Comparing Roundabout Capacity Analysis Methods, or
How the Selection of Analysis Method Can Affect the Design

ABSTRACT

Several analysis methods have been proposed to analyze the vehicular capacity of roundabouts. Some are deterministic equations based on regression equations of observed capacity or observed gap acceptance. Others are stochastic models that simulate driver behavior. Some are equations that can be applied manually or using spreadsheets. Others require computer software to implement. Given these differences, it may not be apparent which method is the best to use for a particular case. When comparing capacity analysis methods, it would be useful to know how the various methods perform over a range of approach and conflicting volumes.

This paper reports on the approach capacity for a single-lane roundabout based on the maximum entering and conflicting circulating volumes for several analysis methods. In *Roundabouts: An Informational Guide* (FHWA, 2000), Exhibit 4-3 shows a capacity chart according to the recommended capacity equations. Similar capacity charts were prepared for six additional methods: HCM 2000, HCM 2010, SIDRA INTERSECTION, SimTraffic, VISSIM, and Paramics.

When applying an analysis methodology, the procedure should be calibrated and validated to field measurements in the study area – particularly for simulation models, which have many adjustable parameters. However, for the comparison presented in this paper, the default parameters were used so that a baseline comparison could be provided. For a particular range of conflicting and entering volumes, some analysis methods predicted higher capacity than others. For different ranges on volumes, other analysis methods were higher. Given this variation, the use of more than one analysis method is suggested so that the analyst will have a higher confidence in the final design recommendation.

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INTRODUCTION

Based on project experience, different roundabout capacity analysis methods provide different delay results. As a result, using more than one analysis method would provide more confidence in the final recommendation (Stanek and Milam, 2004; Pack, Milam and Stanek, 2008). While this provides the set of analysis results for one particular case, it would be useful to know how the analysis methods typically perform over a range of entering and conflicting flows.

Roundabouts: An Informational Guide (FHWA, 2000) provides a capacity chart showing how the maximum entry flow (approach capacity) for a single lane roundabout varies depending on the conflicting volume (see Exhibit 1).

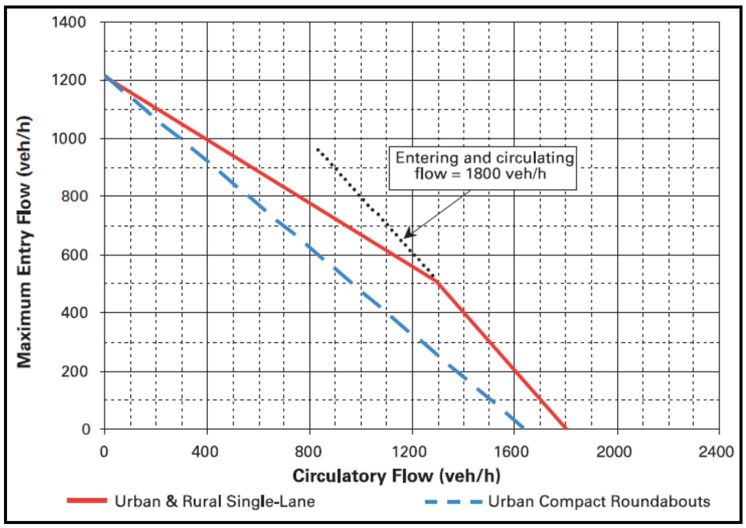

Exhibit 1. Exhibit 4-3 from *Roundabouts: an Informational Guide*

In this paper, capacity curves as shown in Exhibit 1 are presented and compared for the following analysis methods.

- FHWA 2000 – capacity equation from *Roundabouts: An Informational Guide*
- HCM 2000 – capacity equation from *Highway Capacity Manual 2000* (TRB, 2000)
- HCM 2010 – capacity equation from *NCHRP Report 672 – Roundabouts: An Informational Guide, Second Edition* (TRB, 2010)
- SIDRA INTERSECTION – a deterministic analysis software program distributed by SIDRA SOLUTIONS
- SimTraffic – a simulation analysis software program distributed by Trafficware
- VISSIM – a simulation analysis software program distributed by PTV America
- Paramics – a simulation analysis software program distributed by Quadstone Paramics

When applying any capacity analysis methodology, the procedure should include calibration and validation to the study area – particularly for simulation models, which have many adjustable parameters. For the comparison presented here, the default parameters were used for all methods except where noted below. Using the default parameters will provide a baseline comparison of the methods. Adjustments to the methods can be done to alter the capacity curve to match field measurements.

The goal of this paper is not to critique the analysis methods that are presented. These methods have all been thoroughly tested and are commonly applied to estimate roundabout capacity. Rather, the intent here is to inform the reader how the uncalibrated methods perform across varying flow levels so that the effect of model selection can be understood and incorporated into the roundabout design process.

ANALYSIS METHODS

The seven roundabout capacity analysis methods described in this paper can be grouped into deterministic (FHWA 2000, HCM 2000, HCM 2010, and SIDRA) and simulation (SimTraffic, VISSIM, and Paramics) methods. Deterministic models use flow rates and geometry to estimate capacity based on formulas developed from statistical regression analysis or gap acceptance theory. Simulation software models individual vehicles that have a range of driver behavior (car-following, lane-changing, etc.) and vehicle performance, which is assigned randomly (stochastic analysis).

The deterministic analysis methods used in the comparison are described below.

<u>FHWA 2000</u>

Roundabouts: An Informational Guide provides the following capacity equation (Exhibit 2), where Q_e is the entry capacity and Q_c is the conflicting circulating flow.

$$Q_e = 1212 - 0.5447Q_c$$

Exhibit 2. Equation A-8 from *Roundabouts: an Informational Guide*

The above equation is limited so that the combined entry and circulating flow cannot exceed 1,800 vehicles per hour. This occurs when the circulating flow is about 1,291 vehicles per hour. At higher flow rates, the entry capacity is the difference between 1,800 vehicles per hour and the circulating flow.

This equation is a simplification of the British roundabout capacity equations developed by the Transport Research Laboratory (TRL). The TRL equation was simplified by assuming a particular geometric design even though the equation is presented as applicable for a range of diameters from 80 to 180 feet. RODEL, a deterministic software program developed by Barry Crown, fully implements the British method of roundabout capacity analysis. (Application of RODEL to the scenario presented in this paper produced a capacity curve nearly identical to the FHWA 2000 equation for conflicting flows less than 1,300 vehicles per hour).

HCM 2000

The *Highway Capacity Manual 2000* (HCM 2000) provides the following equation (Exhibit 3) for determining the approach capacity for a single-lane roundabout.

$$c_a = \frac{v_c e^{-v_c t_c / 3600}}{1 - e^{-v_c t_f / 3600}}$$

where

c_a = approach capacity (veh/h),
v_c = conflicting circulating traffic (veh/h),
t_c = critical gap (s), and
t_f = follow-up time (s).

Exhibit 3. Equation 17-70 from *HCM 2000*

Two sets of values for the critical gap (t_c) and follow-up time (t_f) were provided: an upper and a lower bound. For the comparison presented here, the average of the upper and lower bounds were used to determine approach capacity.

HCM 2010

The *Highway Capacity Manual 2010* (TRB, 2011) has a new methodology for roundabout capacity analysis as reported in *NCHRP Report 672 – Roundabouts: An Informational Guide, Second Edition*. The HCM 2010 capacity equation is shown in Exhibit 4.

$$c_{e,pce} = 1{,}130 e^{(-1.0 \times 10^{-3}) v_{c,pce}}$$

where

$c_{e,pce}$ = lane capacity, adjusted for heavy vehicles, pc/h; and
$v_{c,pce}$ = conflicting flow, pc/h.

Exhibit 4. Equation 4-3 from *NCHRP Report 672 – Roundabouts: An Informational Guide, Second Edition*

The HCM 2010 roundabout capacity equation is a regression equation based on observed data at 31 sites in the U.S. The background information on this research is provided in *NCHRP Report 572 – Roundabouts in the United States* (TRB, 2007).

SIDRA

SIDRA INTERSECTION (Version 5.0) is a deterministic software program distributed by SIDRA SOLUTIONS (www.sidrasolutions.com). The results tables from SIDRA list the approach capacity as a performance measure along with delay and queue length.

The simulation analysis methods used in the comparison are listed below.

- SimTraffic – Version 773 distributed by Trafficware (www.trafficware.com)
- VISSIM – Version 5.3 distributed by PTV America (www.ptvamerica.com)
- Paramics – Version 6.7 distributed by Quadstone Paramics (www.paramics-online.com)

For the micro-simulation software programs (SimTraffic, VISSIM, and Paramics), a direct equation of entry capacity to circulating flow is not available as it is with the deterministic methods. Although capacity can be measured directly by collecting the volume served on the approach, this does not provide the demand volume on the approach that would correspond to the demand volume used in deterministic methods. Instead, the approach capacity was derived from the approach delay output using the intersection delay equation (see Exhibit 5) from the HCM 2000.

$$d = \frac{3600}{c_{m,x}} + 900T\left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1\right)^2 + \frac{\left(\frac{3600}{c_{m,x}}\right)\left(\frac{v_x}{c_{m,x}}\right)}{450T}}\right] + 5$$

where

d = control delay (s/veh),
v_x = flow rate for movement x (veh/h),
$c_{m,x}$ = capacity of movement x (veh/h), and
T = analysis time period (h) (T = 0.25 for a 15-min period).

Exhibit 5. Equation 17-38 from *HCM 2000*

For a given conflicting volume and analysis time period (15 minutes), the simulation method was applied to determine the delay for a given entry volume. Then, the volume-to-capacity ratio (v/c) was calculated from the above equation. The entry volume was adjusted iteratively until the v/c ratio was approximately equal to one. Because this approach is an approximation, the capacity estimation is affected by the assumptions used to develop the delay formula and the randomness involved in the stochastic modeling.

Micro-simulation software reports total delay; however, the HCM 2000 delay equation above specifies control delay. Total delay is the sum of control delay (due to sign control and conflicting traffic) and geometric delay (caused by slowing to negotiation speed due to deflection angle and other geometric features of the roundabout). As noted in *Roundabouts: An Informational Guide, Second Edition*, the total delay estimated by a simulation method would not be directly comparable to control delay estimated by a deterministic method. Near capacity, geometric delay is relatively small compared to the total delay, so total delay is approximately equal to control delay. For the results presented here, the total delay is assumed to equal the control delay. An investigation of the effect of geometric delay on the capacity curve is presented later in this paper.

MODELING ASSUMPTIONS

To minimize other effects on capacity, a consistent set of modeling assumptions is used in the comparison of analysis methods. These assumptions are listed below.

- No U-turns
- No trucks – 100 percent passenger cars
- No pedestrians or bicycles – no reduction in capacity at crosswalks
- No peak hour factor – peak hour factor set to one
- 15-minute analysis period

In addition, the software programs (SIDRA, SimTraffic, VISSIM, and Paramics) have additional inputs that affect capacity. The following modeling assumptions were used for these methods.

- Inscribed diameter of 100 feet
- Circulating roadway width of 15 feet
- Intersection with four legs intersecting at 90 degrees
- Average link speed of 40 miles per hour on all approaches

Because the software programs model the entire intersection, the flows for the turning movements were assigned in a systematic way. On the measured approach, the flow for left and right turns was set to 20 percent each of the total entry flow (the value of 20 percent was selected for convenience of calculating turning flow from total entry flow rather than for any observation of typical intersection turning flows). On the other three approaches, the flow for left and right turns was set to 20 percent each for conflicting flows of 600 vehicles per hour (vph) or lower. For conflicting flow of 700 vph or higher, the conflicting flow was 20 percent from the opposing left-turn, 20 percent from the adjacent left-turn, and 60 percent from the adjacent through movement. (For the northbound approach at a 90-degree, four-leg intersection, the southbound approach is opposing, and the eastbound approach is adjacent.) Without the modification for volumes 700 vph or higher, another approach would control roundabout operations and, therefore, restrict the conflicting volume for the measured approach.

So that the results would be as comparable as possible, the simulation programs – SimTraffic, VISSIM, and Paramics – used the settings shown in Table 1. The seeding time for Paramics differs from the other two methodologies because the interval time must be the same for all periods. The 15 minute seeding period was used to avoid having to calculate the results over three 5-minute recording periods. The circulating speeds for SimTraffic and Paramics are the default values. For VISSIM, the analysis uses a linear distribution of speed from 15 to 20 mph, with an average at 17.5 mph.

Table 1. Simulation Settings

	SimTraffic	VISSIM	Paramics
Approach link length	3,000 ft	3,000 ft	3,000 ft
Default driver and vehicle parameters	X	X	X
Average of 10 runs with consecutive random seeds	X	X	X
Seeding time	5 minutes	5 minutes	15 minutes
Recording time	15 minutes	15 minutes	15 minutes
Circulating roadway speed	18 mph	17.5 mph	20 mph

The software programs also had additional modeling assumptions are program-specific. Although the gap acceptance parameters can be adjusted in the SIDRA software, the default values were used for this analysis. SIDRA has additional default settings for Environment Factor and Entry / Circulating Flow Adjustment. The default Environment Factor of 1.2 for U.S. locations was used. This factor accounts for the observed lower roundabout capacity in the U.S. compared to the data set that was used to develop the capacity model. The default Entry/Circulating Flow Adjustment of “Medium” was used. This setting increases approach capacity for dominant flows when the conflicting flow is low.

To build the model roadway network in the VISSIM software, Exhibit 3-16 from *Roundabouts: An Informational Guide* (see Exhibit 6) was used as the background. VISSIM provides two options for modeling intersection yielding: priority rules and conflict areas. For this analysis, priority rules were implemented as described in the user manual’s section on modeling roundabouts. The analysis used the default values for minimum gap time and headway.

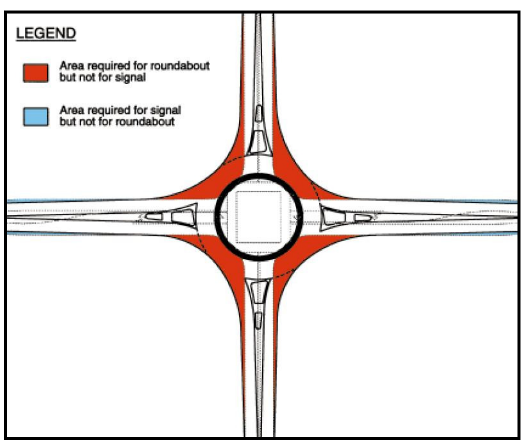

Exhibit 6. Exhibit 3-16 from *Roundabouts: An Informational Guide*

In Paramics, the “create roundabout” function in the junction editor was used to generate the intersection geometry. Although the network can be adjusted to more closely match the actual roadway design, the automatically generated model geometry, which is sufficient in most cases, was used for the analysis.

ANALYSIS RESULTS

Exhibit 7 shows the capacity curves for the roundabout analysis methodologies and software programs.

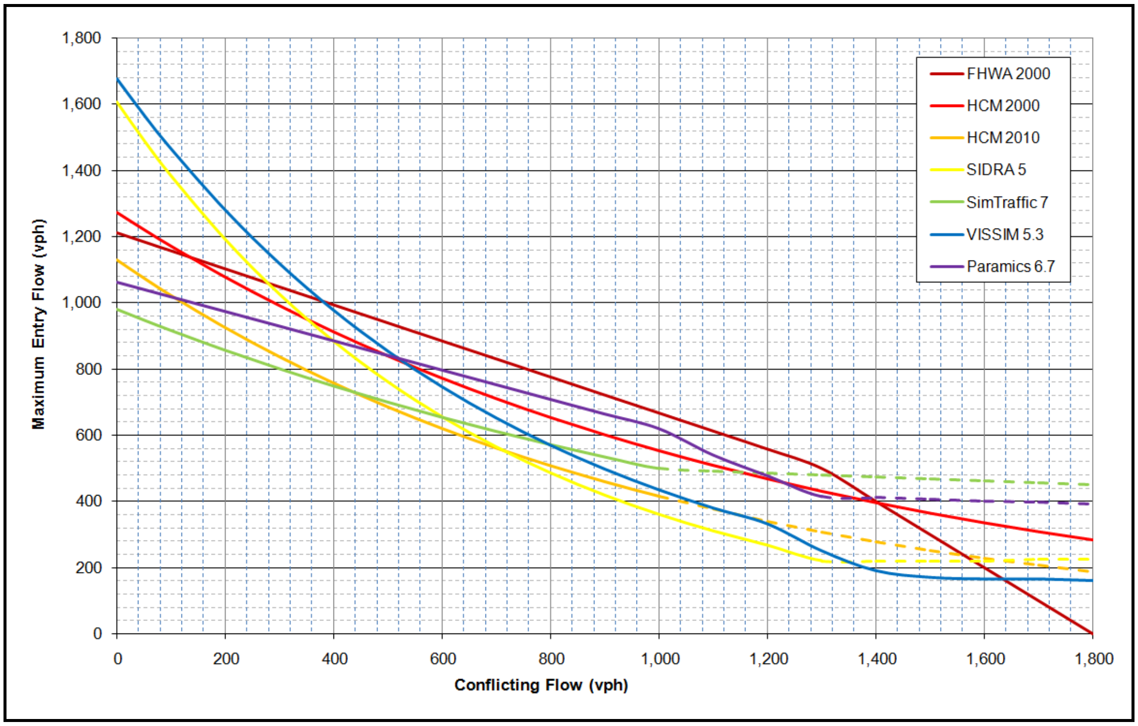

Exhibit 7. Single Lane Roundabout Capacity

The curves for the non-software analysis methodologies (FHWA 2000, HCM 2000, and HCM 2010) are smooth since they are a direct graph of a capacity equation. The curves for the four software programs are not smooth because capacity did not vary continuously over the range of conflicting flow. Exponential and linear regression was used in step-wise fashion to determine an approximate best-fit curve based on data points collected at intervals of 100 vph in conflicting flow.

The chart shows dashed lines for some curves after about 1,000 vph in conflicting flow. For HCM 2010, the dashed line represents an extrapolation because the data set used to develop the capacity equation did not contain data in this range. For the software programs, the dashed line represents the condition that some other approach controls operations (that is, has a v/c ratio greater than 1) such that the conflicting flow is constrained from reaching the measured approach for the given set of turning movement volumes.

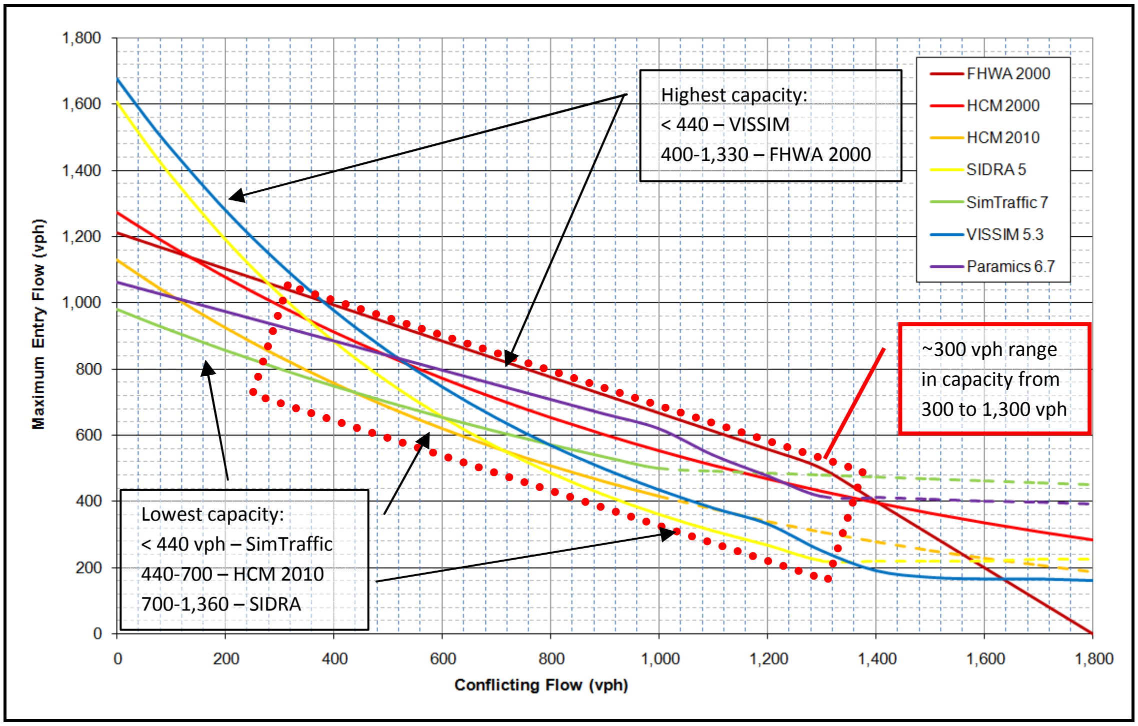

Exhibit 8. Single Lane Roundabout Capacity - Annotated

A general observation of the capacity curves is that the range of approach capacity is relatively constant – about 300 vph – from 300 to 1,300 vph in conflicting flow (see Exhibit 8). Other observations are noted below.

- The FHWA 2000 method predicts the highest approach capacity for conflicting flows from about 400 to 1,300 vph (see Exhibit 8).
- For conflicting flows less than 440 vph, SimTraffic predicts the lowest approach capacity. The HCM 2010 method has the lowest capacity from about 440 to 700 vph. And, SIDRA predicts the lowest capacity from 700 to 1,360 vph (see Exhibit 8).
- The HCM 2010 method has a lower capacity than either the FHWA 2000 or HCM 2000 methods. The HCM 2010 method has the consistently lowest capacity, so it provides a conservative approach (that is, a method that is less likely to result in a design than cannot accommodate the demand volume).
- For low conflicting volume – less than 300 vph, VISSIM and SIDRA predict higher capacity than the other methods. Extrapolating the curves yields a maximum capacity of about 1,600 vph for these two methods compared to a range from 1,000 to 1,300 vph for the other methods.
- The curves for the software programs flatten out at higher conflicting flows because the adjacent upstream approach has a v/c ratio greater than one, which constrains the conflicting flow at the analysis approach. For SimTraffic, the curve flattens at about 1,000 vph. For SIDRA and Paramics, this occurs at about 1,300 vph. For VISSIM, the flattening of the curve happens at

a conflicting flow of about 1,500 vph. The residual approach capacity varies from about 160 to 480 vph.

- Both the FHWA 2000 and Paramics curves are linear for conflicting flows less than 1,000 vph. All other methods have non-linear curves for this range of conflicting flow.

While the methods vary in approach capacity, the measured capacity at roundabouts is also varied. Exhibit 9 shows the capacity curves with the observed data from *NCHRP Report 572 – Roundabouts in the United States*, which was used to develop the HCM 2010 capacity equation. The observed data has an approximate range of 500 vph in conflicting flow that is greater than the 300 vph range for the analysis methods.

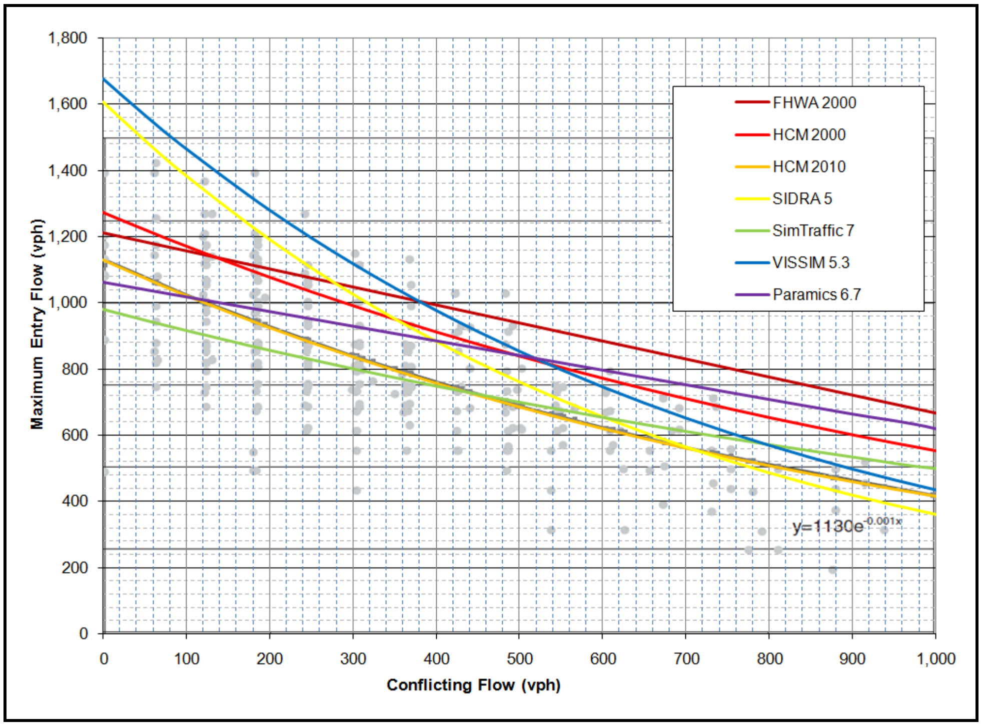

Exhibit 9. Single Lane Roundabout Capacity and
Figure 30 from *NCHRP Report 572 – Roundabouts in the United States*

TOTAL DELAY VERSUS CONTROL DELAY

The software programs provide average total delay as a performance measure. As discussed in *NCHRP Report 672 – Roundabouts: An Informational Guide, Second Edition*, total delay is the sum of the control delay and geometric delay. Control delay is used in the HCM to assign intersection level of service. Geometric delay at the roundabout is caused by drivers slowing to negotiate the roundabout. If no control or geometric features were present, the vehicle would have no delay at the intersection. Typically, the distinction between control delay and total delay is ignored in simulation applications since the comparison among scenarios uses the same analysis method. Additionally, drivers cannot distinguish between control and geometric delay, so presenting total delay is more understandable to the general public.

To test the effect of control delay versus total delay on the capacity curves, the geometric delay for the roundabout was measured using the VISSIM software. First, the average travel time through the roundabout for one vehicle without any conflicting volume was measured. Next, the average travel time of one vehicle without any speed reduction (that is, free-flow speed is maintained instead of slowing to the negotiation speed) was collected. The difference in travel time between these two models produces a delay estimate of 6.1 seconds.

The simulation output data that was used to develop the capacity curve – the iterative selection of entry flow to determine the value at which the v/c ratio equaled one – was reviewed. For conflicting flows of 400 vph or less, a 6-second decrease in delay would shift the maximum entry flow (capacity) lower by 20 vph or more. For larger conflicting flows, the change is capacity would be 10 vph or less. Given the relatively small value for geometric delay, the use of total delay for the capacity curves does not change the overall relationship between the capacity curves for the different methods.

SOFTWARE VERSION

Software programs are continually updated as new features are added and errors are corrected. As a result, the analysis results can vary for an analysis method depending on the version that is applied. The effect of the software version was investigated for two of the analysis methods: SimTraffic and VISSIM.

A comparison of VISSIM versions 4.3 and 5.3 showed almost identical capacity curves. However, the results for SimTraffic versions 6 and 7 were different. Exhibit 10 shows the capacity curves for SimTraffic versions 6 and 7 with HCM 2010 for comparison.

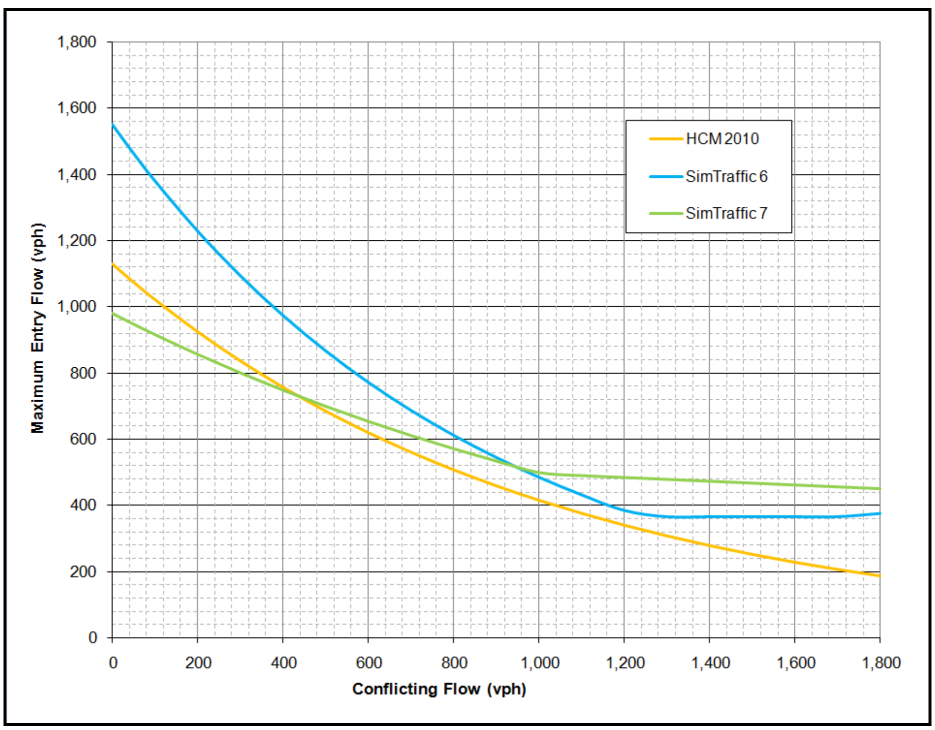

Exhibit 10. Single Lane Roundabout Capacity for SimTraffic 6 and 7

The SimTraffic 6 curve is more similar to those for SIDRA and VISSIM shown in Exhibit 7. In constrast, SimTraffic 7 has a lower capacity for conflicting flows less than 1,000 vph. As a result, its capacity curve is closer to the curve for the HCM 2010 method.

CONCLUSION

This paper has presented a comparison of methods for roundabout capacity analysis. A chart of conflicting flow versus maximum entry flow (capacity) for seven methods was prepared. For the set of assumptions, the methods produced estimates of capacity that were within a 300-vph band although the capacity estimates diverged for a conflicting flows less than 300 vph. The capacity equation from the first edition of *Roundabouts: An Informational Guide* was one of the highest capacity curves, but the equation from the second edition is one of the lowest curves. The shape of the capacity curves was also found to differ across the methods.

Given the variation in capacity estimates, the roundabout design that is selected may be a single-lane roundabout if one method is used, or, if another method is used, the selected design may have two-lane approaches or a right-turn bypass lane. Two example cases are presented below.

Case 1 – Conflicting flow of 160 vph and approach flow of 1,160 vph

> On the capacity curve chart (Exhibit 7), this point falls below the curves for SIDRA and VISSIM, but above the curves for the other five methods. The SIDRA and VISSIM results would indicate that a single-lane roundabout would provide adequate capacity for this condition. The other methods would show this case to be over capacity, such that an additional lane would be needed.

Case 2 – Conflicting flow of 800 vph and approach flow of 600 vph

> On the capacity curve chart, this point falls below the curves for FHWA 2000, Paramics, and HCM 2000, but above the curves for SimTraffic, VISSIM, HCM 2010, and SIDRA. The first set of results would indicate that a single-lane roundabout would provide adequate capacity for this condition. The latter set of results would show this case to be over capacity, such that an additional lane would be needed.

Interestingly, the methods that show sufficient capacity for the first case are the ones that show insufficient capacity in the second case.

Based on these findings in this paper, the following steps are recommended for roundabout capacity analysis.

- Calibrate the model to local conditions – The variation in model capacity is based on different model assumptions and input data. Each method can be adjusted to match local conditions.

- Check other analysis methods – Use more than one analysis method to compare results for reasonableness. If a deterministic method is selected, check the results using another deterministic method. If a more complex method (simulation) is used, check the results using a deterministic method. This may uncover model coding errors and/or lead to a better understanding of network traffic operations.

- Prepare a sensitivity analysis – Given that forecasts are inherently imprecise, analyze roundabout capacity using a set of volumes that are 10 percent higher. Roundabouts approach capacity more quickly than signalized intersections, so this can provide a better sense of how close the roundabout is to capacity.

- Use the HCM 2010 method for a conservative approach – If the goal is to ensure that sufficient capacity will be provided, the HCM 2010 method can be used since it provided the consistently lowest capacity. This decision should be weighed against the limitations of the HCM 2010 method and other factors relating to roundabout design such as construction cost, right-of-way impacts, and pedestrian operations.

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