APPENDIX B
Field Validation of Roundabout Delay Models Using Probe Data

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ABSTRACT

There are many models currently available that are used to predict delay at roundabouts. This study compared observed probe vehicle delay time with estimates of delay obtained from five alternative models (Highway Capacity Manual 2010, Sidra Intersection, Arcady, Vissim, and Synchro with SimTraffic). Traffic volumes and probe vehicle travel data were obtained at a roundabout that regularly experienced periods of unbalanced flows, oversaturation, and vehicle delay greater than 50 seconds on certain approaches during some times of day.

The paper steps through those discrepancies and summarizes the median error and interquartile range of that error for 15-minute analysis periods over a 36-hour period. Not surprisingly, during uncongested off-peak periods, all models performed well. It was only as volumes approached capacity that discrepancies emerged. Those conditions are described in a manner that will allow practitioners to understand the capability boundaries of current analysis models.

This paper does not intend to define the best roundabout modeling approach, but rather proposes a probe data based assessment technique that can be used to validate and further refine roundabout analysis models.
INTRODUCTION

As roundabouts are becoming more widely considered and implemented for intersection traffic control, understanding how to analyze their expected performance is important. Capacity and delay are two design parameters for roundabouts that are commonly used to describe performance, and are frequently studied [1,2,3]. Several models have been developed to evaluate if a given facility or design will perform acceptably with regards to delay or capacity [1,4]. Over the past two decades, engineers have sought to update and enhance a variety of models based upon field evaluation.

For roundabouts, three classes of models have emerged, including regression analysis, analytical models, and microsimulation. Although the distinction between these broad classes of models has began to blur as the various models have matured over the years. Generally speaking, Regression models look at the intersection on a larger scale with volumetric and/or geometric inputs. Analytical models look more closely at vehicle interaction using headway, gap acceptance, and other related parameters [5]. Microsimulation involves running a virtual model of the intersection or facility under user defined conditions, and records the observed performance. Each of these models can be used to help determine the capacity and delay for their designs under varying design conditions. Ideally, these three classes of models would yield similar results closely matching real-world conditions that drivers experience, but the unique characteristics of each model causes variation in the outputs. Unbalanced flows in roundabouts provide particularly challenging conditions to accurately analyze [6,7,8].

OBJECTIVES AND MODELS

The objective of this study is to compare observed probe vehicle delay time with estimates of delay obtained from alternative models that use volume as an input. Traffic volumes and probe vehicle travel data were obtained at a roundabout where there were approaches frequently had delay exceeding 50 seconds (Level of Service F) [9]. This scenario used for analyzing the following five models:

1. 2010 Highway Capacity Manual
2. Sidra Intersection 5.0
3. Arcady 7.1
4. Vissim
5. Synchro 8 with SimTraffic 8
MODELING AND SOFTWARE

To compare each model, all models used were set up with consistent parameters. Geometry was defined with a center island diameter of 90 feet and circulating width of 20 ft, with one circulating lane. An aerial of the roundabout analyzed is shown in Figure 3 and the location in the Carmel, IN is shown in Figure 4. Approach lengths corresponded to the distance of the adjacent intersections for each arm. The WB and NB approaches both had 0% grade while the grade of the SB and EB entering approaches had a 2% and -2% grade respectively. Identical volume data were used in each model using 15-minute count intervals.

2010 Highway Capacity Manual

The 2010 Highway Capacity Model is self-described as a regression-based model with some analytical components. The model instead is a framework of equations specified in the HCM and demonstrated with an example problem. The capacity equation presented in the HCM was used to determine the capacity for each approach based on the circulating volume. With numbers for both the demand volume and the capacity, the volume-to-capacity ratio was determined. The capacity curves for roundabouts were empirically developed in NCHRP Report 572 and the curve, along with the empirical observations those curves are based upon is shown in Figure 1 [10].

Sidra Intersection 5.0

Sidra is an analytical model based on gap acceptance theory. A default environmental factor of 1.2, and default entry/circulating flow adjustment of “medium” for each arm were used. Volumes for Sidra were adjusted with a peak flow factor and flow scale of 1%, and growth rate of 0% per year. Vehicle occupancy was set by default at 1.2 persons per vehicle. Movement data with a queue space of 25 ft, vehicle length of 17 ft, heavy vehicle gap acceptance of 2.0 seconds and all other model settings were all left at default values.

Arcady 7.1

Arcady is a model from the Transport Research Laboratory (TRL) which has roots as an empirical regression model based on extensive field observations under a wide variety of roundabout geometries. Extended settings such as slope, intercept, capacity adjustment, queue options, and analysis options were left at default values.
**Vissim**

Vissim is a microsimulation model. The model was built and 10 simulation runs were carried out to account for stochastic variation and the median delay on each approach as the modeled delay time. Speed reduction zones were used to slow vehicles entering and circulating in the roundabout. The Vissim model was not calibrated specifically for study and used a default gap acceptance of 3.0 seconds.

**SimTraffic 8**

SimTraffic 8 was the second microsimulation model used in this study. The model was built in Synchro 8 and simulated in the SimTraffic package. As with Vissim, 10 simulation runs were carried out and the median delay time was used as the estimated approach delay. Default values were used for gap acceptance and other extended parameters as described in other models.

**FIELD DATA COLLECTION TECHNOLOGY AND STRATEGY**

Figure 3 shows the location of counting stations ("CS": CS-SB, CS-EB, CS-NB, and CS-WB) used to measure entering volume and Bluetooth monitoring stations ("BMS": BMS-SB, BMS-EB, BMS-NB, and BMS-WB) used to collect probe vehicle travel time data [11,12]. The BMS were also used to estimate the O-D patterns of vehicles through the roundabout [0]. Roundabout turning movement counts were obtained by scaling the total number of entering vehicles by the O-D proportions collected from the BMS shown in Figure 3. This method was developed as an alternative to turning movement data collection technique [14,15]. A photograph of BMS-NB is shown in Figure 5 [16].

The concept of calculating travel time between a given BMS is shown in Figure 2a. In this case, a vehicle was observed at the origin at time $t_1$ and again at the destination at time $t_3$. The difference between the two times is the travel time of the vehicle along the path between the two BMS [15]. Note that deceleration, queuing, and acceleration in the vehicle trajectory are included in this observation window. Figure 2b shows an example travel time calculation for the westbound right turn travel time. A sample vehicle passes the BMS at the origin on the westbound approach at 8:00:00 as it approaches the roundabout. The vehicle decelerates as it nears the roundabout, waits in any queue present, maneuvers, and accelerates as it exits on the southbound approach (heading northbound) where it passes the BMS at the destination at 8:01:25. Using these times gives a travel time of 85 seconds [17].

Control delay is calculated by subtracting the free flow travel time from the measured travel time. To determine the free flow travel time, the path distance between Bluetooth monitoring stations (BMS) was measured, and divided by the free flow speed. From Table 1, the path distance for the westbound right turn is 2,489 feet. This distance, divided by the posted speed of 40 miles per hour (approximately 58.7 feet per second), gives a free flow travel time of 44 seconds, as shown in Table 1 and Figure 2b. Subtracting a free flow travel time of 44 seconds from the measured travel time of 85 seconds results in a control delay of 41 seconds.
Figure 6a shows a cumulative distribution function for the westbound Left, Through and Right turning movements. Since each of these movements have different path lengths, there is an offset. Using the methodology described above and illustrated in Figure 2b, cumulative distribution functions for the westbound delays for each turning movement were calculated, and are shown in Figure 6b. Figure 7 illustrates the temporal variation of the westbound delay during the period between 26 April 2010 and 30 April 2010, clearly indicating substantial westbound delay during the afternoon peak.

Turning movement volumes were developed by scaling the total entry volume using the proportions of turns from probe vehicle origin-destination data. For each 15-minute interval, the counts of observed left turns, right turns, and thru movements observed in the probe vehicle origin-destination data were converted to a turning proportions and multiplied with the total entering volume to derive a turning movement volume for entry into the model. This type of assignment was computed for each 15-minute interval for each approach. In this study, a U-turn volume of zero was assumed.

Lastly, for each approach, circulating volumes were derived by adding up all of the other movements that would have to pass through that portion of the roundabout. For example, circulating traffic on the southbound approach consists of northbound left turns, westbound left turns, and westbound through vehicles. This was done on a 15-minute basis using the 15-minute turning proportions.

To summarize the methodology:

- Probe vehicle data was used to obtain measured control delay and an origin-destination matrix;
- Traffic counters were used to determine entering traffic volumes.
- Probe vehicle data was fused with traffic counts to determine turning movement counts and circulating volumes for entry into delay models to obtain control delay estimates.

**ANALYSIS**

Figure 6b shows that approximately 10% of the westbound traffic experiences delay >50s (LOS F). From Figure 7, it is clear that this occurs primarily during the afternoon peak. This serves as an example of a condition that we would want analysis models to identify based upon design volumes. This section details the application of the alternative analysis models to assess their accuracy in predicting substantial delay that was observed in the field.

Looking at the volumetric data from the study period of 4/26 and 4/27 in Figure 8, unbalanced flow patterns can be seen. During the AM peak (0600-1000), the southbound movement dominates the roundabout, while in the PM peak (1500-1900), the northbound movement dominates, although to a lesser extent. This is a fairly common volume pattern with a sharp morning peak and a large, but more diffuse afternoon peak. Significant queuing was observed for the southbound movement as shown in the inset photograph. Figure 9 through Figure 12 contain a set of identical plots for each of the four
approaches during the 36-hour observation period between 5:15 AM on 26 April 2010 and 7:00 PM on 27 April 2010.

Part (a) in each figure shows the raw probe vehicle delay data as well as the median delay for each 15-minute interval. Median delay was selected in this case because it is less sensitive to outliers than average delay; outliers are most likely attributed to vehicles undergoing trip chaining, or crosstalk between devices. Parts (b), (c), (d), (e), and (f) show the raw probe data with the model prediction for each 15-minute interval overlaid for HCM 2010, Sidra, Arcady, Vissim, and SimTraffic, respectively.

The median error between the measured probe vehicle delay and estimated delay from the five models are summarized for the AM peak (0600-1000) and PM peak (1500-1900) in Figure 13a and Figure 13b, respectively. In these plots, the median travel time is plotted with error bars indicating the interquartile range. For example, callout (iii) in Figure 13a notes where SimTraffic had error for both the 75th percentile and 50th percentile greater than 60 seconds; for more than half of the 32 intervals considered, SimTraffic estimated a control delay greater than 60 seconds. These callout numerals correspond to callout numerals used in Figure 9 through Figure 12.

**Southbound Approach**

Figure 9 starts with the synthesis of delay data for the southbound approach. Figure 9a shows the probe vehicle delay data as measured over 4/26 and 4/27 with the median delay time for each 15-minute interval overlaid. Figure 9b shows the delay prediction from the 2010 HCM with callout (i) noting overestimation of delay during the AM peak period. Also, Figure 9c shows that Sidra had a similar overestimation of delay as noted by callout (ii). SimTraffic's prediction shown in Figure 9f had a unique overestimation of both magnitude and duration of delay as noted by callout (iii). In SimTraffic, very long queues tended to develop which took substantial time to clear. Finally, Arcady and Vissim had similar delay estimates for this approach as shown in Figure 9d and Figure 9e, respectively. This is the only approach that Arcady showed any substantial queuing delay, which may be explained by its high entering volume.

For this particular approach, Figure 8a shows heavy volume entering for the AM peak period. Entering volumes are likely to have reached the oversaturation regime of the models, resulting in overprediction of delay. Also, this movement tended to dominate the roundabout, having almost continuous entering flow (thus lower delay than predicted), and effectively increasing circulating volume that restricted entry from other approaches, particularly the eastbound approach.

While Figure 9 shows the trend over the 36-hour study period, the peak period is most relevant for understanding how the models predict when the volume-to-capacity ratio will be near 1.0 or greater. Figure 13a shows a summary of the AM peak period (0600-1000) for each 15-minutes for both days (32 periods considered). The quartiles of the difference between the measured delay time and the predicted delay time. Callouts (i), (ii), and (iii) all identify models that overestimated the AM peak period in Figure 13a as discussed above. Another secondary impact from the heavy southbound entering volume is
identified by callouts (iv) and (vi) of Figure 13a. Both callouts identify models that predicted a lower delay on the adjacent eastbound approach which, as previously discussed, may be impeded by the large volume entering from the southbound approach.

In Figure 10, the results for the eastbound approach show an increase in delay during the AM peak period, but to a lesser extent than observed on the southbound approach. In Figure 8, we see that the peak of the entering volumes is not pronounced compared to the rest of the day, yet there is a spike in delay in Figure 10 that may be attributed to the nearly constant stream of vehicles entering from the adjacent southbound approach. Most of the models seemed to estimate the eastbound delay better than for the southbound approach. Vissim overestimated delay on 26 April 2010 as noted with callout (v) of Figure 10e, had a closer prediction when the modeling the AM peak for 27 April 2010. Also, Figure 10d for Arcady notes that Arcady predicted almost no delay for the AM peak on either day as noted by callout (iv). SimTraffic had similar results to Arcady with almost no delay during the AM peak period as shown in Figure 10f callout (vi).

**Northbound Approach**

The northbound approach is the predominant movement in the PM peak period (1500-1900) as observed in the volumetric data presented in Figure 8. The delay results for the northbound approach in Figure 11 show two instances noted by callout (vii) where the probe data included some obvious outliers, perhaps associated with vehicles making intermediate stops longer than 5 minutes during the a.m. and p.m. peaks. These points were excluded when summarizing error by 15-minute periods in Figure 13. The HCM and Sidra had similar delay characteristics, but different estimated delay magnitudes as observed in Figure 12b and Figure 12c, respectively. Also, SimTraffic predicted a very large delay for 26 April 2010 as noted by callout (viii) in Figure 12. A similar prediction was made for 27 April 2010 which more closely matched the field observations.

**Westbound Approach**

The westbound approach is highly influenced by the dominant flow from the northbound approach during the PM peak period. Especially on Tuesday 27 April 2010, the models all underestimate the delay, as shown in Figure 12. This substantial PM peak in delay is likely caused by a heavy volume entering from the northbound approach, as shown in Figure 8. The HCM (Figure 12b) Sidra (Figure 12c) are the only two models that predict any substantial delay, while Arcady, Vissim, and SimTraffic indicate almost no delay.
CONCLUSIONS

Probe data and volumetric data was collected at a single lane roundabout in Carmel, Indiana and compared to delay output from five different models: the Highway Capacity Manual (2010), Sidra Intersection 5.0, Arcady 7.1, Vissim, and SimTraffic 8. During certain times of the day, the intersection experienced unbalanced flow, and approaches experienced delays greater than 50 seconds.

Not surprisingly, during uncongested off-peak periods (Figure 9, Figure 10, Figure 11, Figure 12), all models performed well. It was only as conditions approached capacity that discrepancies emerged. Figure 13 shows that the Vissim model performed very well during both peak periods, with the exception of a large interquartile range for the eastbound approach during the AM peak period (Figure 13, callout v). Sidra was also noteworthy for only having one substantial outlier (Figure 13, callout ii) that could perhaps have been resolved by calibrating environmental factors and other extended settings.

Moving forward, it is clear that both driver behavior in roundabouts and the practice of modeling roundabout performance is maturing in the United States. This is analogous to developments in signalized intersections where Greenshields’ observed vehicle departure headways from 1947 (19) were used as a basis for saturation flow until the early 1980’s as well Greenshields parabolic Flow-Density model to define capacity thresholds (20). Subsequently, saturation flow rates and analytical techniques have evolved based on increasing data to reflect changes in driver behavior (21, 18). It is expected that as drivers in the US increasingly acquire more experience with roundabouts, performance models will likewise evolve to account for performance changes.

This paper is not intended to define the best roundabout modeling approach, but instead proposes a probe data based assessment technique that can be used to objectively analyze and further refine roundabout analysis models.

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REFERENCES


Figure 1 Single-lane and adjusted critical-lane regression as shown in Figure 37 of NCHRP Report 572 [1]
Figure 2 Conceptual relationship of space-mean speed with regards to control delay
Figure 3  Location of single-lane roundabout study at W 106th Street and Spring Mill Road in Carmel, Indiana during April 2010

Figure 4  Equipment layout at W 106th Street and Spring Mill Road in Carmel, Indiana during April 2010
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<table>
<thead>
<tr>
<th>APPROACH</th>
<th>Left Turn Movement</th>
<th>Thru Movement</th>
<th>Right Turn Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length  (Feet)</td>
<td>Travel Time  (Seconds)</td>
<td>Length  (Feet)</td>
</tr>
<tr>
<td>Southbound</td>
<td>2,646</td>
<td>49</td>
<td>4,039</td>
</tr>
<tr>
<td>Westbound</td>
<td>3,854</td>
<td>65</td>
<td>5,181</td>
</tr>
<tr>
<td>Northbound</td>
<td>6,732</td>
<td>119</td>
<td>4,039</td>
</tr>
<tr>
<td>Eastbound</td>
<td>5,806</td>
<td>103</td>
<td>5,181</td>
</tr>
</tbody>
</table>
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