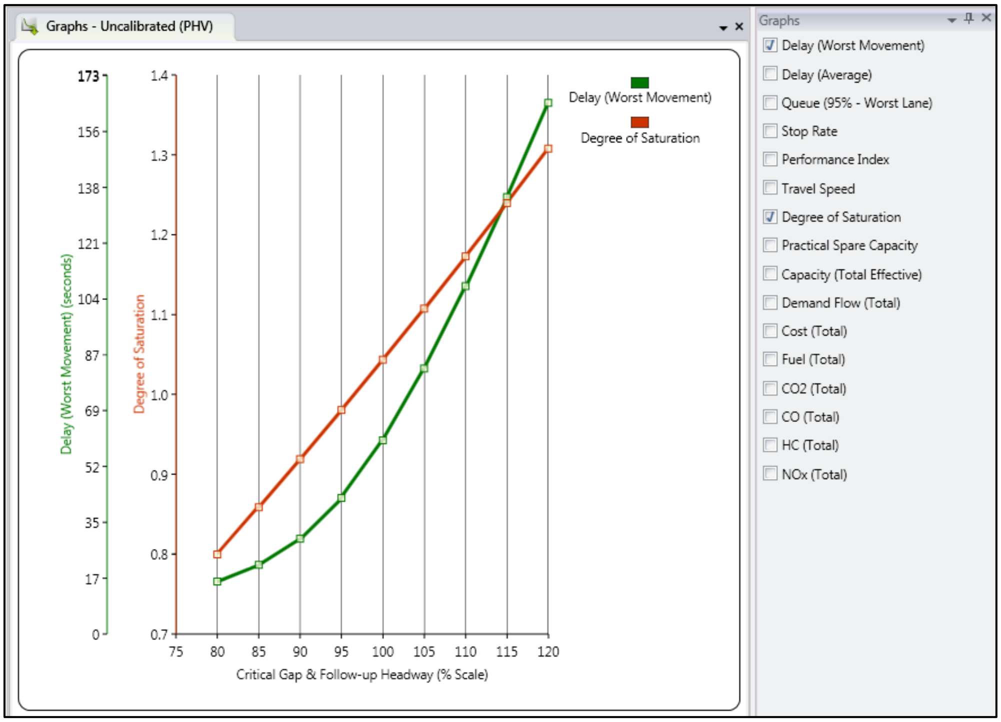


Figure D-3 Example SIDRA Graphical Analysis

GIRABASE 4.0

GIRABASE 4.0 had limited graphing ability, by only showing the entering versus circulating flow graphs. This type of graphical analysis is useful for visualizing where the demand volume is in comparison to capacity. No other graphical analysis is possible. Figure D-4 shows an example entering-circulating graph from GIRABASE.

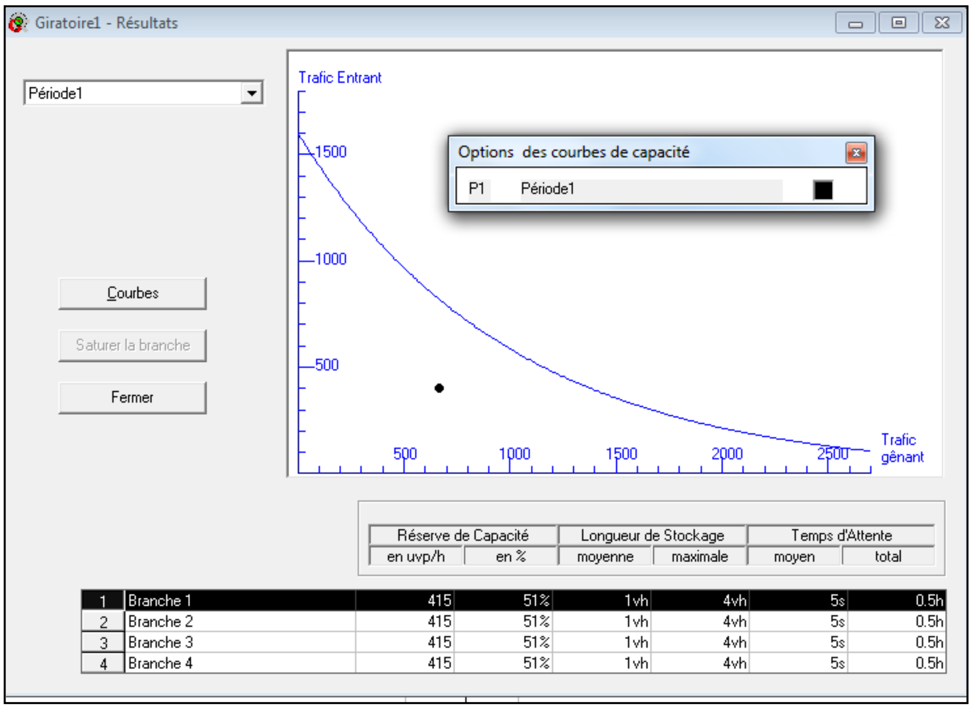


Figure D-4 Example GIRABASE Graph

Appendix E
Using SIDRA Software for HCM Analysis

Overview

Both the Highway Capacity Software 2010 (HCS) version 6.1 and SIDRA 5.1 can be used to evaluate roundabouts with the Highway Capacity Manual 2010 (HCM) methodology. Some differences, however, do exist. Overall, both packages perform similarly or identical for undersaturated conditions. Differences are more pronounced in oversaturated or nearly oversaturated conditions. The reasons for these differences can be understood first by understanding what each software package represents. HCS can be thought of as a literal representation of the HCM method. All assumptions and limitations noted in the actual manual apply within the software. Within SIDRA, the HCM analysis option can be thought of as using the SIDRA standard model philosophy by substituting in HCM equations and parameters where appropriate, which results in four primary differences related to:

- Critical lane identification,
- Capacity constraints in oversaturated conditions,
- Lane utilization, and
- Queuing models

These differences allow SIDRA to extend the HCM methodology to situations not explicitly covered by the HCM. An analogy can be made to signalized analysis: users may choose to use the HCS program or turn to other software packages and methods when analyzing situations where different tools may provide other insights. The following sections further examine the similarities and differences between the HCM model implementation within each software packages.

Model Implementation Comparison

Approaches and Lane Configuration

HCS

Up to four approaches, or legs, and up to two lanes on each approach are allowed. One right turn bypass lane can be specified for each approach in addition to the primary number of lanes. HCM 2010 equations are based on the NCHRP Report 572 research which only observed single and double lane entry roundabouts with a maximum of four legs, thus causing the limits in HCS.

SIDRA

SIDRA extends the HCM and allows up to 8 approaches with up to 9 entering lanes on each approach (up to 6 circulating lanes are allowed). Any or all of the approach lanes can be coded as bypass lanes. More than two entering lanes allows for a wider variety of lane discipline possibilities; however, the NCHRP Report 572 research did not evaluate any sites with more than two lane entries.

Lane Utilization and Critical Lane Identification for Multilane Approaches

HCS

For two-lane entry approaches with shared lanes in HCS, lane utilization is assumed to be similar to signals *(1)*. Default values are 43% of the approach volume using the shared left-through lane and 53% of the approach volume using the shared through-right lane. User specified lane utilization percentages are allowed within HCS. A de facto turn lane on an approach is automatically assigned by the program when the high volume turning movement (left or right) exceeds the sum of the remaining turning movement volumes on that approach.

The current HCS version 6.1 used in this research identifies a critical lane on each approach as the lane with the highest volume. However, the critical lane designation has no impact on the model equations used in HCS. This is consistent with the HCM which provides capacity equations, regardless of critical lane designation, that are always used for the left lane and equations that are always used for the right lane. Critical lane designation will be removed from the final version of the software to avoid confusion. *(2)*.

NCHRP Report 572 only presents a capacity equation for the critical lane on a two lane approach. Observations in NCHRP 572 did not evaluate many sites with critical left lanes, so all data was combined from sites with either critical-right or critical-left lanes, noting that:

> *Regression suggests that the critical left-lane capacity is lower; however, there are limited left-lane observations, most of which occurred at MD04-E (Baltimore County, Maryland). Because of limited critical left-lane observations, it is difficult to establish if there is any difference in the capacity between the right lane and left lane and therefore there is insufficient evidence to suggest the need for factors that correct the regression.*

From the combined data, a single capacity equation was developed to apply for any critical lane, left or right. No specific equation was developed for non-critical lanes.

The HCM 2010 stated the two-lane entry model as follows:

$$
\begin{aligned}
c_R &= 1130e^{-0.7\cdot 10^{-3} q_c} \\
c_L &= 1130e^{-0.75\cdot 10^{-3} q_c}
\end{aligned}
$$

where

$$c_R = \text{capacity for the right entry lane (pcu/h)}$$
$$c_L = \text{capacity for the left entry lane (pcu/h)}$$
$$q_c = \text{circulating flow (pcu/h)}$$

which takes the generic form of

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

where

$$c = \text{capacity for an entry lane (pcu/h)}$$
$$A = \frac{3600}{t_f}$$
$$B = \frac{\left(t_c - \frac{t_f}{2}\right)}{3600}$$
$$q_c = \text{conflicting flow (pcu/h)}$$
$$t_f = \text{follow-up headway (s)}$$
$$t_c = \text{critical gap (s)}$$

No reference is given to how the critical gap parameters were chosen to develop the left lane capacity equation. However, the left lane equation is consistent with observations that showed that the left lane tended to have a larger critical gap value, and thus lower capacity, than the right lane.

SIDRA

SIDRA uses the principle of equal lane saturation to determine lane utilization, which is different than the HCM method that uses a default percentage. In essence, this iterative method first forces the degree of saturation (v/c ratio) for every lane on an approach to be identical and then assigns the demand flows accordingly. SIDRA, however, will automatically determine lane underutilization or a de facto turn lane and allow for unequal degrees of saturation amongst the approach lanes accordingly.

Treatment of critical lanes in SIDRA is also different from HCS. Entering lanes are either identified as "dominant" or "subdominant," in an iterative manner. The lane with the highest flow becomes the dominant lane, similar to the NCHRP Report 572 definition of the critical lane. A dominant lane is then treated with the HCM right lane capacity equation, regardless of the actual lane position. Under this assumption, SIDRA can model multilane approaches that have more than two lanes. Capacity for subdominant, or non-critical, lanes are determined by treating the HCM left lane equation as a subdominant lane equation, again regardless of actual lane position.

Consider a scenario of a two lane approach for which SIDRA identified the left lane as critical, or dominant. In this situation, left lane capacity would be calculated from the HCM right lane equation (which is identical to the NCHRP 572 critical lane equation). Also, the right lane capacity would be calculated from the HCM left lane equation. Here, a contrast in interpretation by HCS and SIDRA of the HCM becomes apparent: SIDRA follows the more general approach used in NCHRP Report 572, while HCS keeps to the HCM.

Oversaturation

HCS provides no special treatment for oversaturated conditions (v/c ratio larger than 1.0); the degree of saturation is simply determined from the original entered demand volumes and calculated capacities. SIDRA, on the other hand, adjusts the capacity for approaches downstream of an oversaturated approach. Not all of the given demand volume would enter the roundabout in an oversaturated condition, leading to less conflicting volume and increased capacity on downstream approaches. This gives SIDRA the ability to avoid underpredicting capacity on downstream approaches which could occur when using HCS that does not include an iterative procedure.

Delay and Level of Service

Both HCS and SIDRA use the HCM 2010 roundabout delay formula and LOS scale for reporting delay and level of service. Level of service is also partially based on v/c ratio in the case where v/c exceeds 1.0 the lane is assigned LOS F. HCS does not compute or include any estimates of geometric delay. SIDRA computes geometric delay based upon the SIDRA standard method, but reports the estimated value separate from any LOS or control delay estimation in order to remain compatible with the HCM method. Differences in delay reported by HCS and SIDRA are due to the as previously described differences in capacity, lane utilization, and oversaturation assumptions.

Queue Length

For HCS, a 95th percentile queue length is calculated based on the formula presented in the HCM. SIDRA always returns a 95th percentile back of queue length based upon the SIDRA standard method, but uses "various parameters based on the HCM 2010 roundabout capacity model" according to the SIDRA users guide *(3).* SIDRA justifies this difference because the HCM queue formula is based upon an average queue length rather than a, arguably more useful, back of queue definition.

Calibration

Gap acceptance parameters, critical gap (t_c) and follow-up headway (t_f), are used for calibrating the HCM model. HCS allows for direct entry of t_c and t_f values for each lane. SIDRA allows the user to manually calculate the "A" and "B" parameters of the generic HCM capacity equation , or entering gap acceptance parameters directly (although parameters are entered per movement, not per lane).

HCM Implementation Summary

As a summary of the above discussion on the differences between the implementation of the HCM in both HCS and SIDRA software, Table E-1 presents a brief side-by-side comparison.

Table E-1. Side-by-Side Model Implementation Comparison Summary

	HCM Implementation in **HCS 2010 (v 6.1)**	***HCM Implementation in*** **SIDRA (v 5.1)**
Number of Approaches	4	8
Lane Configuration	2 lanes, plus one additional right turn bypass lane	9 lanes entering, any of which can be coded as bypass lanes. Limited to 6 lanes circulating.
Lane Utilization	Demand volume based; uses a default of 47% using the left lane, can be user specified	Based on equal degrees of saturation for the subject approach, can also be user specified
De Facto Turn Lanes	Automatically determined by demand volumes	Automatically determined by iterative method within software
Critical Lane Assignment for Multilane Approaches	Not relevant; left lane capacity is always treated with the left lane capacity formula, regardless of demand flows (same is true for right lane)	Relevant; the HCM right lane capacity formula is treated as the dominant lane formula, regardless of lane position (likewise the HCM left lane formula is associated with subdominant lanes)
Oversaturation	No capacity adjustments made to approaches downstream from the oversaturated approach	Capacity automatically adjusted upward for approaches downstream of the oversaturated approach
Calibration	Enter t_c and t_f values for each lane	Enter A & B parameters for dominant and subdominant lanes (or t_c and t_f per movement)

Software Results

Table E-2 through Table E-5 present calibrated and uncalibrated results from each of the study sites. Values shown are raw output from the software (no rounding of decimal places), except for the capacities from SIDRA were converted to pcu/h by hand using the appropriate heavy vehicle factor. Lane assignments are shown for each approach and those assignments receiving an asterisk (*) were automatically treated as de facto turn lanes by the software. Both HCS and SIDRA identified the same de facto turn lanes: none at the Canal St site, and both the NB left lane and SB right lane at the De Pere site. A row has been included to draw attention to differences between the software results. The "difference" row in each table either contains a "Y" value, indicating a difference or no value at to indicate no difference. Thresholds for determining the Y value are as follows:

- Capacity: 10 or more pcu/h difference;
- v/c ratio: 0.05 or more difference;
- Delay: 5 or more seconds difference;
- LOS: any letter difference; and
- Queue: 5 or more vehicle difference.

Canal St Site: Canal St and 25th St

Table E-2. Canal Site Uncalibrated Software Results

	Field Studied?		**Capacity (pcu/h)**		**v/c ratio**		**Delay (sec)**		**LOS**		**Queue (# of veh)**	
SB 25th St	**Yes**	**Lanes**	**LTR**		**LTR**		**LTR**		**LTR**		**LTR**	
		HCS	575		1.04		74.2		F		16.2	
		SIDRA	575		1.036		74.3		F		18.3	
		Different?										
WB Canal	No	**Lanes**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	1065	1065	0.63	0.71	12.3	15	B	C	4.7	6.4
		SIDRA	1066	1066	0.674	0.674	13.5	13.5	B	B	6.0	6.0
		Different?										
EB Canal	No	**Lanes**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	739	739	0.22	0.24	7.4	7.8	A	A	0.8	0.9
		SIDRA	750	750	0.225	0.225	7.4	7.4	A	A	0.8	0.8
		Different?	Y	Y								

Table E-3. Canal Site Calibrated Software Results

	Field Studied?		Capacity (pcu/h)		v/c ratio		Delay (sec)		LOS		Queue (# of veh)	
		Lanes	**LTR**		**LTR**		**LTR**		**LTR**		**LTR**	
SB 25th St	**Yes**	**HCS**	449		1.32		186.6		F		26.4	
		SIDRA	448		1.327		187.9		F		56.8	
		Different?									Y	
		Lanes	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
WB Canal	No	**HCS**	1065	1065	0.63	0.71	12.3	15	B	C	4.7	6.4
		SIDRA	1066	1066	0.674	0.674	13.5	13.5	B	B	6.0	6.0
		Different?										
		Lanes	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
EB Canal	No	**HCS**	739	739	0.22	0.24	7.4	7.8	A	A	0.8	0.9
		SIDRA	820	820	0.206	0.206	6.7	6.7	A	A	0.8	0.8
		Different?	Y	Y								

De Pere Site: Main Ave (Bridge) and Broadway St

Table E-4. De Pere Site Uncalibrated Software Results

	Field Studied?		**Capacity (pcu/h)**		**v/c ratio**		**Delay (sec)**		**LOS**		**Queue (# of veh)**	
NB Broadway St	**Yes**	**Lanes**	**L***	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	425	454	0.91	0.65	55.4	24.7	F	C	9.9	4.5
		SIDRA	542	514	0.714	0.571	25.3	18.9	D	C	3.5	2.3
		Different?	Y	Y	Y	Y	Y	Y	Y		Y	
EB Main Ave (Bridge)	**Yes**	**Lanes**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	880	894	1.18	1.31	112	164.1	F	F	31.8	44.1
		SIDRA	880	895	1.245	1.245	137.4	137.1	F	F	84.8	85.6
		Different?			Y	Y	Y	Y			Y	Y
SB Broadway St	No	**Lanes**	**LT**	**R***	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	548	575	0.51	0.82	15.8	33.5	C	D	2.8	8.4
		SIDRA	547	575	0.507	0.826	15.8	33.6	C	D	2	5.3
		Different?										
WB Wisconsin St	No	**Lanes**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	549	576	0.5	0.54	15.5	16.0	C	C	2.7	3.2
		SIDRA	582	608	0.488	0.488	14.5	14.0	B	B	1.9	1.8
		Different?	Y	Y		Y			Y	Y		

Table E-5. De Pere Site Calibrated Software Results

	Field Studied?		Capacity (pcu/h)		v/c ratio		Delay (sec)		LOS		Queue (# of veh)	
NB Broadway St	**Yes**	**Lanes**	**L***	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	461	603	0.84	0.49	41.6	14.1	E	B	8.3	2.7
		SIDRA	512	665	0.756	0.441	29.7	11.9	D	B	4.0	1.3
		Different?	Y	Y	Y	Y	Y		Y			
EB Main Ave (Bridge)	**Yes**	**Lanes**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	973	982	1.07	1.19	69.2	114.3	F	F	24.2	35.6
		SIDRA	966	981	1.135	1.135	92.5	92.2	F	F	62.0	62.6
		Different?	Y		Y	Y	Y	Y			Y	Y
SB Broadway St	No	**Lanes**	**LT**	**R***	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	548	575	0.51	0.82	15.8	33.5	C	D	2.8	8.4
		SIDRA	547	575	0.507	0.826	15.8	33.6	C	D	2.0	5.3
		Different?										
WB Wisconsin St	No	**Lanes**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**	**LT**	**TR**
		HCS	549	576	0.5	0.54	15.5	16	C	C	2.7	3.2
		SIDRA	569	595	0.499	0.499	15.1	14.5	C	B	2.0	1.9
		Different?	Y	Y						Y		

Discussion of Differences in Software Results

Major differences in the capacity results are due the treatment of oversaturation by SIDRA, causing more capacity on approaches downstream of oversaturated approaches. For instance, in Table E-4, the EB Main Ave approach has a v/c ratio larger than 1.0, so SIDRA increases the capacity of both the NB and WB approaches to reflect the decrease in circulating vehicles. Interestingly, the NB approach is also a situation where the left lane is dominant, so SIDRA is using the HCM right lane equation (NCHRP 572 critical lane equation) for the left lane. These combined differences effects cause SIDRA to report 117 pcu/h more for the left lane and 60 pcu/h more for the right lane compared to HCS. In the calibrated scenario, Table E-5, the increase in capacity is reduced to 51 pcu/h and 62 pcu/h for the NB left and right lanes respectively.

In Table E-2 and Table E-3, the oversaturation effect is not confounded with left lane dominance in SIDRA. SB 25th St is oversaturated and EB Canal St is allocated 11 to 81 pcu/h more capacity, depending on the magnitude of oversaturation.

Minor differences in capacity and v/c ratio results are due to the assumption by SIDRA of equal lane saturation, unless lane underutilization is determined or user specified. This causes SIDRA to adjust the demand volumes in each lane in order to achieve equal v/c ratios. A good example of this is in Table E-2 for WB Canal St. SIDRA shows the v/c ratios for each lane are 0.674, and no de facto turn lanes, resulting each lane to have 50% of the demand volume in each lane. This differs from the HCS default assumption of 47% utilization in the left lane.

Delay results are nearly identical between HCS and SIDRA because both software packages use the same HCM delay formula. Differences only arise when the v/c ratios are substantially different because the HCM delay formula is heavily dependent on the degree of saturation. In the case of WB Wisconsin St in both Table E-4 and Table E-5, the level of service is on the bubble between LOS B and LOS C due to delay closely straddling 15 seconds, depending on which software was used, but in reality there would be little operational difference.

While SIDRA uses its own queuing model, modified with HCM parameters, the results are similar for small queue lengths. Differences were identified once queue lengths exceeded around 25 vehicles as is the case for SB 25th St and EB Main Ave (see respective queue lengths in Table E-3, E-4, and E-5). In these cases, SIDRA generally reports longer queues of about 30 vehicles to as much as 53 vehicles more. Focusing on the De Pere site, the EB Main Ave (Bridge) approach queues seem long in Table E-4 and Table E-5, but anecdotal observations revealed that queue lengths were about 70 vehicles in the right lane and 35 vehicles in the left lane. SIDRA comparatively predicted about 85 vehicles (or 62 vehicles in the calibrated scenario) queued in the right lane and the same length in the left lane. Using the equal degree of saturation assumption forces queue length to be the same in each lane because SIDRA did not report any lane underutilization. HCS reported lower queuing, of 44 and 32 vehicles (or 36 and 24 vehicles in the calibrated scenario) for the right and left lanes respectively, but shows some imbalance due to the default lane utilization assumptions and no program determined de facto lanes. Queue lengths for NB Broadway de facto left lane from both programs in the uncalibrated and calibrated scenarios seemed short based upon anecdotal field evidence which revealed queues of at least 15 vehicles or more.

Extensions

Beyond a basic analysis of roundabouts, SIDRA allows for its extended features to be used in conjunction with the HCM equations, such as *(3)*:

- Analyzing the influence of upstream signals through the use of the extra bunching (platooning) factor;
- Estimates of probability of blockage of upstream lanes;
- Modeling closely spaced roundabouts, or nearby pedestrian crossings with capacity adjustment factors;
- Effects of short lanes (e.g. turn bays) where adjacent lanes are effected in overflow situations;
- Heavy vehicle adjustments per lane rather than per approach;
- Estimates of geometric delays;
- Optional use of origin-destination pattern effects on capacity;
- Roundabout metering with signals; and
- Fuel consumption, emissions, and operating cost estimates.

Conclusions

In the case of undersaturated approaches, both HCS and SIDRA performed similarly if not identically for the evaluated situations and assumptions. Often cases of near or oversaturation are of more concern, and in these cases SIDRA interpretation of the HCM revealed some differences in capacity, and thus delay, as well as queuing. Unfortunately there is no easy answer if either software is better for performing HCM analysis. Partially, the answer lies in how the analyst wants to apply the HCM guidelines. SIDRA has interpreted the HCM to allow for more flexibility in the configuration of the lanes and approaches to allow modeling of situations beyond original scope of the HCM. Also SIDRA has the advantage of using an iterative method to avoid underpredicting capacity on approaches downstream of oversaturated entries. While capacity has been closely studied, some questions remain about the validity of the delay and queuing models. The HCM delay model and both the HCM and SIDRA queuing models would also need verification for best results. In either software, the analyst still needs to exercise engineering judgment and caution when applying any model to site specific situations.

Appendix E References

1. *Highway Capacity Manual*. TRB, National Research Council, Washington, D.C., 2010.
2. Sampson, B. *Personal email correspondence.* Jul 15, 2011.
3. SIDRA Intersection 5.1 User Guide. Akcelik and Associates Pty Ltd., Melbourne, Australia, 2011.

Appendix F
Future Software Considerations

Future RODEL Versions

Since the onset of this research, RODEL software has been developing beta versions of RODEL V1-Win as an interim program to RODEL V2. Details of this version are as follows:

Hardware Requirements

Any typical modern computer would be capable of running RODEL V1-Win with modest hardware requirements of: 100mHz or faster CPU, 32 KB of RAM, Windows XP or 7, and 5 MB of hard drive space.

Licensing Options

An initial license costs $1,295 with each additional license at $495. Licenses are available as standalone or server based. Existing public agency licensees of RODEL may upgrade free; existing private sector licensees may upgrade for $175.

Availability and cost of support services

Free support is available through website contact, email, and telephone. A variety of training options are available (webinars, 1 to 3 day workshops, etc) and can be tailored to meet specific needs. Costs can be lowered depending on the number of attendees of the seminar, as an approximately estimate from $2,400 to $3,900 per day.

Special Features

- A new capacity model is being developed. Users can select between the new and traditional (RODEL 1.9) capacity models.
- 'Effective geometry' is automatically computed for wide entries. Users can enter the actual field measured geometry and the software will choose the effective geometry.
- English or Metric units
- A Peak Hour Factor may be used as an alternative to the synthetic or direct flow options
- Calibration by slope and intercept adjustments
- Warning messages for incorrect or questionable inputs
- Features from the past version of RODEL are also incorporated such as:
    - While using a native Windows interface, the input/output screen layout is similar to the previous DOS version
    - Performance measures by time slice
    - Confidence level adjustment to account for capacity variation about the mean for more robust designs
    - Direct flow analysis for user defined time slices

Recent and Future Developments

- The most recent beta version as of September 14th, 2011 (Beta v0.78), has been reported to include HCM capacity modeling and control delay options.
- Accident and economic models are being incorporated
- Future RODEL V2 will allow by-lane modeling

Screen Interface

A sample screenshot of RODEL V1-Win Beta 0.78 is shown in Figure F-1.

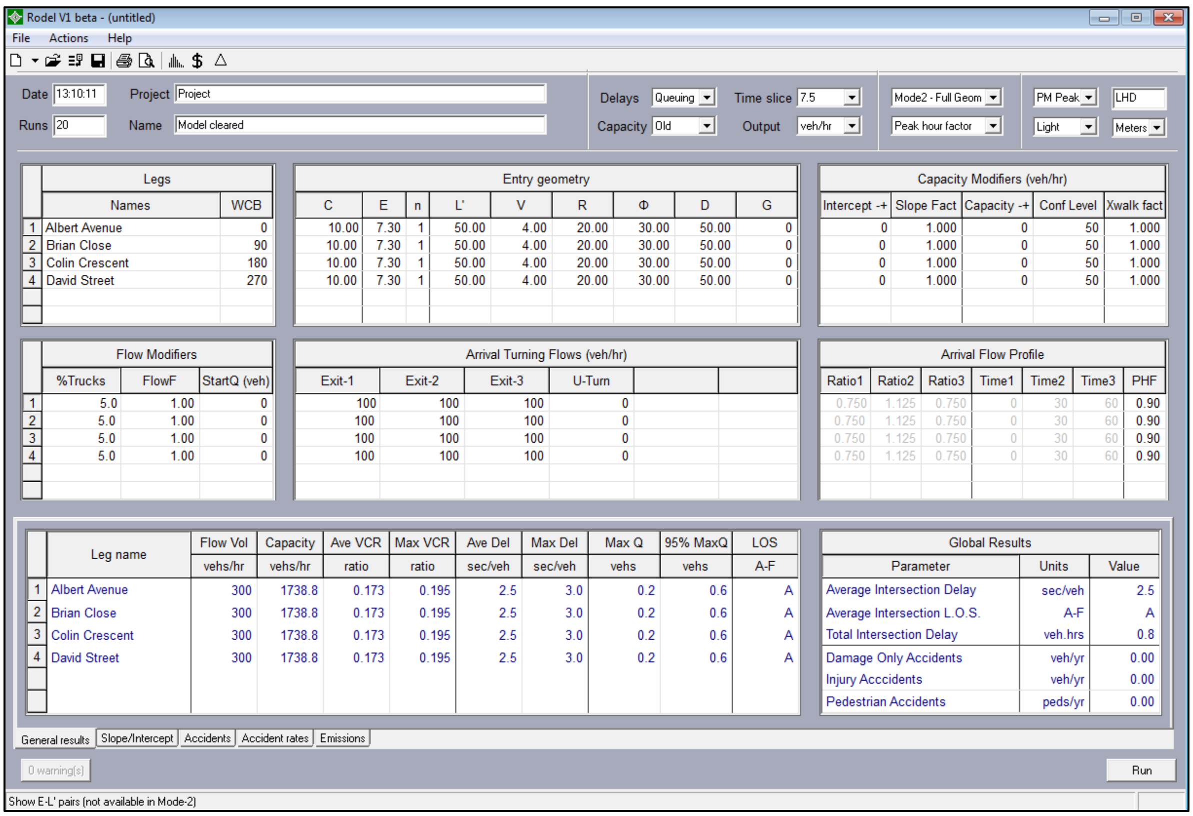


Figure F-1. RODEL V1-Win Beta 0.78 Screenshot

Appendix G
SIDRA and Synchro Discussion

To successfully compare Synchro and SIDRA, using HCM parameters, an understanding of differences between each of their implementations of the Highway Capacity Manual (HCM) and Highway Capacity Software (HCS) must be understood. A Venn diagram in Figure G-1 illustrates a way of thinking about the relationships between the HCM methodology, Synchro HCM reports, and SIDRA HCM reports. The extent and significance of the overlaps and differences in methodologies varies and is situational dependent.

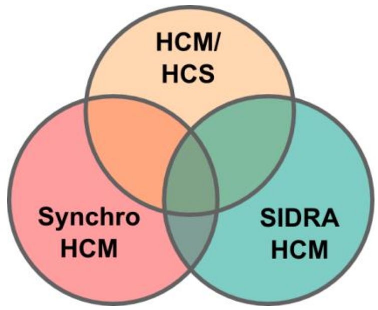


Figure G-1. Methodology Similarities and Differences

For the most part, deviations from the HCM in other software packages arise due to the need to model complex situations not easily modeled within HCS or address limitations of the HCM. Issues of software versions and HCM versions also complicate matters. Table G-1 shows which versions of SIDRA and Synchro are compatible with which version of the HCM.

Table G-1. HCM Compatibility Between Software Versions

HCM 2000		HCM 2010	
SIDRA 5.0	Synchro 7	SIDRA 5.1	Synchro 8

For evaluating roundabout software, SIDRA 5.1 was used due to the new NCHRP 572 and HCM 2010 procedures. However, as Synchro 7 is still prevalent for signalized analysis, the older SIDRA 5.0 software may be needed to make certain comparisons. SIDRA 5.0 had some known complications when set to use HCM 2000 parameters which have been improved in SIDRA 5.1 for the new HCM 2010 procedures. Therefore SIDRA 5.1 is more desirable for comparison purposes, but is not backward compatible with the HCM 2000 and Synchro 7 output.

Given these complications for comparison purposes, several points of discussion of the differences between each software are worth considering.

Synchro 7 HCM

From Synchro User Guide, various aspects of differences between HCM reports generated by Synchro and those by HCS are discussed. Table G-2 summarizes the differences that contribute to observed differences in capacity, other performance measures, and cycle length.

Table G-2. Synchro HCM 2000 and HCS 2000 Differences (Adapted from Table 15-2 of the Synchro 7 User Guide)

Issue	Reason	Capacity Difference	Delay Difference
Queue Delay is not included in the HCM and HCS	New since Synchro 6 is an added measure for queue interaction delays. This measure is not included in the HCM Signal Report or the HCS.	No	Yes
PF (Platoon Factor) Does not match HCM	Affects of coordination are calculated explicitly by Synchro.	No	Yes
Different Green Times	According to the Synchro user manual, "Synchro uses an average of five percentile green times for calculating the actuated green times used with the HCS and the HCM Signal Delay report." See discussion after this table.	Yes	Yes
Dual Ring Controller	HCS does support dual ring controllers and cannot model overlapping clearance intervals (yellow times) for the two rings overlap. It is possible to have actuated green times overlap even if the maximum green times are not overlapping.	Yes	Yes
Rounding Differences	Programs round numbers to different precision.	Minor	Minor
Effective Green Times with Permitted + Protected Left Turns	When both directions have a leading Permitted plus Protected left turn of the same length, the HCS assumes that the interval between the green arrow and the green ball is part of the permitted green time. This causes the HCS to give higher effective green times, lower v/c ratios, lower left turn adjustment factors (F_{LT}), and lower delays.	Yes (Synchro has lower capacity)	Yes (Synchro has higher delay)
Effective Green Times with lagging Permitted + Protected Left Turns	With lagging Permitted plus Protected left turn phasing, the HCS assumes that the interval between Turns the green ball and the green ball counts towards the protected green time. This causes the HCS to give higher effective green times, lower v/c ratios, and lower delays.	Yes (Synchro has lower capacity)	Yes (Synchro has higher delay)

One difference regarding actuated signals is the method used to obtain actuated effective green times. Synchro uses a “percentile scenario” method where five scenarios are evaluated (90th, 70th, 50th, 30th, and 10th) with correspondingly adjusted traffic volumes. In low percentile scenarios, the actuated phases are more likely to gap out, due to lower demand volumes, and in higher percentile scenarios may experience maximum green time more often. While this method is different than the HCM methods, the user guide notes that the actuated green times will be similar.

A difference not highlighted in Table G-2 is that Synchro 7 does not offer HCM queue length calculations and Synchro always reports queues based on its methods. Synchro uses a 95th percentile volume scenario to calculate a 95th percentile back of queue length. The HCM provides a table of factors, which differ for pretimed and actuated signals, in order to adjust an average queue length into a 95th percentile queue length rather than a percentile scenario volume adjustment.

SIDRA 5.1 HCM

Obtaining HCM results from SIDRA can be thought of using the SIDRA philosophy with HCM parameters where appropriate. SIDRA version 5.1 allows both the HCM 2010 delay and queue equations to be used, however some differences between the overall methodologies include:

- Lane-by-lane analysis versus lane-group analysis in the HCM;
- Turn bays (short lanes) are modeled effect adjacent lanes when queues exceed available storage;
- Saturation flow adjustment factors include effects of turn radius;
- Saturation flow for opposed turns is calculated by SIDRA methodology rather than by an adjustment factor; and
- Actuated green times are calculated in a slightly different manner from the HCM.

All of these differences contribute to different estimates of capacity, delay, queue, and cycle length. For the previous SIDRA 5.0, other differences needed to be considered when considering the HCM 2000 due to slight differences in definitions and calculations, mainly associated with delay.

Comparing Synchro HCM and SIDRA HCM

Due to the above differences seen both in terms of software implementation of the HCM as well as different HCM versions, a straight-forward comparison between SIDRA and Synchro proves difficult. Largely the difficulty in making comparisons lies within the issue of cycle length. Each software would likely arrive at different optimal cycle length for the same intersection. Then with different cycle lengths, delay queue and other performance measures cannot be directly compared due to differences in effective green times.

Therefore, one comparison needed would be to investigate and compare differences in estimated optimal cycle length. Comparing delay, queue, and other measures would then require each software to use the same cycle length resulting in another set comparisons. In this case, actuated signals add a layer of complexity due to variations in the way actuated green times are calculated as previously discussed. Therefore a pre-timed scenario would allow for better comparison of delay and queue. In light of the differences, a refined goal of the purpose of comparing Synchro and SIDRA needs further consideration before analysis and reaching conclusions.