City of Bend

Roundabout Evaluation and Design Guidelines

April 2010

Prepared For:
The City of Bend

Prepared By:
Kittelson & Associates, Inc.

Introduction

In the 2001 Transportation Implementation Plan for the *City of Bend Transportation System Plan*, the Bend City Council adopted a policy stating that roundabouts are the preferred option for intersection improvements. This policy formalized the City's practice of giving preference to roundabouts as a safe and efficient form of intersection control. The evolution of roundabout implementation in Bend has resulted in designs with varying details and attributes. Furthermore, the analysis tools used to evaluate the operational characteristics of roundabouts have often varied.

To achieve consistency in roundabout evaluation and design, the City of Bend has developed the following guidelines. These guidelines represent the City's preferred methodologies for roundabout evaluation and design.

Roundabout Operational Analysis Guidelines

The *City of Bend Roundabout Operational Analysis Guidelines* establish a consistent methodology for analyzing the operational characteristics of roundabouts within the City's jurisdiction. These guidelines apply to analyses conducted for development applications or to support the evaluation and selection of City-sponsored capital improvement projects. Methodologies for calculating capacity, delay, and queues are presented for single-lane and multilane roundabouts.

Roundabout Design Consistency Guidelines

The purpose of the *City of Bend Roundabout Design Consistency Guidelines* is to promote consistent roundabout design within the City by:

- reinforcing the design guidelines contained in the FHWA's *Roundabouts: An Informational Guide* (*FHWA Guide*, Reference 1) and subsequent national research, and
- supplementing the *FHWA Guide* by documenting criteria and considerations for certain design elements according to specific objectives of the City.

In addition to providing general design guidance, these guidelines present specific design elements the City of Bend expects in roundabout designs within the City's jurisdiction.

Intersection Form Evaluation Framework

While the City of Bend has adopted a "roundabouts first" policy, the City also recognizes that site-specific conditions or other factors may ultimately necessitate other intersection forms. The *City of Bend Intersection Form Evaluation Framework* provides a framework and criteria for comparing roundabouts and other intersection forms. A case study that applies the intersection comparison process is included.

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Introduction

The intent of these operational guidelines is to establish a consistent methodology for analyzing roundabouts within the City's jurisdiction. These guidelines apply to analyses conducted for development applications or to support the evaluation and selection of City-sponsored capital improvement projects.

Much of the guidance provided within this document is based on NCHRP Report 572, *Roundabouts in the United States* (Reference 1), which summarizes a comprehensive review of U.S. roundabouts. The operational findings and recommendations from NCHRP Report 572 form the basis of the procedures that are anticipated to be included in the 2010 update of the Highway Capacity Manual (2010 HCM). Once the 2010 HCM is released, these guidelines could be revisited and modified to be consistent with national practice. However, the local calibration factors presented in these guidelines will still be applicable to the anticipated HCM capacity models.

Measures of Effectiveness

VOLUME-TO-CAPACITY RATIO

Volume-to-capacity (V/C) ratios are the primary measure of effectiveness for evaluation against the City's performance standards. V/C ratios for roundabouts should be calculated based on the entry demand and capacity for the most critical approach (i.e. approach with the highest v/c ratio) for single-lane roundabouts and the most critical lane (i.e. individual lane with the highest v/c ratio) for multilane roundabouts.

QUEUING

Queuing estimates should be included with all near-term roundabout operational analyses (e.g., development applications, capital improvement projects). Depending on site-specific conditions and at the City's discretion, queuing analyses may be required for long-term operational analysis (e.g., transportation system plan, transportation planning rule (TPR)). Queues between roundabouts and adjacent intersections and/or driveways have the potential to impact the safety and efficiency of the roadway and intersection elements away from the intersection being analyzed.

DELAY

While the City's operational performance standard for roundabouts is measured against a V/C ratio, to ensure a balanced comparison of alternative intersection forms, delay estimates should be developed when comparing alternative intersection forms to the roundabout. As a general rule, under the same traffic conditions, roundabouts typically will result in lower overall delay than traffic signals and all-way stop control but may result in higher overall delays than two-way stop control. Delay estimates can also be used to estimate vehicle emissions that result from various forms of intersection control.

LEVEL OF SERVICE

Level of service should be defined by the delay values presented in Table 1. These values are consistent with NCHRP Report 572 and are the same as the delay thresholds for other unsignalized intersections, as defined in the 2000 HCM (Reference 2) and the proposed 2010 HCM.

Table 1 Level of Service Thresholds for Roundabouts

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

Roundabout Operational Analysis Models

The following models are the City's preferred roundabout operational analysis models for capacity, delay, and queuing. The models described in this section are calibrated to either local conditions (single-lane roundabouts) or general U.S. conditions (multilane roundabouts).

CAPACITY

The City's base entry capacity model is consistent with NCHRP Report 572 and is shown in Equation 1.

$$c_{pce} = A \cdot exp(-B \cdot v_{c,\, pce}) \quad \textbf{(Equation 1)}$$

where,

c_{pce} = lane capacity, adjusted for heavy vehicles, (pc/h)
$A = 3600/t_f$
$B = (t_c - t_f/2)/3600$
t_c = critical headway (s)
t_f = follow-up headway (s)
$v_{c,\, pce}$ = conflicting circulating flow rate, adjusted for heavy vehicles, (pc/h)

If project specific values for critical headway (t_c) and follow-up headway (t_f) are identified, this generalized model should be used to develop a project specific capacity model. If the analyst intends to collect project specific values for t_c and t_f, City staff should first be consulted to ensure an appropriate data collection methodology.

Bend Calibrated Capacity Model for Single-Lane Roundabouts

The capacity model shown in Equation 2 should be used for all single-lane entry capacity analyses, unless project specific values for critical headway (t_c) and follow-up headway (t_f) have been developed.

$$c_{pce} = 1333 \cdot \exp(-0.0008 \cdot v_{c,\,pce}) \quad \textbf{(Equation 2)}$$

where,

c_{pce} = *capacity, adjusted for heavy vehicles, (pc/h)*
$v_{c,\,pce}$ = *conflicting circulating flow rate, adjusted for heavy vehicles, (pc/h)*

Equation 2 is based on Bend-specific values for critical headway (4.1s) and follow-up headway (2.7s) observed at single-lane roundabouts in 2009.

Capacity Model for Multilane Roundabouts

Recognizing the need to provide a variety of lane configurations to accommodate a range of traffic patterns and the lane use imbalances that may result, multilane capacity analysis should be conducted on a lane-by-lane basis and reported for the most critical lane (i.e. lane with the highest volume) on each approach.

For entry lanes conflicted by one circulating lane, the single-lane capacity model presented in Equation 2 should be applied to the most critical lane on each approach.

For entry lanes conflicted by two circulating lanes, Equation 3 should be applied to the most critical lane on each approach.

$$c_{pce} = 1130 \cdot \exp(-0.0007 \cdot v_{c,\,pce}) \quad \textbf{(Equation 3)}$$

where,

c_{pce} = *capacity, adjusted for heavy vehicles, (pc/h)*
$v_{c,\,pce}$ = *conflicting circulating flow rate, adjusted for heavy vehicles, (pc/h)*

Equation 3 reflects the multilane capacity model identified in NCHRP Report 572. Given that single-lane roundabouts in Bend perform at a higher capacity than the national average, it is possible that the capacities of multilane roundabouts in Bend will also exceed the national average. However, at the time these guidelines were prepared, no multilane roundabouts in Bend operated near or at capacity to enable accurate measurements. Care is recommended when assessing multilane roundabouts that are projected to operate near capacity.

(Note: If conditions permit future data collection at multilane roundabouts in Bend, Equation 3 could be calibrated to local conditions.)

DELAY AND LOS

Equation 4 provides a delay estimation model to be used in determining delay for each approach or critical lane. This model is based on the HCM unsignalized delay model and is consistent with recommendations from NCHRP Report 572. The delay estimates resulting from this model should be used to determine LOS according to the thresholds identified in Table 1.

$$D = \frac{3600}{c} + 900T \times \;\; x - 1 + \sqrt{(x-1)^2 + \frac{\frac{3600}{c}\,x}{450T}} \;\; + 5 \times \min[x,1]$$

(Equation 4)

where,

D = average control delay (s/veh)
x = volume-to-capacity ratio of the subject lane
c = capacity of the subject lane (veh/h)
T = time period (h) = 0.25 for a 15-minute analysis

QUEUING

Queue lengths should be estimated using Equation 5 for each single-lane approach and for the critical lane on each multilane approach. As shown, Equation 5 will result in the 95th-percentile queue likely to occur during the peak fifteen minutes of the hour being analyzed. If an hourly queue evaluation is desired, the flow rate should not be adjusted by the PHF and T will equal 1.0.

$$Q_{95} = 900T \times \;\; x - 1 + \sqrt{(1-x)^2 + \frac{\frac{3600}{c}\,x}{150T}} \;\; \times \frac{c}{3600}$$

(Equation 5)

where,

Q_{95} *= queue length (veh)*
x = volume-to-capacity ratio of the subject lane
c = capacity of the subject lane (veh/h)
T = time period (h) = 0.25 for a 15-minute analysis

Roundabout Analysis Process

The following diagram outlines the analysis process to be used for analyzing roundabouts within the City of Bend.

Step 1: Convert movement demand volumes (V, veh/h) to flow rates (v, veh/h).

Peak 15-minute analysis: $v = V/PHF$ Hourly analysis: $v = V$

Step 2: Adjust flow rates for heavy vehicles.

$v_{pce} = v/f_{HV}$, $f_{HV} = 1/[1 + P_T(E_T - 1)]$, P_T = Heavy Vehicle %, E_T = 2.0 for Heavy Vehicles

Step 3: Determine circulating and exiting flow rates.

Step 4: Determine entry flow rates by lane.

Step 5: Determine the capacity of each entry lane in passenger car equivalents.

(see Equations 2 and 3)

Step 6: Determine pedestrian impedance (f_{ped}) to vehicles.

(see *FHWA Roundabout Guide* (Reference 3) Exhibits 4-7 and 4-8)

Step 7: Convert lane flow rates and capacity into vehicles per hour.

$v = v_{pce} f_{HV}$ $c = c_{pce} f_{HV} f_{ped}$

Step 8: Compute the volume-to-capacity ratio for each lane.

$x = v/c$

Step 9: Compute the average control delay and corresponding LOS for each lane.

(see Equation 4)

Step 10: Compute 95th-percentile queues for each lane.

(see Equation 5)

Comparison with Alternative Intersection Forms

Roundabouts are often evaluated against a signalized intersection alternative. Phase splits at a signalized intersection can be adjusted to meet varying demand. Therefore, analysis for signalized intersections is conducted and reported for the intersection as a whole. When comparing a roundabout alternative to a signalized intersection or all-way stop control alternative, Equation 6 should be used to develop a weighted average of the delay estimate for the roundabout intersection as a whole. All movements, including those using bypass lanes, should be included in the weighted average.

$$D_{\text{intersection}} = \frac{\sum_i D_i V_i}{\sum_i V_i} \qquad \textbf{(Equation 6)}$$

where,

$D_{intersection}$ = *intersection control delay, s/veh*

D_i = *control delay on approach i, s/veh*

V_i = *volume on approach i, veh/hr*

Additional guidance on conducting comparative analyses for different intersection forms is provided in the *City of Bend Intersection Form Evaluation Framework* (Reference 3).

Alternative Tools for Operational Analysis

At the discretion of City staff, additional analysis tools, such as other deterministic tools or microsimulation, may be required to augment the methodologies described in this document. If alternative operational analysis tools will be used on a project, the analyst should consult with City staff early in the process to ensure appropriate calibration of the analysis method.

References

1. Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, W. Brilon, N. Wu, B. Persaud, C. Lyon, D. Harkey, and D. Carter. *NCHRP Report 572: Roundabouts in the United States*, TRB, National Academy of Sciences, Washington, D.C., 2007. [online] http://www.trb.org/Main/Public/Blurbs/158299.aspx

2. Transportation Research Board. *Highway Capacity Manual*. TRB, National Research Council, Washington, DC, 2000.

3. Kittelson & Associates, Inc. *City of Bend Intersection Form Evaluation Framework*. City of Bend, November 2009.

Photo: Lee Rodegerdts

Exhibit 6 Appropriate entry design with proper path alignment (18th Street / Cooley Road)

Roundabout Design Elements

PEDESTRIAN TREATMENTS

Roundabouts simplify pedestrian roadway crossings by providing a two-stage crossing. As such, roundabout splitter islands should serve the anticipated volume of pedestrians and have a raised refuge area of adequate width to accommodate the anticipated user types. The City prefers a pedestrian refuge area of at least 8 to 9 feet in width. In no case should the refuge area be less than 6 feet in width. The pedestrian crossing and refuge area should be located a minimum of 20 feet from the circulatory roadway and preferably not more than 25 feet.

At roundabouts, cyclists have the option to exit the roadway, which means pedestrians and bicycles must coexist at roundabouts. Therefore, in the areas around a roundabout and bound by the bicycle ramps, the pedestrian facilities should be designed as a multiuse path with a width of preferably no less than 10 feet and a minimum of 8 feet. In constrained areas, the multiuse path may need to be designed curb-tight to attain the minimum width; alternatively, cyclists may need to walk their bicycles if they choose not to ride through as a vehicle.

The City supports mobility for all users and takes care to provide appropriate facilities and designs for special user needs. Roundabouts must include grades, access ramps, and detectable warning surfaces at all pedestrian-roadway interfaces to make them accessible per the requirements of the *ADA Accessibility Guidelines* (ADAAG, Reference 5) and the best practices described in the draft *Rights-of-Way Accessibility Guidelines* (PROWAG, Reference 6). Pedestrian facilities should support wayfinding. For roadway crossings, the crossing should be designed perpendicular to the center line of the roadway and provide as linear a path as possible from one access ramp to the other via the refuge area. If a crosswalk must be oriented perpendicular to the traveled way due to site constraints, a defined angle point should be provided in the refuge island to help orient visually impaired pedestrians to the receiving access ramp.

Application of Traffic Control Devices

An update to the *Manual on Uniform Traffic Control Devices* (MUTCD) was released by FHWA in late 2009. The updated MUTCD includes revised information for roundabout signing and striping. The following is not intended to replace the MUTCD but instead provide guidance to designers on the optional pavement markings and signs in the 2009 MUTCD (Reference 9).

PAVEMENT MARKINGS

Yield Line and Yield Legend

The MUTCD identifies the use of yield lines and yield legends as optional at roundabouts. The City's preference is to not use the yield line or legend to reduce ongoing maintenance.

Lane-Use Arrows

Lane-use arrows should be used on all multilane approaches and within the circulatory roadway of multilane roundabouts. Lane-use arrows should not be used at single-lane roundabouts. Where used, the City prefers to use the traditional (i.e. not fish-hook) lane-use arrows without a dot symbolizing the central island, as described in the 2009 MUTCD.

SIGNING

Lane-Use Signs

The City prefers to use lane-use signs depicting traditional (i.e. not fish-hook) lane-use arrows and without a dot symbolizing the central island. Lane-use signs should only be used on multilane approaches.

Yield Sign

Yield signs (R1-2) shall be placed on the outside edge of all single-lane approaches. Depending on the approach geometry and sign visibility, a yield sign may also be necessary in the splitter island on single-lane approaches. Yield signs shall be placed on both the outside edge and in the splitter island on all multilane approaches.

Circular Intersection Sign

The Circular Intersection sign (W2-6) should be used in advance of all roundabout intersections. A plaque should be included with each W2-6 sign indicating the name of the upcoming cross-street.

Pedestrian Crossing Sign

The pedestrian crossing sign (W11-2) and associated downward arrow plaque should not be used at crossings of single-lane approaches except at single-lane approaches within a school zone. At crossings of multilane approaches, a W11-2 and associated downward arrow plaque should be placed on both the outside edge and in the splitter island.

Directional Arrow and Street Name Sign Assembly

Consistent with the R6-4 sign series in the 2009 MUTCD, a horizontal, rectangular sign with black chevrons on a white background should be placed in the central island opposite each roundabout entry. A street sign indicating the name of the cross-street should be mounted above the directional arrow sign.

Exhibits 10 and 11 demonstrate the typical pavement markings and signing described above for single-lane and multilane roundabouts, respectively.

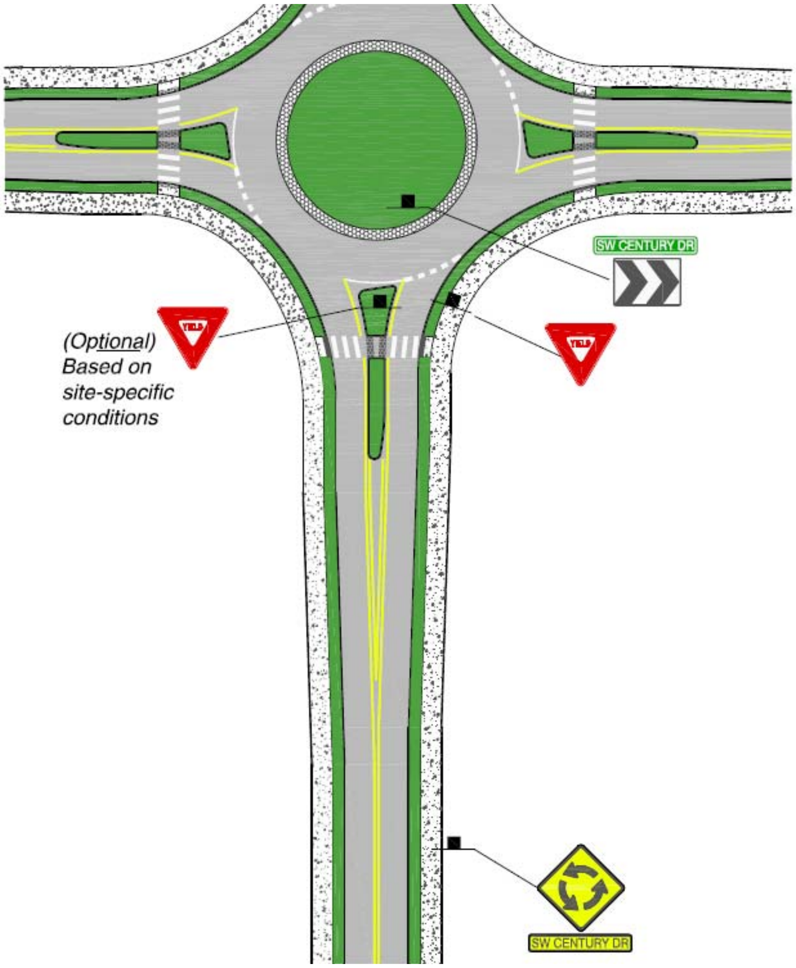
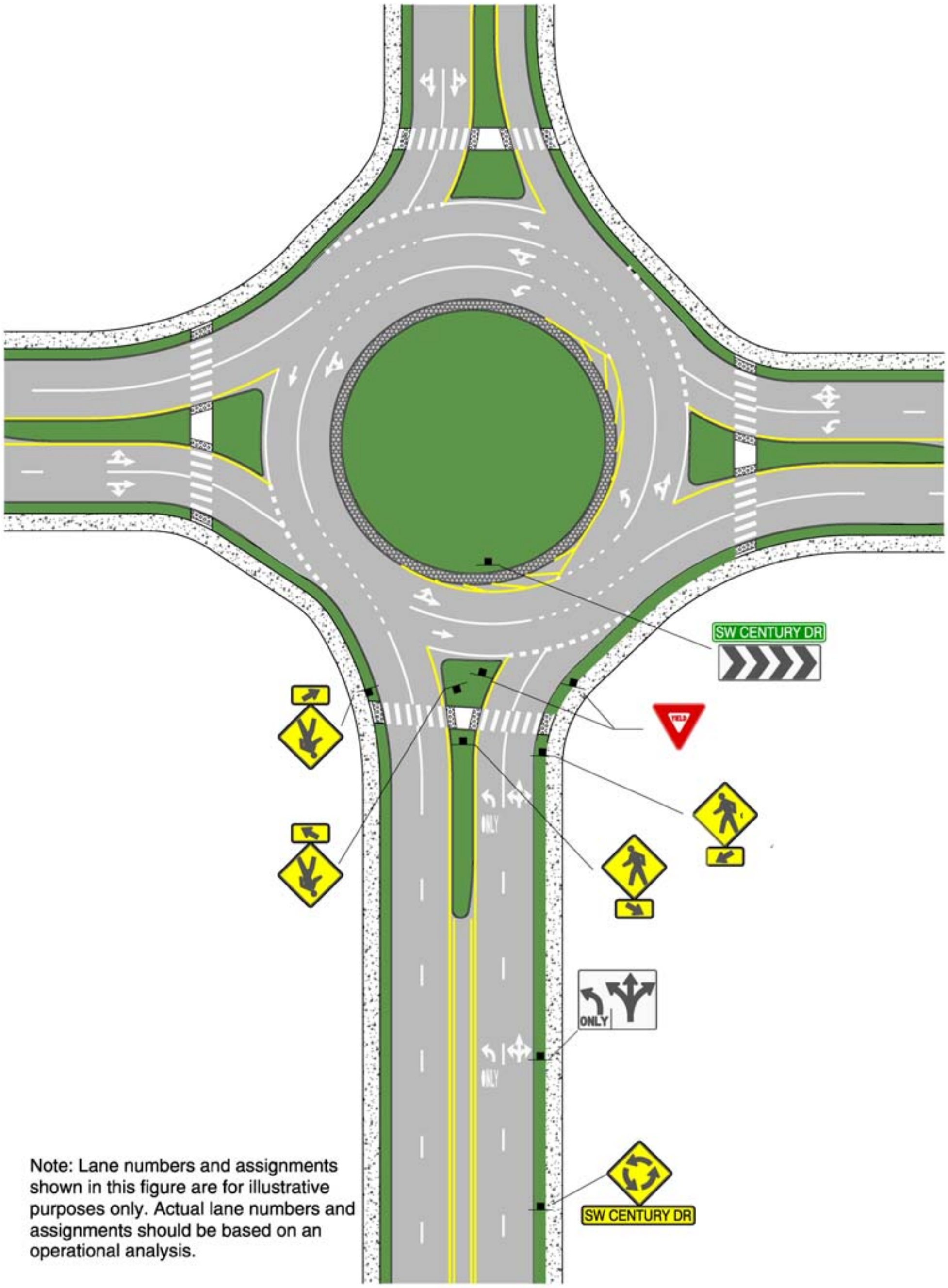


Exhibit 10 Pavement markings and signing for single-lane roundabouts



Note: Lane numbers and assignments shown in this figure are for illustrative purposes only. Actual lane numbers and assignments should be based on an operational analysis.

Exhibit 11 **Pavement markings and signing for multilane roundabouts**

Access Management

The City recognizes access management as a valuable tool to enhance the flow of traffic, reduce user conflicts, and improve safety. Access management is a means of optimizing the available capacity of a roadway and perhaps eliminating or postponing expensive or impacting roadway widening. Roundabouts provide opportunities to support access management objectives and should be considered explicitly for this purpose. Roundabouts may also support flexibility in access management. For instance, right-in/right-out driveways that would not be permitted within the influence area of a conventional intersection may be permitted near a roundabout as the roundabout will facilitate U-turn movements. Furthermore, the low speed environment in the influence area of a roundabout may permit driveways that would not be permitted at a conventional intersection to operate safely. The context of each location should be reviewed on a case-by-case basis when considering access management near a roundabout.

References

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