Capacity and Performance of Roundabouts: A Summary of Recommendations in the FHWA Roundabout Guide

BRUCE W. ROBINSON
LEE A. RODEGERDTS
Kittelson & Associates, Inc., USA

ABSTRACT

The U.S. Federal Highway Administration (FHWA) publication, *Roundabouts: An Informational Guide*, presents a comprehensive discussion of roundabout planning, performance analysis, and design. One of its features is the definition of six categories of roundabouts, ranging from small, urban mini-roundabouts to relatively large, rural double-lane roundabouts. Distinctions have been made between the various categories in terms of characteristics, planning procedures, operational analysis, and design treatments. This paper presents the various elements of operational analysis included in the guide, including measures of capacity and performance analysis, and provides a discussion of many of the decisions made during the development of the guide. The paper presents capacity curves for urban compact roundabouts, single-lane roundabouts, and double-lane roundabouts, as well as adjustment factors to account for the effect of short lanes (flaring). The paper also presents the methodologies and recommended practices for determining degree of saturation, delay, and queuing.

1. INTRODUCTION

The FHWA publication, *Roundabouts: An Informational Guide* (hereafter referred to as the FHWA Roundabout Guide), presents a comprehensive discussion of roundabout planning, performance analysis, and design for a variety of categories of roundabouts, ranging from small, urban mini-roundabouts to relatively large, rural double-lane roundabouts. The draft *Highway Capacity Manual* 2000 (TRB 1999) is limited to the capacity analysis of single-lane roundabouts and is insensitive to the wide range of geometric configurations possible with roundabouts. In addition, the methodology in the HCM does not provide any guidance on estimation of delay or queues. Therefore, it was necessary to extend beyond the HCM to develop an operational analysis procedure commensurate with the scope of the FHWA Roundabout Guide. This entailed review of many of the major models and findings of other countries, principally the United Kingdom (Kimber 1980), France (Guichet 1997), Germany (Brilon et al. 1997), and Australia (Akçelik 1998; Akçelik and Troutbeck 1991; Austroads 1993).

This paper presents a summary of the recommendations in the FHWA Roundabout Guide with respect to operational analysis. In addition, it presents the rationale behind many of the decisions made during the development of the guide. It is recognized at the outset that the methodology presented in this document is based on the experience from other countries and the judgment of the authors of the FHWA Roundabout Guide. As more research is conducted in the United States, it is expected that the procedures presented here will be improved and refined. However, in the judgment of the authors, the methodologies

presented here represent a reasonable starting point from which good design decisions can be made.

This paper begins by presenting a discussion of the capacity models chosen for three key categories of roundabouts proposed in the FHWA Roundabout Guide. It then presents a discussion of the models for performance measures selected for the guide. The paper closes with a conclusion and list of references.

2. CAPACITY

The FHWA Roundabout Guide categorizes roundabouts according to size and environment to facilitate discussion of specific performance or design issues. There are six basic categories based on environment, number of lanes, and size:

- Mini-roundabouts
- Urban compact roundabouts
- Urban single-lane roundabouts
- Urban double-lane roundabouts
- Rural single-lane roundabouts
- Rural double-lane roundabouts

This paper focuses on the formulations of capacity and performance measures for urban compact, urban single-lane, and urban double-lane roundabouts. The FHWA Roundabout Guide conservatively assumes that rural roundabouts have the same capacities as their urban counterparts, even though the geometric features of rural roundabouts may yield higher capacities. In addition, mini-roundabout capacities have not been specifically defined but are addressed in the FHWA Roundabout Guide on a planning level using daily maximum service volumes. Multi-lane roundabouts with more than two approach lanes are acknowledged but not covered explicitly in the FHWA Roundabout Guide.

2.1   Single-Lane Roundabouts

The following sections discuss the two principal roundabout categories with single-lane entries: the urban compact roundabout and the urban single-lane roundabout.

2.1.1   Capacity of urban compact roundabouts

Urban compact roundabouts have nearly perpendicular approach legs that require very low vehicle speeds to make a distinct right turn into and out of the circulatory roadway. These roundabouts have typical inscribed circle diameters in the range of 25 m to 30 m. All legs have single-lane entries. The recommended design of these roundabouts is similar to those in Germany and other northern European countries. Figure 1 provides an example of a typical urban compact roundabout.

Reflecting its style of design and its effect on operations, the capacity curve for the urban compact roundabout is based on the capacity curves developed for roundabouts in Germany with single-lane entries and a single-lane circulatory roadway. This equation, developed by Brilon et al. (1997), is as follows:

$$Q_e = 1218 - 0.74 Q_c \tag{1}$$

where: Q_e = entry capacity, pce/h
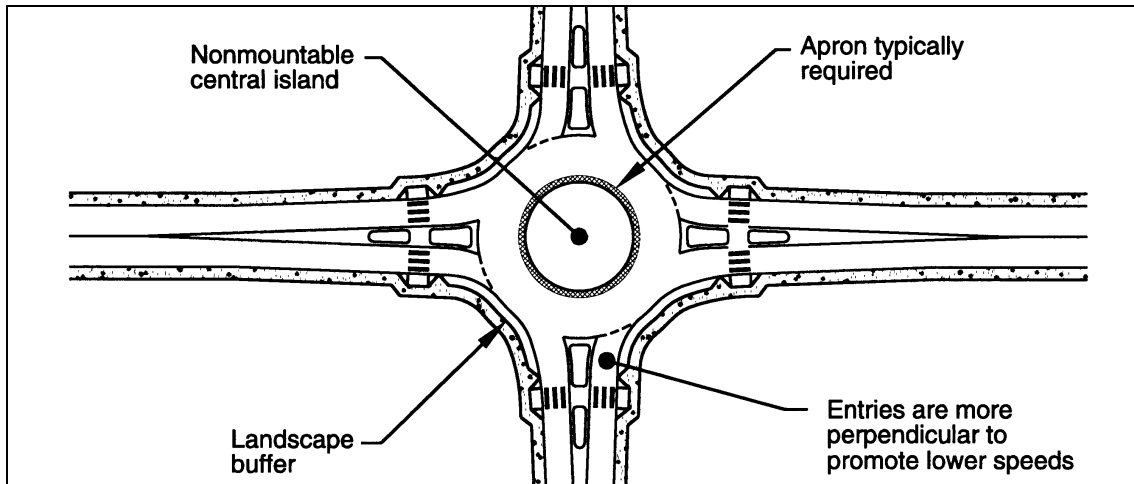Q_c = circulating flow, pce/h

FIGURE 1   Typical urban compact roundabout.

2.1.2   Capacity of urban single-lane roundabouts

Urban single-lane roundabouts are distinguished from urban compact roundabouts by their larger inscribed circle diameters (typically in the range of 30 to 40 m) and somewhat more tangential entries and exits, resulting in higher capacities. Urban single-lane roundabouts are likely to be the most common category built in the United States due to their higher capacity and ability to handle the largest design vehicles. Figure 2 provides an example of a typical urban single-lane roundabout. Their design allows slightly higher speeds at the entry, on the circulatory roadway, and at the exit. The design of these roundabouts is similar to those in Australia, France, and the United Kingdom.

The capacity equation for urban single-lane roundabouts is based on the equations developed in the United Kingdom by Kimber (1980). The Kimber equations were chosen as a starting point for a U.S. model over the models from other countries based on simplicity of Kimber's
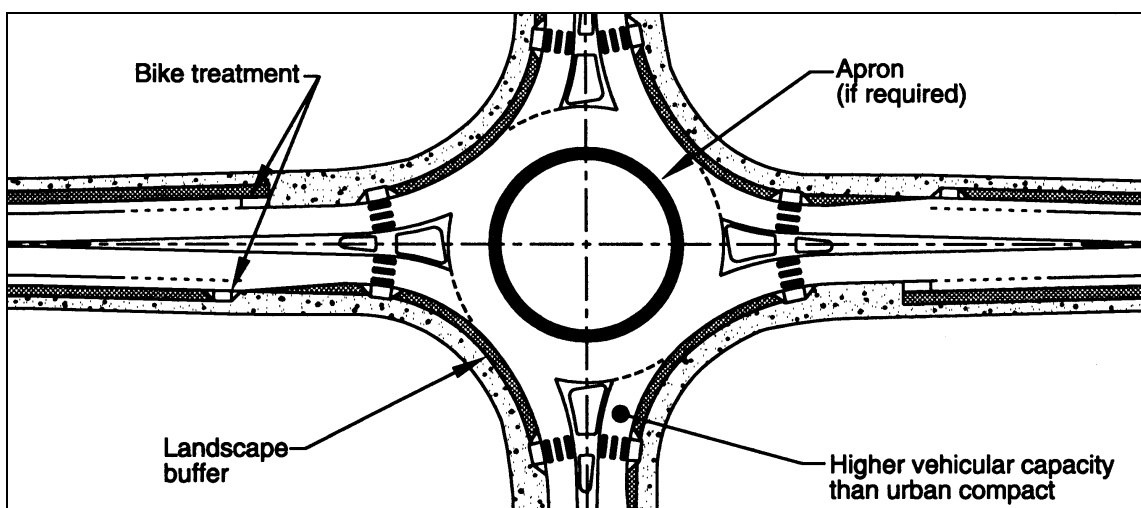

FIGURE 2   Typical urban single-lane roundabout.

linear relationship between entry capacity and circulatory flow and the large set of data underlying the Kimber equations. These equations are as follows:

$$Q_e = k(F - f_c Q_c), \quad f_c Q_c \le F$$
$$= 0, \qquad\qquad f_c Q_c > F \tag{2}$$

$$k = 1 - 0.00347(\phi - 30) - 0.978\left(\frac{1}{r} - 0.05\right) \tag{3}$$

$$F = 303x_2 \tag{4}$$

$$f_c = 0.210t_D(1 + 0.2x_2) \tag{5}$$

$$t_D = 1 + \frac{0.5}{1 + \exp\left(\dfrac{D - 60}{10}\right)} \tag{6}$$

$$x_2 = v + \frac{e - v}{1 + 2S} \tag{7}$$

$$S = \frac{1.6(e - v)}{l'} \tag{8}$$

where: Q_e = entry capacity, pce/h
Q_c = circulating flow, pce/h
e = entry width, m
v = approach half width, m
l' = effective flare length, m
S = sharpness of flare, m/m
D = inscribed circle diameter, m
ϕ = entry angle, °
r = entry radius, m

The following geometric parameters were chosen in developing a simplified capacity relationship for entries to single-lane roundabouts: $D = 40$ m, $r_e = 20$ m, $\phi = 30°$, $v = 4$ m, $e = 4$ m, and $l' = 40$ m. These parameters were specifically chosen to reduce the Kimber equations to a simpler form. Specifically, it can be seen that setting $e = v$ results in $S = 0$ and $x_2 = v$. In addition, it can be seen that setting $r_e = 20$ m and $\phi = 30°$ results in $k = 1$. Substituting these assumptions into the above equations results in the following equation:

$$Q_e = 1212 - 0.5447Q_c \tag{9}$$

The above equation allows total flow immediately downstream of an entry, $Q_e + Q_c$, to exceed 2,200 veh/h. Although a flow rate of this magnitude is possible for a freeway lane, a

maximum flow rate of 1,800 veh/h is more plausible for the circulatory roadway of a single-lane roundabout. This results in the following equation:

$$Q_e = \min \begin{bmatrix} 1212 - 0.5447\,Q_c, \\ 1800 - Q_c \end{bmatrix} \tag{10}$$

2.2   Double-Lane Roundabouts

Urban double-lane roundabouts include all roundabouts in urban areas that have at least one entry with two lanes. They include roundabouts with entries on one or more approaches that flare from one to two lanes. These require wider circulatory roadways to accommodate more than one vehicle traveling side by side. Typical inscribed circle diameters are in the range of 45 to 55 m. Figure 3 provides an example of a typical urban multi-lane roundabout. The design of these roundabouts is based on the methods used in the United Kingdom, with influences from Australia and France.

2.2.1   Capacity of urban double-lane roundabouts

The Kimber equations presented earlier form the basis for the capacity equation derived for the double-lane roundabout. The following geometric parameters were assumed: $D = 55$ m, $r_e = 20$ m, $\phi = 30°$, $v = 8$ m, $e = 8$ m, and $l' = 40$ m. As with the case of the single-lane roundabout, these parameters were specifically chosen to reduce the Kimber equations to a simpler form. Substituting these assumptions into the above equations results in the following equation for predicting the capacity of a double-lane entry:

$$Q_e = 2424 - 0.7159\,Q_c \tag{11}$$

2.2.2   Capacity effect of short lanes at flared entries

When the capacity requirements can only be met by increasing the entry width, this can be done by either (a) adding a full lane upstream of the roundabout and maintaining parallel lanes through the entry geometry or (b) widening the approach gradually (flaring) through the entry geometry. Figure 4 illustrates the latter of these two widening options.
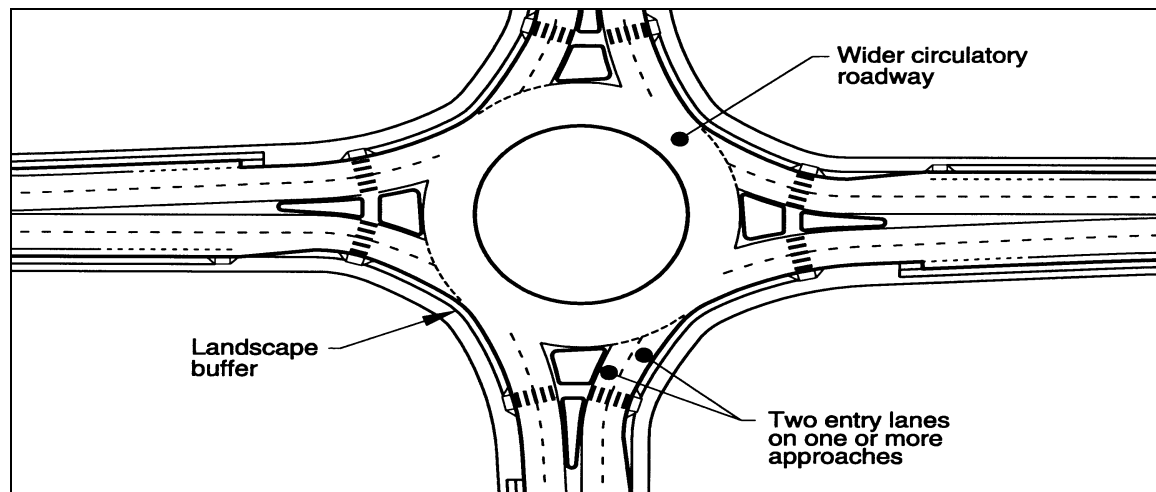

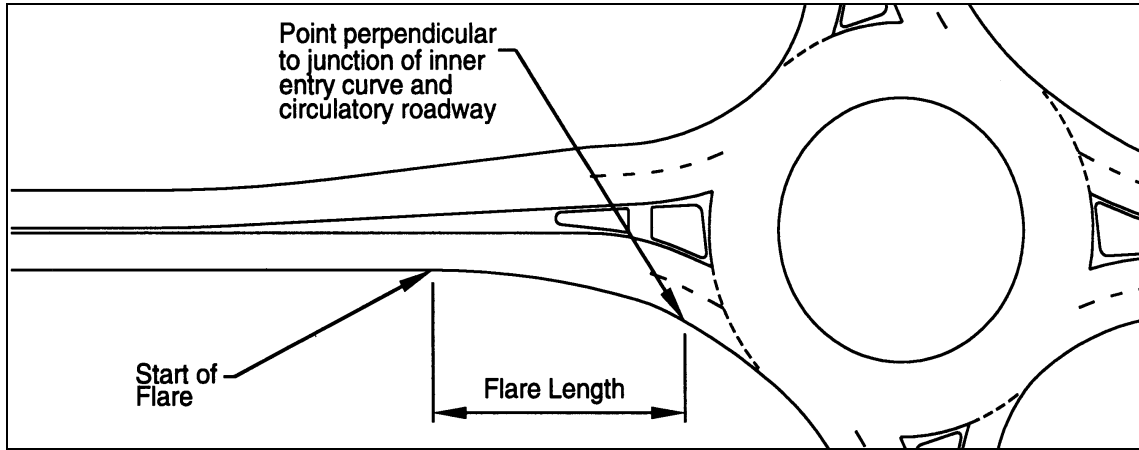**FIGURE 3   Typical urban double-lane roundabout.**

FIGURE 4   Approach widening by entry flaring.

By flaring an approach, short lanes may be added at the entry to improve the performance. If an additional short lane is used it is assumed that the circulatory road width is also increased accordingly. The capacity of the entry is based on the assumption that all entry lanes will be effectively used.

Wu (1997) documented the effect of short lanes on capacity. Wu determined that for a right flared approach,

$$k_{f,right} = \frac{1}{\sqrt[n_{f,right}+1]{(x_L + x_T)^{n_{f,right}+1} + x_R^{n_{f,right}+1}}} \tag{12}$$

where: $k_{f,right}$ = factor for estimating the capacity of a shared lane
  $n_{f,right}$ = length of queue space in number of vehicles
  x_L = degree of saturation, left-turning traffic stream
  x_T = degree of saturation, through traffic stream
  x_R = degree of saturation, right-turning traffic stream

Troutbeck (personal communication, 1999) adapted the Wu formulation for use in the FHWA Roundabout Guide. By dropping some subscripts and assuming that the capacities and flows in each lane are the same (that is, the entries are constantly fed with vehicles), this gives:

$$k = \frac{1}{x \cdot \sqrt[n+1]{2}} \tag{13}$$

with $x_{LT} = x_R$. With the flow in each lane equal to q_i and $q = q_1 = q_2$, capacity q_{max} is then

$$q_{max} = k \sum q_i = \frac{2q}{x \cdot \sqrt[n+1]{2}} \tag{14}$$

Defining q_{max2} as the capacity of an entry at a double-lane roundabout, the capacity of each entry lane is $q_{max2}/2$ and this is equal to the flow, q, divided by the degree of saturation, x.

$$q_{max} = \frac{q_{max\,2}}{\sqrt[n+1]{2}} \tag{15}$$

The capacity of a single-lane approach to a double-lane roundabout can be approximated by the limiting case of $n = 0$.

2.3   Comparison of Capacities

Figure 5 shows a comparison of the expected capacity for a full double-lane approach, a double-lane approach with a short lane (flare length) of two vehicles, and single-lane approaches to the urban compact and urban single-lane roundabouts.

2.4   Exit Capacity

An exit flow on a single lane of more than 1,400 veh/h, even under good operating conditions for vehicles (i.e., tangential alignment and no pedestrians and bicyclists) is difficult to achieve. Under normal urban conditions (e.g., with a more speed-reducing design, such as with an exit curb radius of 15 m), the exit lane capacity is in the range of 1,200 to 1,300 veh/h (Brilon, personal communication, 1999). Therefore, exit flows exceeding 1,200 veh/h may indicate the need for a double-lane exit.

3.   PERFORMANCE ANALYSIS

Three performance measures are typically used to estimate the performance of a given roundabout design: degree of saturation, delay, and queue length. In all cases, a capacity estimate must be obtained for an entry to the roundabout before a specific performance measure can be computed.
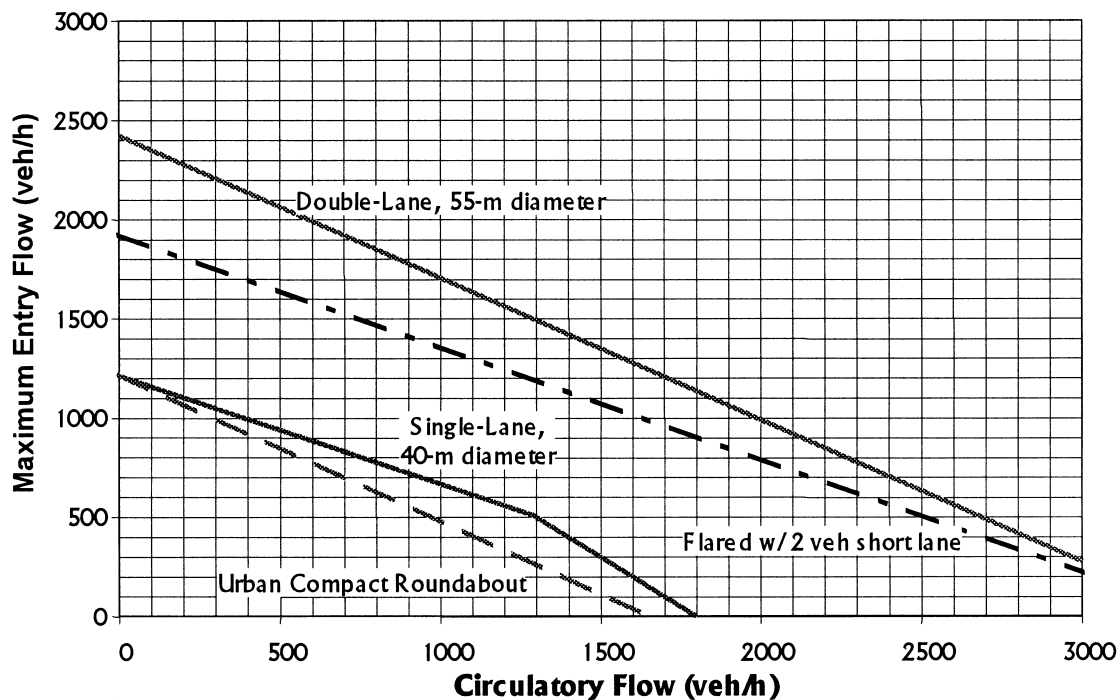

FIGURE 5   Capacity comparison of urban compact, single-lane, flared, and double-lane roundabouts.

3.1   Degree of Saturation

Degree of saturation is the ratio of the demand at the roundabout entry to the capacity of the entry. It provides a direct assessment of the sufficiency of a given design. While there are no absolute standards for degree of saturation, a number of sources (Austroads 1993; Brown 1995) suggest that the degree of saturation for an entry lane should be less than 0.85 for satisfactory operation. When the degree of saturation exceeds this range, the operation of the roundabout will likely deteriorate rapidly, particularly over short periods of time. Queues may form and delay begins to increase exponentially.

3.2   Delay

Delay is a standard parameter used to measure the performance of an intersection. The *Highway Capacity Manual* (TRB 1999) identifies delay as the primary measure of effectiveness for both signalized and unsignalized intersections, with level of service determined from the delay estimate. Currently, however, the *Highway Capacity Manual* only includes control delay, the delay attributable to the control device. Control delay is the time that a driver spends queuing and then waiting for an acceptable gap in the circulating flow while at the front of the queue. The formula for computing this delay is given as follows [1994 HCM, based on Akçelic and Troutbeck (1991)]:

$$d = \frac{3600}{c_{m,x}} + 900T \times \left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1 \right)^2 + \frac{\left(\frac{3600}{c_{m,x}} \right)\left(\frac{v_x}{c_{m,x}} \right)}{450T}} \right] \tag{16}$$

where: d = average control delay, sec/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-minute period).

Figure 6 shows how control delay at an entry varies with entry capacity and circulating flow. Each curve for control delay ends at a volume-to-capacity ratio of 1.0, with the curve projected beyond that point as a dashed line.

This equation differs slightly from the delay equation presented for two-way stop-controlled intersections in the 1997 HCM and HCM 2000. Specifically, the additional 5 s of delay added in the HCM to the delay for stop-controlled intersections to account for deceleration to and acceleration from a complete stop was not included in the formulation for roundabouts. This reflects that control delay at a roundabout under conditions with very low traffic flows can be less than 5 s, as vehicles are not required to come to a complete stop.
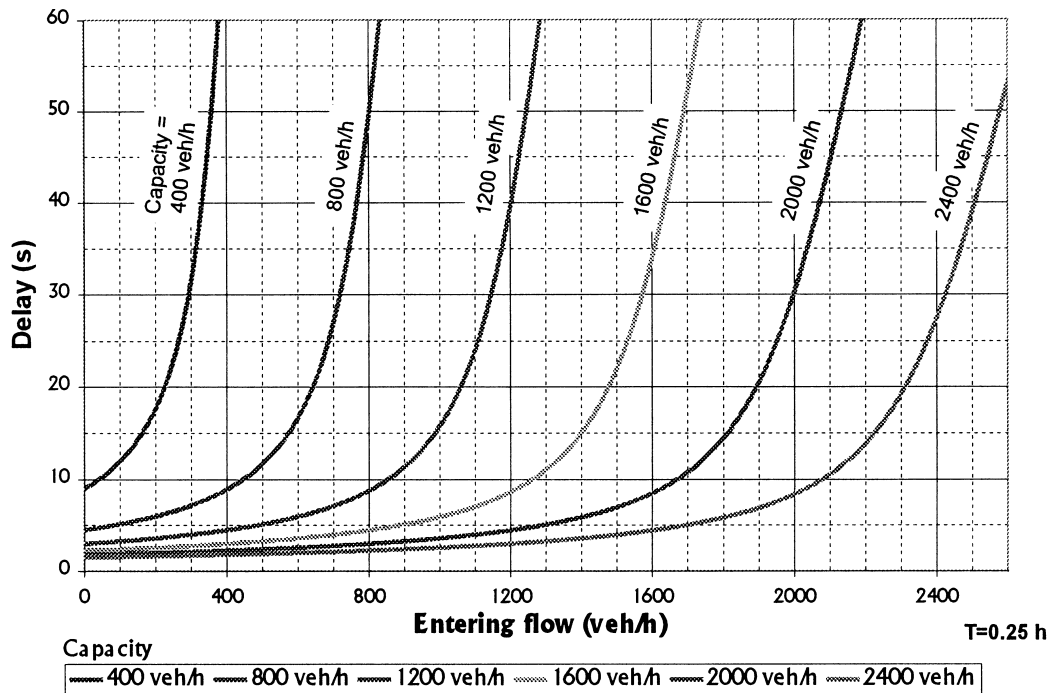
FIGURE 6   Control delay as a function of capacity and entering flow.

Note that as volumes approach capacity, control delay increases exponentially, with small changes in volume having large effects on delay. An accurate analysis of delay under conditions near or over saturation requires consideration of the following factors:

- *The effect of residual queues.* Roundabout entries operating near or over capacity can generate significant residual queues that must be accounted for between consecutive time periods. The method presented above does not account for these residual queues. These factors are accounted for in the delay formulae developed by Kimber and Hollis (1979); however, these formulas are difficult to use manually.

- *The metering effect of upstream oversaturated entries.* When an upstream entry is operating over capacity, the circulating volume in front of a downstream entry is less than the true demand. As a result, the capacity of the downstream entry is higher than what would be predicted from analyzing actual demand.

For most design applications where target degrees of saturation are no more than 0.85, the procedures presented in the FHWA Roundabout Guide are sufficient. In cases where it is desired to more accurately estimate performance in conditions near or over capacity, the authors recommend the use of software that accounts for the above factors.

3.3   Queue Length

Queue length is important when assessing the adequacy of the geometric design of the roundabout approaches. Figure 7 shows how the 95th-percentile queue length varies with the degree of saturation of an approach (Wu 1994).
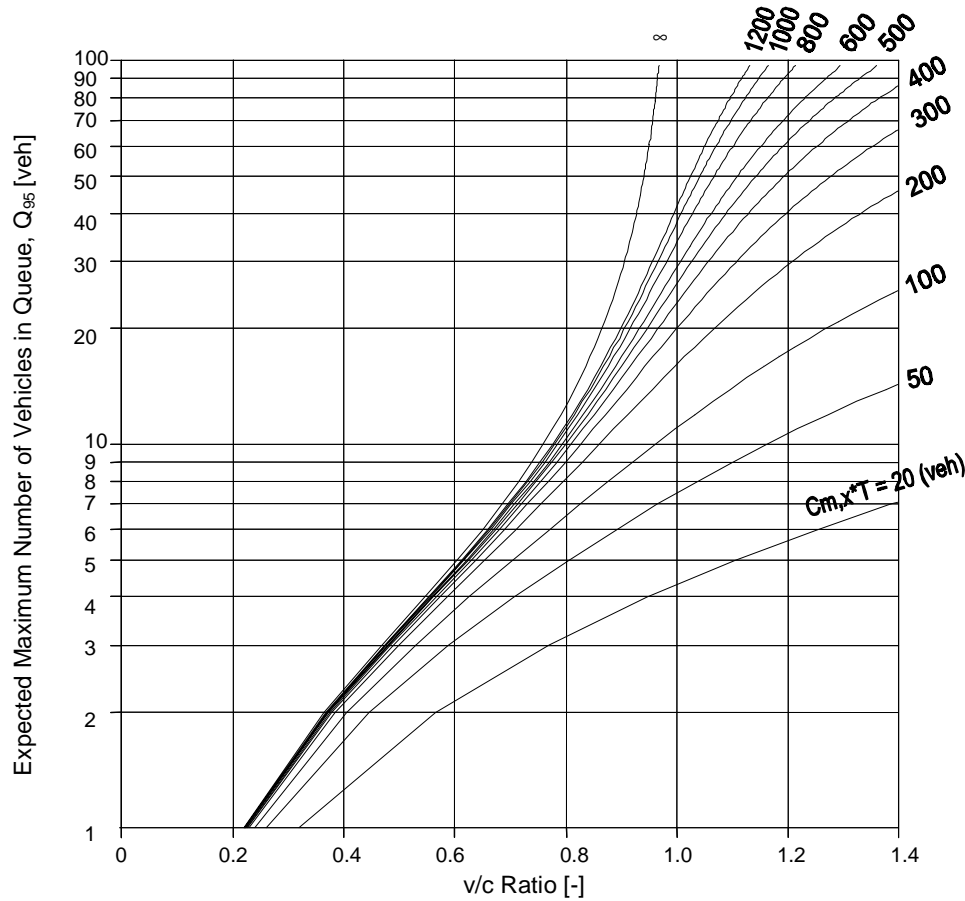
FIGURE 7 95th-percentile queue length estimation.

Alternatively, Equation (17) can be used to approximate the 95th-percentile queue (Wu, personal communication, 1999). The graph and equation are only valid where the volume-to-capacity ratio immediately before and immediately after the study period is no greater than 0.85 (in other words, the residual queues are negligible).

$$Q_{95} \approx 900T \left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(1 - \frac{v_x}{c_{m,x}}\right)^2 + \frac{\left(\frac{3600}{c_{m,x}}\right)\left(\frac{v_x}{c_{m,x}}\right)}{150T}} \right] \left(\frac{c_{m,x}}{3600}\right) \tag{17}$$

where: Q_{95} = 95th-percentile queue, 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 (0.25 for 15-minute period).

4.   CONCLUSION

The operational analysis methodology presented in this paper and in the FHWA publication, *Roundabouts: An Informational Guide*, represents an important step towards establishing a uniform methodology for estimating the capacity and performance of roundabouts in the United States. Capacity methodologies have been directly linked to the category of roundabout under consideration, allowing an analyst to determine the effects of design decisions. The authors recognize that models developed in other countries demonstrate greater sensitivity to traffic flow conditions or geometric variations than are presented here. The primary goal of the guide is to establish reasonable and consistent parameters within which the designer may develop safe and effective designs. Once a sufficient number of roundabouts have been built in the United States, further research should be conducted to refine and perhaps change the form of the capacity and performance measure models presented in the FHWA Roundabout Guide.

ACKNOWLEDGMENTS

REFERENCES

Akçelic, R. (1998). *Roundabouts: Capacity and Performance Analysis*. ARRB Research Report ARR 321. ARRB Transport Research, March 1998.

Akçelic, R., and Troutbeck, R.J. (1991). Implementation of the Australian roundabout analysis method in SIDRA. In *Highway Capacity and Level of Service: Proc., International Symposium on Highway Capacity* (U. Brannolte, ed.), Karlsruhe, Germany. Rotterdam, Germany: Balkema Publisher, pp. 17–34.

Austroads. (1993). *Guide to Traffic Engineering Practice, Part 6 - Roundabouts*. Austroads, Sydney, Australia.

Brilon, W., Wu, N., and Bondzio, L. (1997). Unsignalized Intersections in Germany – A State of the Art 1997. In *Proc., Third International Symposium on Intersections without Traffic Signals* (M. Kyte, ed.), Portland, Oregon, U.S.A., University of Idaho.

Brown, M. (1995). *TRL State of the Art Review — The Design of Roundabouts*. HMSO, London.

Guichet, B. (1997). Roundabouts In France: Development, Safety, Design, and Capacity. In *Proc., Third International Symposium on Intersections Without Traffic Signals* (M. Kyte, ed.), Portland, Oregon, U.S.A., University of Idaho.

Kimber, R.M. (1980). *The traffic capacity of roundabouts*. TRRL Laboratory Report LR 942. Transport and Road Research Laboratory, Crowthorne, England.

Kimber, R.M., and Hollis, E.M. (1979). *Traffic queues and delays at road junctions.* TRRL Laboratory Report LR 909. Transport and Road Research Laboratory, Crowthorne, England.

Transportation Research Board. (1994). *Special Report 209: Highway Capacity Manual*. Transportation Research Board, National Research Council, Washington, D.C.

Transportation Research Board. (1999). *Special Report 209: Highway Capacity Manual*. Transportation Research Board, National Research Council, Washington, D.C. July 1999 (draft).

Wu, N. (1994). An Approximation for the Distribution of Queue Lengths at Unsignalized Intersections. In *Proc., Second International Symposium on Highway Capacity* (R. Akçelik, ed.), Australian Road Research Board, Sydney, Australia.

Wu, N. (1997). Capacity of shared/short lanes at unsignalized intersections. In *Proc., Third International Symposium on Intersections without Traffic Signals* (M. Kyte, ed.), Portland, Oregon, U.S.A., University of Idaho.