Queue Lengths at Single Lane Roundabouts in Oregon

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Executive Summary

This study observed and analyzed single lane roundabout queue lengths. Cities and counties have actively utilized the benefits of roundabouts. Consequently, roundabouts have been and continue to be located all across the state. A manual data collection procedure was developed for recording queue lengths as video was taken for traffic counts. Equipment, contracts, and help were obtained. Miovision processed video recordings into counts.

Sites were scoped for consideration. Some examples were not considered for different reasons, such as only having two legs (not enough conflict to create queues), or due to resource limitations. A site might be dropped for not having a required element, yield control or splitter islands. Sites were then scoped for placement of equipment and personnel. Multi-lane roundabouts were dropped from study due to operational differences and lack of existing sites.

Roundabout data was collected, such as number of legs and splitter island widths.
Factors investigating for potential to influence roundabout operation and queues: number of legs, presence of a school, inscribed diameter, splitter island width, entry flow, and circular flow.

This study finds the Two-Minute Rule greatly overestimates queues at Oregon roundabouts. An empirically estimated equation was developed but found to be less accurate than the HCM 2010 methodology. The HCM 2010 roundabout queuing methodology is recommended to replace the Two-Minute Rule to estimate 95th percentile queue lengths for conditions that are applicable as per the HCM (isolated roundabouts, few pedestrians, undersaturated, etc.). For other situations alternative tools should be used, such as microsimulation.

1 Introduction

Considerable work has been invested in observing roundabout operation to study and explore predictive queue methodologies.

1.1 Methodologies

1.1.1 Two-Minute Rule

The Two-Minute Rule methodology estimates queue lengths for major street left turns and minor street movements during a two-minute stoppage of the turning movement. This method does not consider impacts of conflicting flows on a queue. Currently in the Analysis Procedures Manual (APM) the Two-Minute Rule is used to estimate queues at roundabouts except where simulation is appropriate. The two-minute rule calculation of the 95th percentile queue:

$$S = vtL$$

Where:

S = 95th percentile queue (feet)

v = average left-turn volume arriving in a 2-minute interval

t = storage ability; usually 1.75 to 2.0 (Table 1-1)

L = average stored vehicle length based on truck percentage (Table 1-2)

Table 1-1 Selection of "t" Values (source: APM)

Minimum "t" Value	Percentile
2.0	98 %
1.85	95 %
1.75	90 %
1.0	50 %

The L variable starts with a value of 25-feet in the equation until the truck percentage of the turning volume equals five percent, as per Table 1-2.

Table 1-2 "L" Storage Length Adjustments for Trucks (source: APM)

Percent Trucks in Turning Volume	Average Vehicle Storage Length
< 2%	25 ft
5%	27 ft
10%	29 ft

For dual left turn lanes, the results can be divided by 1.8. This follows an assumption that queued vehicles will not evenly distribute between turn lanes.

1.1.2 Highway Capacity Manual

The HCM 2010 procedures are founded on National Cooperative Highway Research Program 3-65(1) recommendations based on a database (31 sites) of U.S. roundabout operation.

The HCM 2010 states that roundabouts share the same basic control delay formation as two-way and all-way stop controlled intersections. There is an adjustment for the effect of yield control, rather than stop control. In the absence of research on traveler perception of quality of service at roundabouts, HCM 2010 roundabout service measures and thresholds follow those of unsignalized intersections.

The general procedure for automobile analysis of roundabouts is summarized in HCM 2010 Exhibit 21-9. There are 12 steps of analysis (please see HCM 2010 for full procedure):

Step 1: Flow rates from demand volumes

Step 2: Passenger car equivalents (bicycles and trucks)

Step 3: Circulating and exiting flow rates, addition of movements

Step 4: Entry flow rates by lane

Step 5: Capacity of entry lanes

Step 6: Pedestrian impedance to vehicles

Step 7: Vehicles /hour /lane from capacities and factors

Step 8: Volume/capacity ratio for each lane

Step 9: Average control delay

Step 10: LOS for each lane on each approach

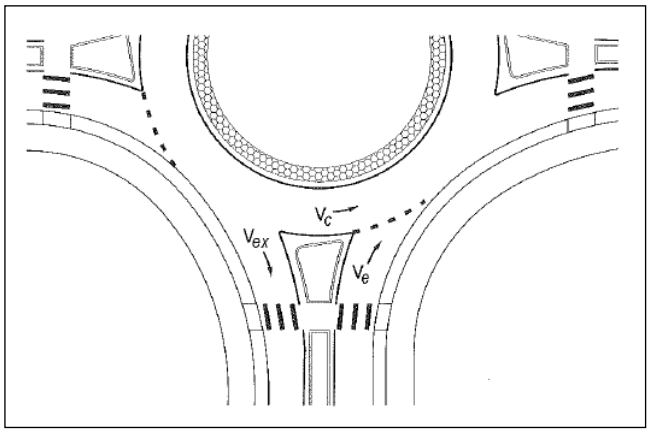
Step 11: Average Control Delay and LOS for entire roundabout

Step 12: 95th percentile queues

For a single lane roundabout automobile analysis, the following steps are applicable (excludes steps 3B, 4, 5, and 6B).

2010 HCM Exhibit 21-2 (Exhibit 1) shows a single lane roundabout with an entry flow conflicting with a circulatory flow. Please note the subscripts: “c” is for circulatory, “e” is for entry, and “ex” is for exiting flow. Entry vehicles yield to circulatory vehicles.

Exhibit 1-1 Flow Rate Nomenclature



Step 1: Flow rates from demand volumes

Volumes should be gathered from an intersection count. Bicyclists using the crosswalks are counted as pedestrians. Bicyclists using the roundabout as vehicles are added to the intersection volumes for each movement (including U-turns). The count should also provide a PHF for each movement. HCM 2010 Equation 21-8 finds the demand flow rate for each movement.

$$v_i = \frac{V_i}{PHF}$$

Where:

v_i = demand flow rate for movement (veh/h)
V_i = demand volume per movement, bicycle = vehicle (veh/h)
PHF = peak hour factor

Step 2: Passenger car equivalents (bicycle and trucks)

Flow rates in vehicles per hour (vph) are converted to equivalent passenger cars per hour (pce/h) using vehicle factors.

Exhibit 1-2 HCM 2010 Exhibit 21-10

Vehicle Type	Passenger Car Equivalent, E_T
Passenger car	1.0
Heavy vehicle	2.0

Demand volumes (vph) are converted to passenger car equivalents (pce/h), using a heavy vehicle factor equation. E_T and E_B are the equivalent factors for trucks and bicycles. The proportion that these vehicle types occur in a count is designated as P_T and P_B.

A possible variation of the heavy vehicle adjustment factor equation:

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_B(E_B - 1)}$$

Where:

f_{HV} = heavy vehicle adjustment factor
P_T = proportion of demand volume that consists of heavy vehicles (decimal)
E_T = passenger car equivalent for heavy vehicles (table)
P_B = proportion of demand volume that consists of bicycles (decimal)
E_B = passenger car equivalent bicycles (0.5, page 21-21)

This f_{HV} is then used in HCM 2010, equation 21-9.

$$v_{i,pce} = \frac{v_i}{f_{HV}}$$

Where:

$v_{i,pce}$ = demand flow rate for movement (veh/h)
v_i = demand flow rate for movement (veh/h)
f_{HV} = heavy vehicle adjustment factor

Step 3: Circulating and exiting flow rates; addition of movements

The circulating flow rates in front of each entry are summed in terms of passenger car equivalents. See HCM 2010 equation 21-11 below.

$$v_{c,NB,pce} = v_{WBU,pce} + v_{SBL,pce} + v_{SBU,pce} + v_{EBT,pce} + v_{EBL,pce} + v_{EBU,pce}$$

Where:

v_c = Circulating flow rates in front of specified entry; in passenger car equivalents

$v_{WBU,pce}$ = Flow rates of a specified movement

Step 3B: If considering a bypass lane, calculate the conflicting flow rates

The conflicting flow rates for where the bypass lane merges into the exiting lane can be calculated with HCM 2010 Equation 21-12, similar to Equation 21-11.

Step 4: Entry flow rates by lane, if more than one lane

This step is for a multi-lane roundabout/more than one entry lane. For more than one entry lane, it is important to identify current lane utilization and nearby attractions. Future developments should be considered as well. This may be a good opportunity to apply a travel demand model. If this is not available, see the HCM 2010 exhibits in chapter 21.

Step 5: Capacity of entry lanes; uses value from Step 3

HCM 2010 Equation 21-1 finds capacity for movements using circulatory flow rate.

$$c_{e,pce} = 1{,}130e^{\left(-1.0\times10^{-3}\right)v_{c,pce}}$$

Where:

C = lane capacity (passenger cars per hour; pc/h)
V_c = Conflicting flow (pc/h)

If considering more than one entry lane, see the HCM 2010 Exhibits in Chapter 21.

Step 6: Pedestrian impedance to vehicles

This is the pedestrian impedance for single lane roundabouts; for two entry lanes, consult the HCM 2010, Exhibit 21-19. For one entry lane, use HCM 2010 Exhibit 21-17, to find the entry capacity adjustment factor for pedestrians.

$$IF \qquad v_{c,pce} > 881 \qquad f_{ped} = 1$$

$$Else \quad IF \qquad n_{ped} \le 101 \qquad f_{ped} = 1 - 0.000137 n_{ped}$$

$$Else \qquad f_{ped} = \frac{1119.5 - 0.715 v_{c,ped} + 0.00073 v_{c,pce} n_{ped}}{1068.6 - 0.654 v_{c,pce}}$$

Where:

f_{ped} = entry capacity pedestrian adjustment factor
v_c = conflicting flow (pc/h)
n_{ped} = conflicting pedestrians (p/h)

Fewer than 40 pedestrian crossings of a leg in one hour do not have a significant effect on roundabout operation. If following the HCM 2010 procedure, an adjustment factor for pedestrians of 1.0 is recommended if there are fewer than 40 pedestrian crossings of a leg. Following the HCM, if the number of passenger car equivalent vehicles circulating in front of an entrance is over 881, then the adjustment factor for pedestrians is a factor of 1.0. If that is not the case and the number of pedestrians crossing at a crosswalk is less than or equal to 101, then the second equation determines the adjustment factor for pedestrians. Otherwise, see the final equation represented from HCM 2010 Exhibit 21-17.

Step 6B: If considering more than one entry lane, see HCM 2010 Exhibit 21-19.

Step 7: Vehicles /hour /lane from capacities and factors

A weighted vehicle adjustment factor is created with HCM 2010, Equation 21-15.

$$f_{HVe} = \frac{f_{HV,U} v_{U,PCE} + f_{HV,L} v_{L,PCE} + f_{HV,T} v_{T,PCE} + f_{HV,R,e} v_{R,e,PCE}}{v_{U,PCE} + v_{L,PCE} + v_{T,PCE} + v_{R,e,PCE}}$$

Where:

f_{HVe} = averaged heavy vehicle adjustment factor for entry lane
f_{HVi} = heavy vehicle adjustment factor for movement i
$v_{i,PCE}$ = demand flow for movement i (pc/h)

The flow rate is converted back to vehicles per hour with HCM 2010, Equation 21-13, which is a rearrangement of Equation 21-9.

$$v_i = v_{i,PCE} f_{HV,e}$$

Where:

$v_{i,pce}$ = demand flow rate for movement (veh/h)
v_i = demand flow rate for movement (veh/h)
f_{HVe} = heavy vehicle adjustment factor

Step 7.5: The capacity of a lane is converted back to vehicles per hour in Equation 21-14.

$$c_i = c_{i,PCE} f_{HVe} f_{ped}$$

Where:

$c_{i,pce}$ = demand flow rate for movement (Epc/hr)
c_i = demand flow rate for movement (veh/hr)
f_{HVe} = heavy vehicle adjustment factor
f_{ped} = entry capacity pedestrian adjustment factor

Step 8: Volume/capacity ratio for each lane

The volume/capacity ratio of a lane is calculated in Equation 21-16.

$$x_i = \frac{v_i}{c_i}$$

Where:

x_i = volume-to-capacity ratio of the subject lane i (only looking at one lane here)
v_i = demand flow rate of the subject lane i (veh/h)
c_i = capacity of the subject lane i (veh/h)

Step 9: Average control delay, similar to unsignalized intersections

Signal timers aiding in the study stated that a signal would likely not get such small queues or delays as the roundabouts studied. The HCM 2010 states the delay to be similar to unsignalized intersections, per United Sates roundabout data. The 2010 HCM makes a good point about delay at the peak hour or design hour:

> "At higher volume-to-capacity ratios, the likelihood of coming to a complete stop increases, thus causing behavior to resemble STOP control more closely."

At higher volumes, it is likely that motorists may stop before the crosswalk as well as the yield/stop line. The 2010 HCM describes this as resembling STOP control.

The average control delay of a lane is calculated in 2010 HCM Equation 21-17. The adding of the third term, the lesser of the v/c or 1.0, is new for the 2010 HCM.

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

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) (T = 0.25 for a 15-min analysis)

Step 10: LOS for each lane on each approach

The delay from Step 9 determines LOS of each lane via 2010 HCM Exhibit 21-1.

Exhibit 1-3 HCM 2010 Exhibit 21-1

Control Delay (s/veh)	LOS by Volume-to-Capacity Ratio[a] v/c ≤ 1.0	v/c >1.0
0–10	A	F
>10–15	B	F
>15–25	C	F
>25–35	D	F
>35–50	E	F
>50	F	F

Note: [a] For approaches and intersectionwide assessment, LOS is defined solely by control delay.

Step 11: Average Control Delay and LOS for entire roundabout

The average control delay of a roundabout is calculated in 2010 HCM Equations 21-18 and 21-19. As this process is only considering single lane roundabouts, these equations will boil down to an average of approach (2010 HCM Equation 21-19):

$$d_{intersection} = \frac{\sum d_i v_i}{\sum v_i}$$

Where:

$d_{intersection}$ = average control delay for entire intersection (s/veh)
d_i = control delay for approach i (s/veh)
v_i = flow rate for approach I (veh/h)

With the intersection control delay, look up the LOS via the 2010 HCM Exhibit 21-1 (as shown in Step 10).

Step 12: 95th percentile queues for each lane

The 95th percentile queue for a given approach lane is calculated using Equation 21-20.

$$Q_{95} = 900T\left[x - 1 + \sqrt{(x-1)^2 + \frac{\left(\frac{3600}{c}\right)x}{150T}}\right]\left(\frac{c}{3600}\right)$$

Where:

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

1.2 Challenge

The current APM methodology of using the Two-Minute rule has been observed to overestimate queue lengths at roundabouts. The challenge was to observe and collect data in regard to roundabout observations. The goal was to find a better way to estimate single lane roundabout queue lengths for planning level analysis. Geometric dimensional factors were included in the study to assess the importance and impact of physical design elements. Inscribed diameter and splitter island width appeared to be factors based on visual observations.

1.3 Purpose

This study documents roundabout observations, study locations, data collection, development of an empirical roundabout maximum queue predictive equation, and compares other queue predictive methods.

1.4 Data Collection and Use

Data collection required prior effort: identifying potential parameters influencing queue behavior, location, selection, and data to record. After collection, data was processed to get the calculation inputs. Methodologies were compared to the developed empirical equation. Equation validation was conducted to check and compare accuracy.

2 Data Collection & Analysis

Data was used in equation development, validation, and comparing methods for accuracy.

2.1 Potential Data

Table 2-1 shows the locations of the 69 single lane roundabouts in Oregon at the data collection time.

Table 2-1 Locations of Single Lane Roundabouts in Oregon

City	#
Albany	2
Beaverton	1
Bend	28
Central Point	1
Clackamas	3
The Dalles	1
Eugene	3
Hillsboro	2
Lake Oswego	2
Madras	2
Medford	1
Newberg	3
Oregon City	1
Portland	3
Redmond	1
Sherwood	3
Springfield	5
Sunriver	1
Tigard	1
unincorporated	2
Wilsonville	3

County	#
Clackamas	9
Deschutes	30
Jackson	2
Jefferson	2
Wasco	1
Lane	8
Linn	2
Multnomah	2
Washington	10
Yamhill	3

Region	#
Region 1	21
Region 2	13
Region 3	2
Region 4	33
Region 5	0

2.2 Data Collection

Studied roundabouts were chosen to cover a range of geographic regions, physical features, traffic volumes, and traffic conditions. Multi-lane roundabouts were dropped primarily due to the low number existing in Oregon. Some data did not prove to be useful, such as city's various roadway classifications.

There are 69 single lane roundabouts in Oregon at this time. During the data collection period 53 roundabouts were visited. Unfortunately some were not visited due to distance and funding limitations (Central Point, Medford, and The Dalles). The amount studied in Bend is very small in proportion to the number of roundabouts in Bend. Two-leg roundabouts did not have enough conflicting flow for this study. Conflicting flow and driver behavior affected roundabouts that were at a parking lot entrance or turn around. Some roundabouts were scouted, but could not be videoed due to obstacles (usually trees) in the center island. Some video recorded roundabouts were dropped from the study due to technical counting difficulties. Other videos came back with pictures that did not seem to match the roundabout. Of those, 23 were video recorded. With data cleaning and removal of outliers, 13 roundabouts were used for the equation set and 15 roundabouts were used in the validation set. Some roundabouts were represented in both data sets, but that no roundabout approaches were duplicated in the two data sets. These roundabouts are listed in Appendices B and C. Some roundabouts were visited, but not studied. Data collection procedures that were followed are listed in Appendix D.

Three, four, and five leg roundabouts were initially considered. Roundabouts with five operating legs were dropped from analysis. There weren't many five leg roundabouts and they operated differently. The equation was created for only three and four leg roundabouts. Three leg roundabouts were considered if the volumes and conflicts were observed or predicted to be abundant. Two leg roundabouts were not considered for the study due to a lack of conflict points. They slowed traffic with their physical presence, as roundabouts are designed to do, acting as a speed bump.

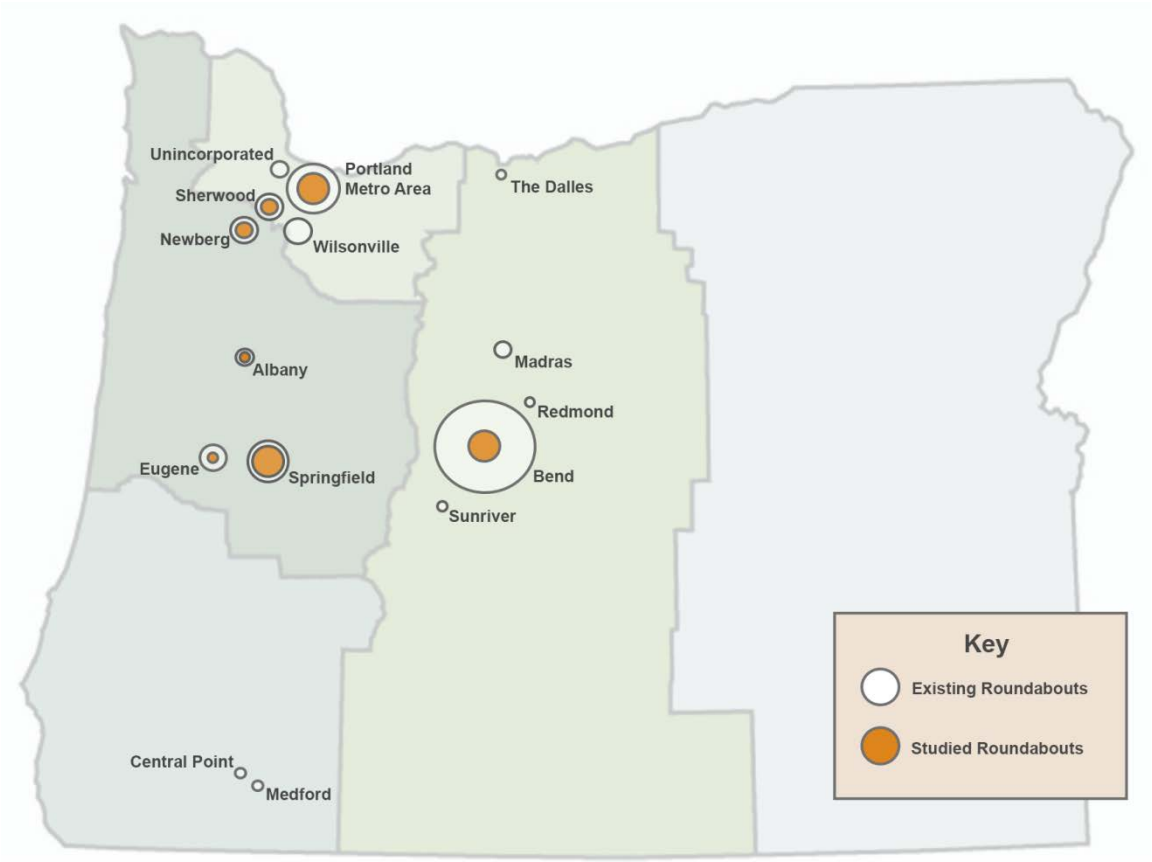
In total, 15 different roundabouts were used for data, shown in Appendices B and C. Out of 15 roundabouts:

- One roundabout was studied in: Albany, Hillsboro, Lake Oswego, Eugene, Sherwood/Newberg, Portland, and Tigard
- Two roundabouts were studied in: Happy Valley
- Three roundabouts were studied in: Bend, Springfield
- Three roundabouts were not near a school
- Three roundabouts had three legs

Two of the better performing roundabouts have inscribed diameters greater than 160 feet. Roundabouts with larger inscribed diameters and splitter island widths appeared to have improved performance among those observed.

Exhibit 2-4 shows the data collection in respect to the 69 existing single lane roundabouts in the state of Oregon.

Exhibit 2-1 Data Collection Map



The development and validation roundabouts are in Appendices B and C respectively. All data was collected in 2011. Where the data is available, both AM and PM peak periods were recorded.

Queue data was collected through observations during video recordings of traffic volumes. The maximum queue length and number of vehicles in the stopped queue was noted for every 15 minute interval.

Generally, an hour of traffic was recorded or selected. Of that hour, there were four 15 minute intervals (for four legs). An hourly traffic volume was created by multiplying 15 minute intervals by four.

It was recorded if the intersection was within a half mile of a school. School names, start times, and release times were sought out. Several cities have decided to build roundabouts near schools. This changed the peak hour of the roundabouts and the times they were studied. The proximity of the schools also infused a larger number of buses and pedestrians as this intersection may be a point all would have to pass to approach the school from one side of the city.

General items recorded were the date, city, intersection, and street classification. Geographic information was recorded including: number of legs, inscribed diameter, and splitter island width, see Exhibit 2-5. If it was a multi-lane roundabout, then that was also noted.

During data collection, it was observed that three leg roundabouts performed better than observed four leg roundabouts. The queue lengths were observed to be shorter. With fewer inputs into an intersection, operation had fewer conflicts.

In a cost savings measure, bicycle and pedestrian traffic was manually recorded. Video counts were developed with vehicle classifications of auto, medium truck and heavy truck.

The movements recorded were left, through, right, and U-turn. These movements were recorded for several modes: autos, medium trucks, heavy trucks, bicycles, and pedestrians. Pedestrians were recorded for which approach they crossed. If a bicycle used a pedestrian crossing, then the crossing was recorded as a pedestrian occurrence. If a bicycle moved into the approach lane and navigated through the roundabout, then they were counted as a bicycle, but also part of the vehicle group (much like a truck).

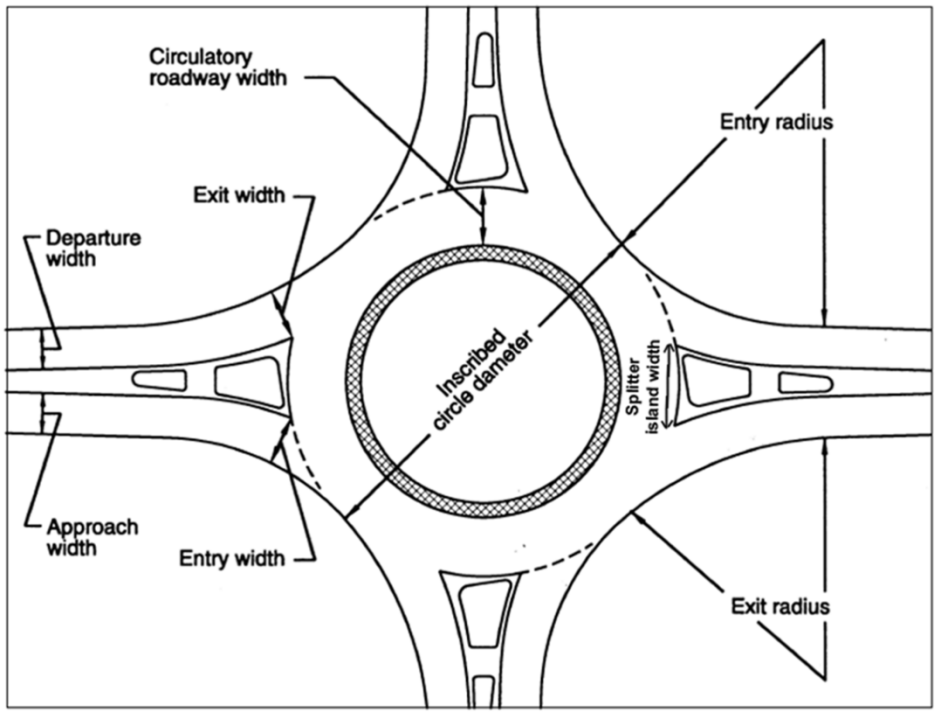
Roundabout information:

- number of legs
- if within ½ a mile of a school (“yes” or “no”)
- portion of an hour studied
- inscribed diameter

Inscribed diameter and splitter island dimensions are shown in Exhibit 2-5.

Exhibit 2-2 Roundabout Dimensions

Information per leg



- number of pedestrian crossings of each approach in the studied hour
- splitter island width adjacent to the circular roadway (larger is better)

The entry flow rate, circular flow or conflicting flow, and the exiting flow rates were calculated after observation and recordings. This information was computed with the aid of a spreadsheet.

2.3 Factors Observed to Influence Queue/Operation Behavior

While at the roundabout sites, it was observed that certain factors appeared to influence queue behavior and overall operation.

- Splitter island width
- Circulatory and entering volumes
- Within ½ a mile of a school

Circulating (interrupting) and entering (queue creating) volumes were the primary factor on operations.

Roundabouts with wide splitter islands appeared to improve operation and lower queue lengths. The wider a splitter island, the more time a waiting vehicle has to move from the approach leg into the circulatory roadway.

Roundabouts slowing traffic near a school (near a school zone) were observed to have an increase in school buses and young pedestrian crossings. The slower buses and crossing children appeared to increase queue lengths. School proximity may be an environmental type of variable similar to CBD, as an aggregate indicator of area characteristics such as parking, speeds, driver behavior, school zones, signs, markings, etc. Proximity of a school may indicate conditions where drivers tend to be more alert to the potential for school age children to be in the area and may tend to exercise a bit more caution than in non-school areas. School age children may not actually have to be present for the effect to exist.

3 Equation Data

3.1 Data Analysis

The data was split into two data sets, one for development of the predictive queue equation and another for validation (See Appendix A). Due to differences observed in the field and in calculations as well as lack of available sites, the multi-lane roundabouts were dropped and the study narrowed to single lane roundabouts.

3.2 Equation Data

Data for creating the equation and comparing methodologies included 243-15 minute sample sets. These 15 minute data sets were expanded to represent an hour. These data sets were from Region 1, Region 2, and Region 4. The data sets include the cities of Albany, Bend, Happy Valley, Hillsboro, Lake Oswego, Springfield, Portland, and Tigard.

Heavy vehicle percentages were calculated prior to equation development. The data influencing queues were identified and their significance considered.

3.3 Volume to Flow Rates

The intersection counts were converted into flow rates, making adjustments for bicycles, medium trucks, and heavy trucks for each movement.

The hour movement volumes of all vehicles, bicycles, medium trucks, and heavy trucks will be required. The highest 15 minute movement volume of the roundabout should also be recorded to determine the PHF for each movement.

Use the HCM 2010 Equation 21-8 to find the demand flow rate for each movement.

$$v_i = \frac{V_i}{PHF}$$

Where:

v_i = demand flow rate for movement (veh/h)
V_i = demand volume for movement, include bicycles as a vehicle (veh/h)
PHF = peak hour factor

Bicycles were part of the intersection volumes equaling a car for each movement (including U-turns). This does not involve the passenger car equivalent at this step. This is also the case for trucks; they are all counted as one vehicle entering the roundabout.

Roundabout data needed include the number of legs, if within ½ a mile of a school, decimal portion of an hour studied (1.0 for an hour), and the inscribed diameter.

The number of pedestrian crossings of each leg (including bicycles using pedestrian crossings) and splitter island width adjacent to the circular roadway (larger improves operation) were recorded. Inputs for the entire roundabout would include: number of legs (3 or 4), located within ½ of a mile of a school, portion of an hour studied (recommend 1.0), inscribed diameter, and passenger car equivalents.

Recommended Passenger Car Equivalents for bicycle, medium, and heavy truck are as shown in Table 3-1.

Table 3-1 Recommended Passenger Car Equivalents

Vehicle Type	Passenger Car Equivalents (E)
Passenger Car	1.0
Bicycle	1.0
Medium truck (two axles, UPS truck)	1.5
Heavy vehicle	2.0

Demand volumes (vph) were converted to passenger car equivalents (PCE/h), using a heavy vehicle factor equation similar to that found in the 2010 HCM. E_m and E_h are the equivalent factors for medium and heavy vehicles, 1.5 and 2 respectively. The proportion of these vehicle types occurring was calculated and designated as P_m and P_h.

Note that the recommended value of 1.0 PCE for bicycles (E_b) cancels out one term in the HCM 2010 equation below. The proportion of these vehicle occurrences was calculated. The heavy vehicle adjustment factors were calculated using the following equation.

$$f_{HV} = \frac{1}{1 + P_m(E_m - 1) + P_h(E_h - 1)}$$

Where:

f_{HV} = heavy vehicle adjustment factor
P_m = proportion of demand volume that consists of medium trucks (decimal)
P_h = proportion of demand volume that consists of heavy vehicles (decimal)
E_m = passenger car equivalent for medium trucks (Passenger Car Equivalents given)
E_h = passenger car equivalent for heavy vehicles (PCE s given)

This f_{HV} is then used by the Single Lane Roundabout Calculator in the form of HCM 2010, Equation 21-9.

$$v_{i,pce} = \frac{v_i}{f_{HV}}$$

Where:

$v_{i,pce}$ = demand flow rate for movement (PCE/hr)
v_i = demand flow rate for movement (veh/hr)
f_{HV} = heavy vehicle adjustment factor

Circulating and exiting flow rates were then calculated. The circulating flow rates in front of each entry are summed in terms of passenger car equivalents. See HCM 2010 Equation 21-11 below.

$$v_{c,NB,pce} = v_{WBU,pce} + v_{SBL,pce} + v_{SBU,pce} + v_{EBT,pce} + v_{EBL,pce} + v_{EBU,pce}$$

Where:

v_c = Circulating flow rates in front of specified entry; in passenger car equivalents

$v_{WBU,pce}$ = Flow rates of a specified movement

3.4 Empirical Queue Length Equation

From the equation and validation data sets mentioned, an equation was developed to estimate queue lengths at a roundabout. Outliers were taken out of the data set.

The empirically developed equation to predict queue for an approach:

$$Q = 25 \text{ X } \exp(-2.071 + 0.6829L + 0.4673S - 0.003466D - 0.03644I + 0.002454v_e + 0.000004307 \text{ X } v_e \text{ X } v_c + 0.0201P)$$

Where:

- Q = max queue (ft)
- L = number of legs (3 or 4)
- S = School within ½ mile of a roundabout, then 1 (0 otherwise)
- D = inscribed Diameter (ft)
- I = splitter Island width (ft)
- v_e = entry flow adjusted for PHF and vehicle type (pc/h)
- v_c = adjusted circular flow conflicts with approach (pc/h)
- P = total pedestrians or bicyclists in crosswalk (#/h)

As an additional test, only data points with queues 50 feet or greater were considered. Often accurate prediction of less than two cars is not significant to the roundabout operation. The empirical $Q \geq 50$ equation to predict queues for an approach greater than one car:

$$Q_{50} = 25 \text{ X } \exp(-0.02165 + 0.1445L + 0.2809S + 0.001321v_e + 0.000003877 \text{ X } v_e \text{ X } v_c + 0.009111P)$$

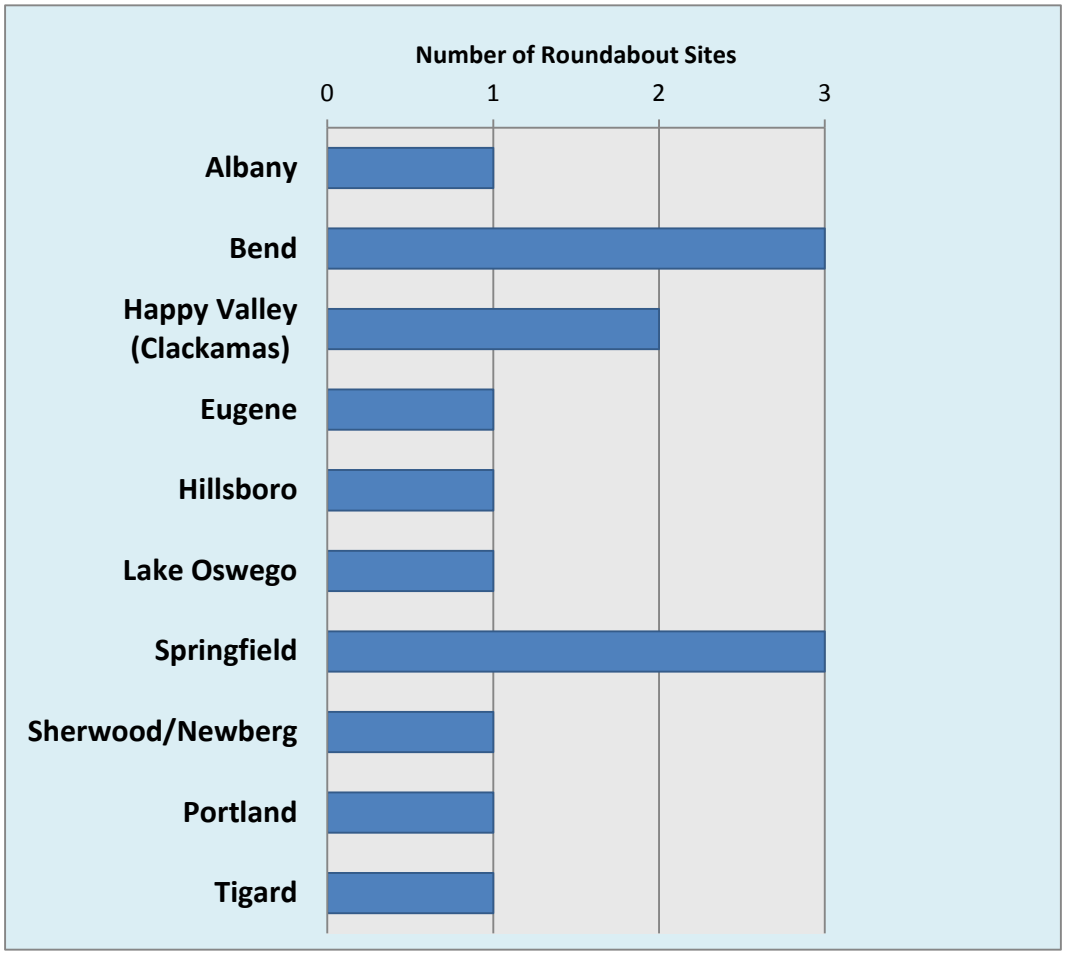
4 Validation Data

Validation tests the accuracy of equations in predicting queue lengths. Validation was processed with a subset of data previously set aside. The validation set was randomly created. The validation data, while smaller, was collected and treated just the same as the original data set.

4.1 Comparison

Data for validating the equation and comparing methodologies included 113 15 minute sample sets. The validation data set is shown in Exhibit 4-1.

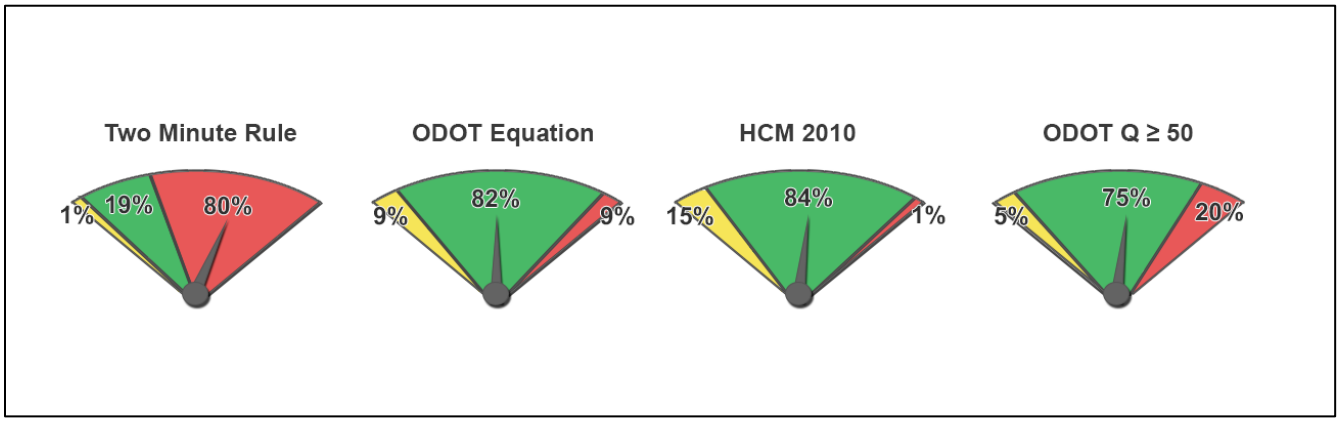
Exhibit 4-1 Validation Set: City



The validation data set included sites in Region 1, Region 2, and Region 4.

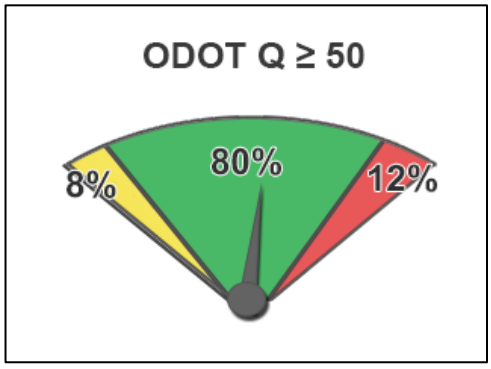
Predictive queue methods were compared using an accuracy window of being within two vehicles or 50 feet (+ or – two vehicles). In the validation set, the accuracy of the Two Minute Rule is 19%, with 80% of queue lengths overestimated. The accuracy of the HCM predictive queue methodology is 84%. The empirical equation predicted queues with an accuracy of 82%. Overall, the HCM 2010 model provided the highest accuracy level (Exhibit 4-2).

Exhibit 4-2 Results of Validation Set Comparison of Methods



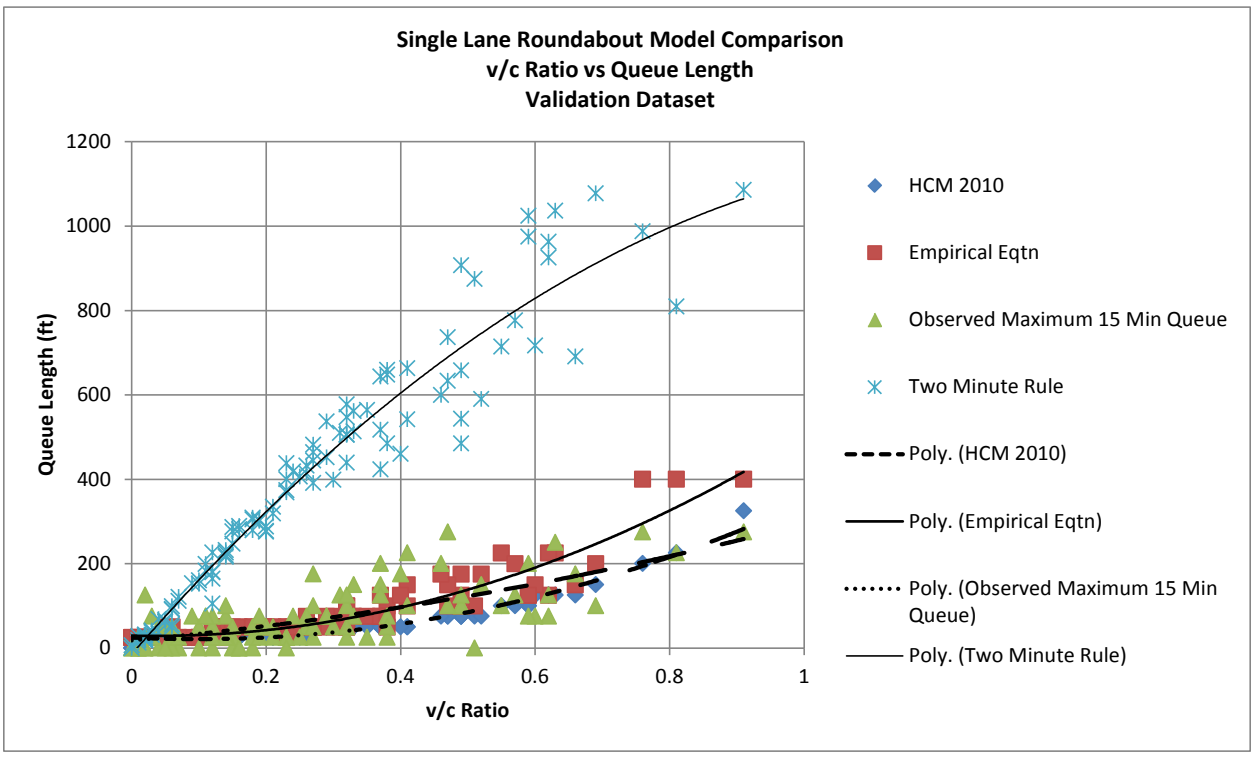
Since queue prediction may not be necessary for one or zero (1 - 0) cars at an approach, a potential alternative empirical equation was developed for queues 50 feet (two car lengths) or greater. Data points with zero or one vehicle in queue were excluded. When applied to the same data set, the accuracy was 75%. The accuracy was 80% when applied to the 65 samples that had queues of two cars or greater (Exhibit 4-3). This alternative empirical equation did not perform as well as the empirical equation which included all data points.

Exhibit 4-3 Using only 65 of 113 Samples (Queues ≥ 50)



A comparison of methodologies was also made in terms queue length versus HCM 2010-computed v/c ratio using the validation dataset. The results are shown in Exhibit 4-4. Queue lengths generally increase with v/c ratio, although other factors may affect the queue length. As shown, the Two Minute Rule significantly overestimates most of the observed data points. The HCM model and the empirically estimated equation are generally within the range of the observed data. However, the empirical equation overestimates queue lengths where v/c ratios exceed about 0.75. This may be attributable to the lack of high volume roundabouts in the estimation dataset. The HCM 2010 equation has better accuracy at the higher v/c ratios. The HCM model may also be a better estimate of 95th percentile queues, which may be slightly less than the observed maximum 15-minute queues.

Exhibit 4-4 V/C Ratio Versus Queue Length Comparison



5 Conclusions & Scope for Future Study

5.1 Conclusions

This study finds the Two-Minute Rule greatly overestimates queues at Oregon roundabouts. The estimated empirical equation has better accuracy, but overestimates queues at higher v/c ratios. The HCM 2010 equation provides the highest accuracy level, and is likely to better represent 95th percentile queue lengths which may be somewhat less than the maximum observed 15-minute queue lengths collected in this study.

The HCM 2010 roundabout queuing methodology is recommended to replace the Two-Minute Rule to estimate 95th percentile queue lengths for conditions that are applicable as per the HCM (isolated roundabouts, few pedestrians, undersaturated, etc.). For other situations alternative tools should be used, such as microsimulation.

5.2 Potential Future Research

The HCM 2010 methodology is applicable to typical isolated roundabouts. There are several limitations of the methodology as discussed in the HCM, which advises the use of alternative tools to produce more accurate results in those circumstances. Further study and development of guidance on the use of alternative methods/tools is desirable. Both deterministic software as well as microsimulation could be evaluated in order to develop guidance, settings and parameters for use.

Appendix A – Empirical Queue Length Equation

Empirical Queue Length Equation for Oregon Single-Circular-Lane Roundabouts

1. Equation Development

The roundabout data were divided into two data sets for equation development and validation respectively. The estimation data set has 244 records, and the validation data set has 112 records. The dependent variable is the maximum queue length at a roundabout leg in 15 minutes. Poisson regression is a regular method to model count data, and could be used to estimate the number of vehicles in the queue.

The following equation was developed from the estimation dataset to predict maximum 15-minute queue length. Statistical methods and engineering judgment was used to select variables.

$$Q = 25 \times exp\left(-2.071 + 0.6829\mathrm{L} + 0.4673S_c - 0.03644S_p + 0.002454v_e + 0.000004307v_e v_c + 0.0201\mathrm{P} - 0.003466\mathrm{I}\right)$$

Where:
Q = queue length (ft)
L = number of legs (3 or 4)
S_c = School within ½ mile of a roundabout, then 1 (0 otherwise)
I = Inscribed diameter (ft)
S_p = Splitter island width (ft)
v_e = entry flow adjusted for PHF and vehicle type (pc/h)
v_c = adjusted circular flow conflicts with approach (pc/h)
P = total pedestrians or bicyclists in crosswalk (#/h)

In Figure 1, observed queue lengths from data are compared with predicted queue lengths from the equation. Queue lengths less than or equal to 50 ft are slightly over-estimated but it is not an issue because queue lengths more than 50 ft are more concerned.

Figure 2 shows diagnostic plots of the model. These plots show good fit of the model. The model explains 58.2% of the variance.

Figure 1 Comparison of observed and predicted queue lengths

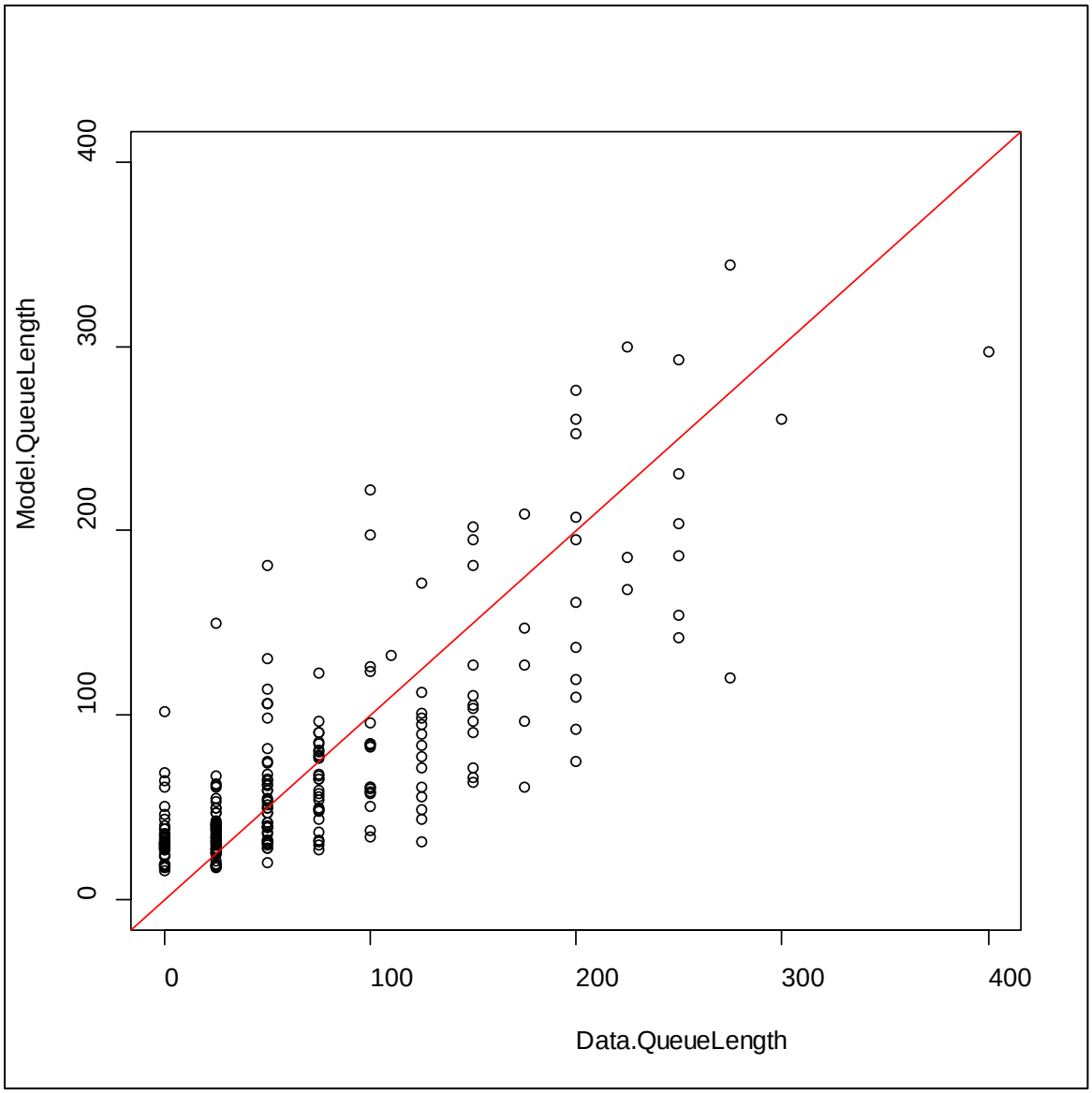
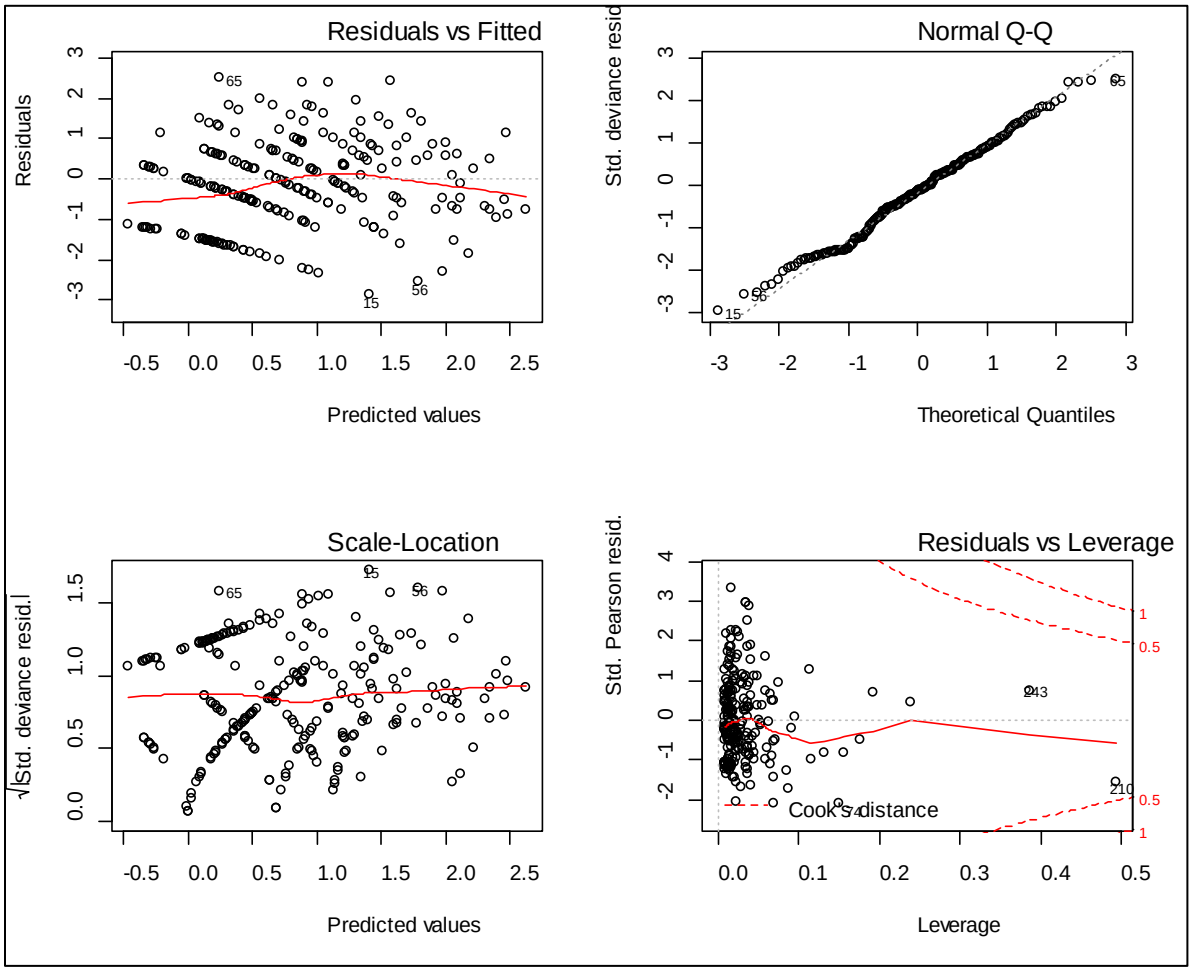


Figure 2 Diagnostic Plots of the Model



2. Sensitivity Analysis

R software provides effect display (Fox, 2003) that plots sensitivity of variables. In the estimated model, the entry flow rate and circular-lane flow rate have interactions. In Figure 3, the vertical axis is the queue length (in vehicles) generated from the model. The horizontal axis is circular-lane flow rate. The “l” in red color above each graph shows the value of the entry flow rate. The low-left graph shows that the modeled queue length is close to zero when the entry flow rate is zero. The low-right graph shows that for the entry flow rate of 233, the queue length increases when the circular-lane flow rate increases. In the up-left graph, the entry flow rate is 466 and the queue length increases with a higher rate. In the up-right graph, the entry flow rate is 700 and the queue length increases quickly when the circular-lane flow rate increases.

Figure 3 Effort Display of EntryFlowRate*CircFlowRate

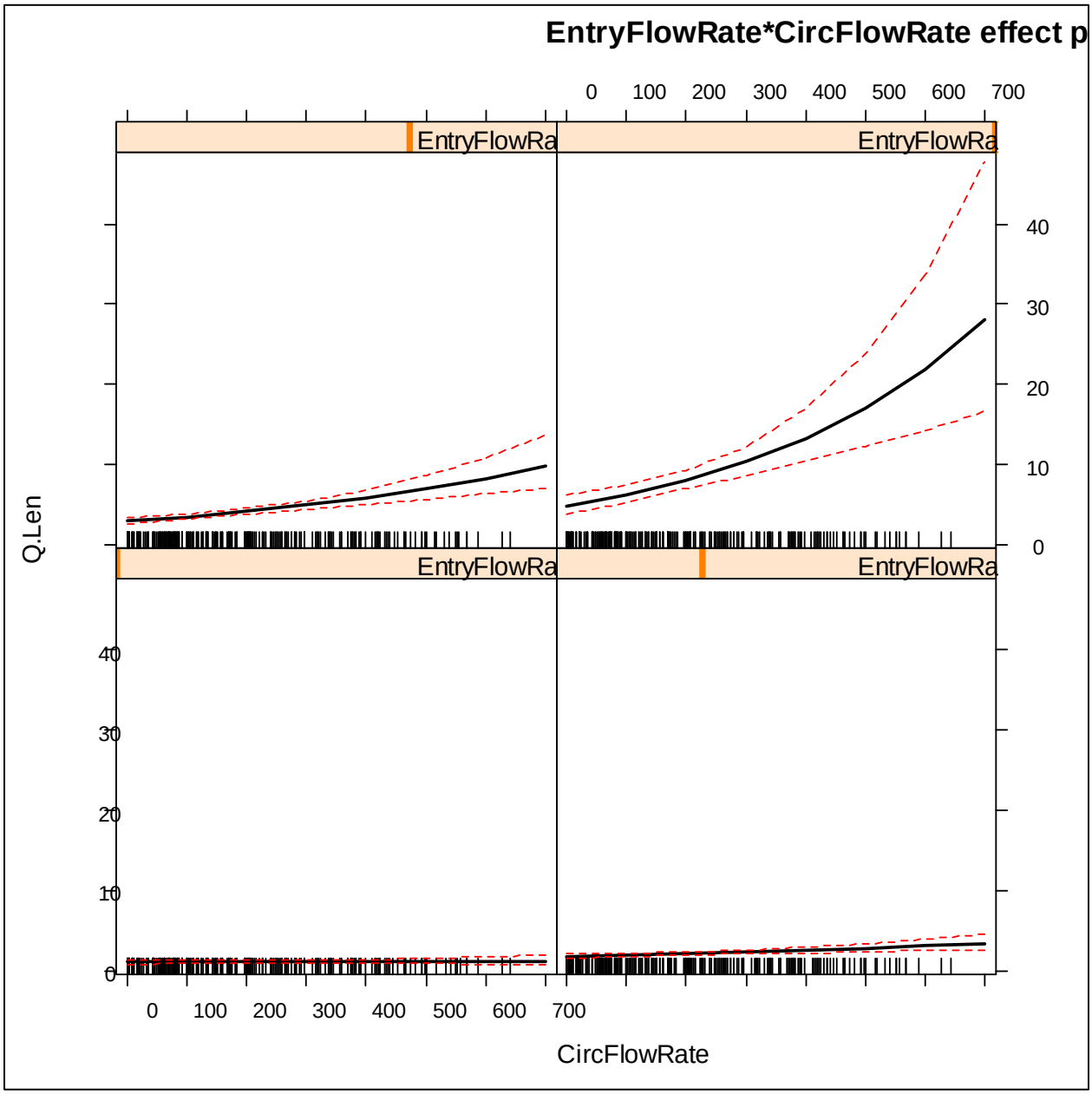


Figure 4 shows the sensitivity of other model variables. The observations are as follows. The three-leg roundabouts have less queue lengths than the four-leg roundabouts do. The queue length is larger when a school is nearby. The queue length increases when the pedestrian-crossing occurrence increases. The queue length decreases when the inscribed diameter or splitter island width increases. These observations of model sensitivity are consistent with the field observations.

Figure 4 Effect Displays of Model Variables

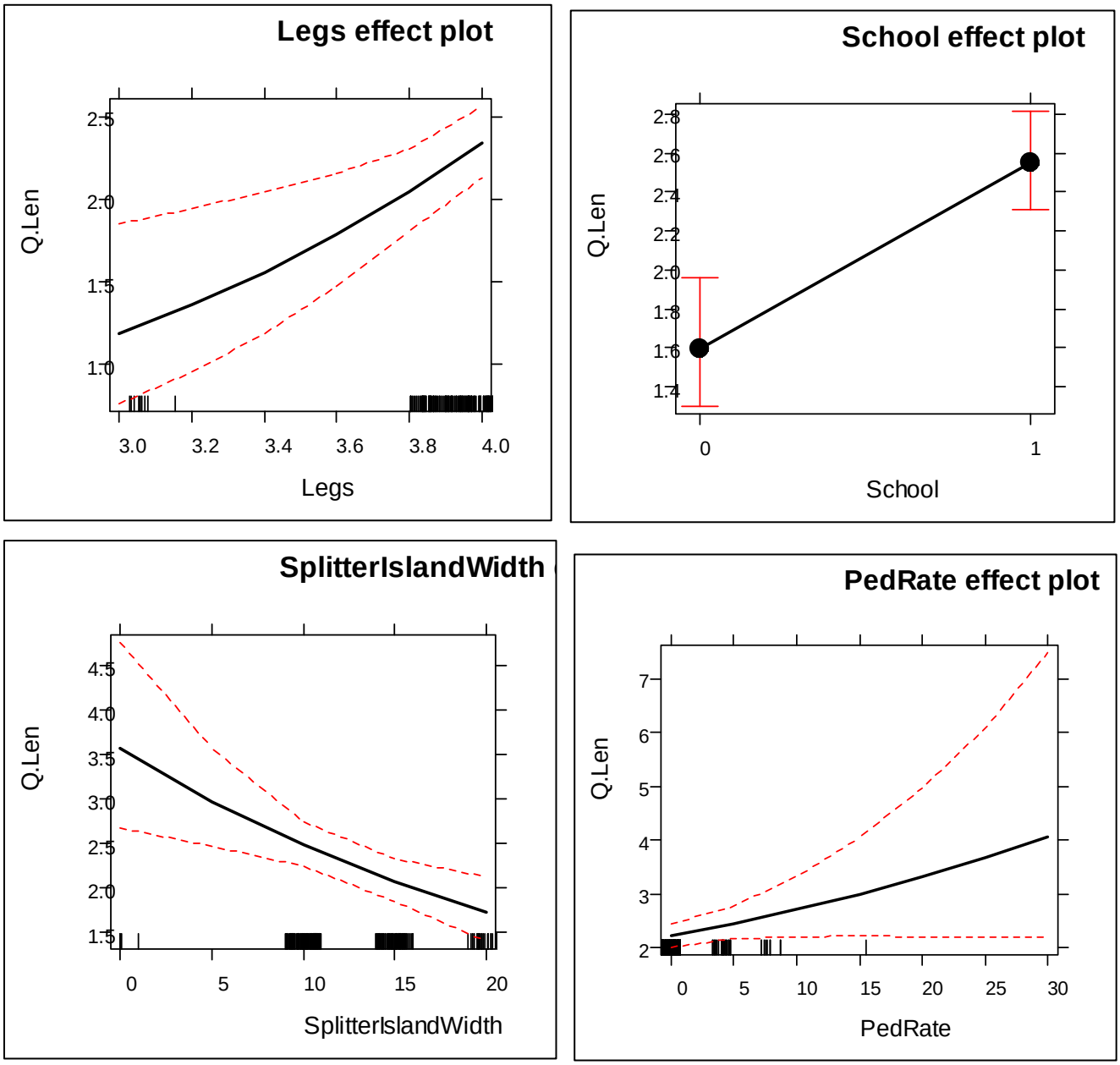
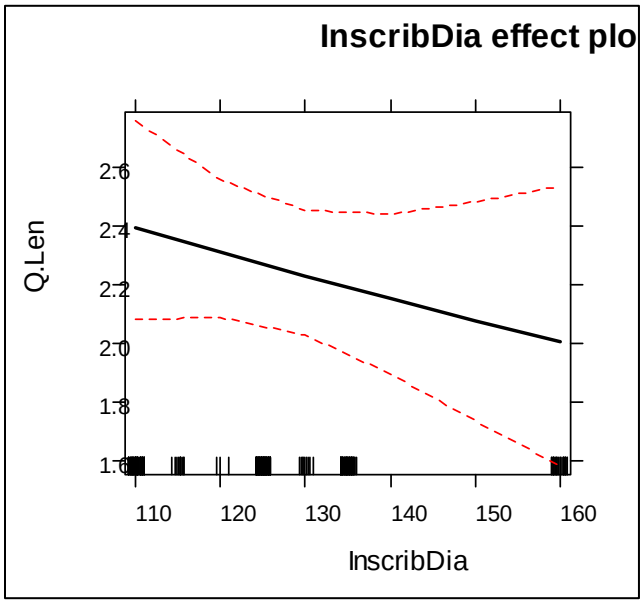


Figure 4 Effect Displays of Model Variables (continued)



References
Fox, J. (2003) Effect displays in R for generalised linear models. Journal of Statistical Software8:15, 1–27, <http://www.jstatsoft.org/counter.php?id=75&url=v08/i15/effect-displays-revised.pdf&ct=1>.

Appendix B – Data Set Sites

Table B- 1 Development Intersections

City	Intersection	# Legs	School	Inscribed Dia (ft)	Splitter Island Width (ft) (N, E, S, W)
Albany	NW Gibson Hill Rd and NW North Albany Rd	4	Yes	125	15, 15, 20, 20
Bend	Butler Market Rd and NE 8th Street	3	Yes	120	NA, 10, 10, 0
Bend	Franklin Ave and NE 8th Street	4	Yes	125	10, 10, 10, 10
Bend	NW Shevlin Park Rd/Newport Ave and NW College Way	4	No	135	10, 10, 15, 15
Happy Valley	Monteray Ave and Stevens Rd	4	Yes	135	20, 20, 15, 15
Happy Valley	Monteray Ave and Causey Ave	3	Yes	130	15, 15, 10, 15
Hillsboro	SE Alexander St and SE Brookwood Ave	4	Yes	160	15, 20, 10, 10
Lake Oswego	SW Stafford Rd and Rosemont Rd/Atherton Dr	4	Yes	135	15, 15, 15, 15
Springfield	Thurston Road and 58th Street	4	Yes	110	10, 10, 10, 10
Springfield	Jasper Road and 42nd Street	4	Yes	125	20, 20, 15, 15
Springfield	Corporate Way (Maple Island Farm Rd) and International Way	4	No	110	0, 10, 10, 10
Portland	SW Terwilliger and SW Palater Rd	4	Yes	125	20, 10, 15, 10
Tigard	Barrows Rd and Roshack Rd	4	No	115	15, 15, 15, 15

Table B- 2 Validation Intersections

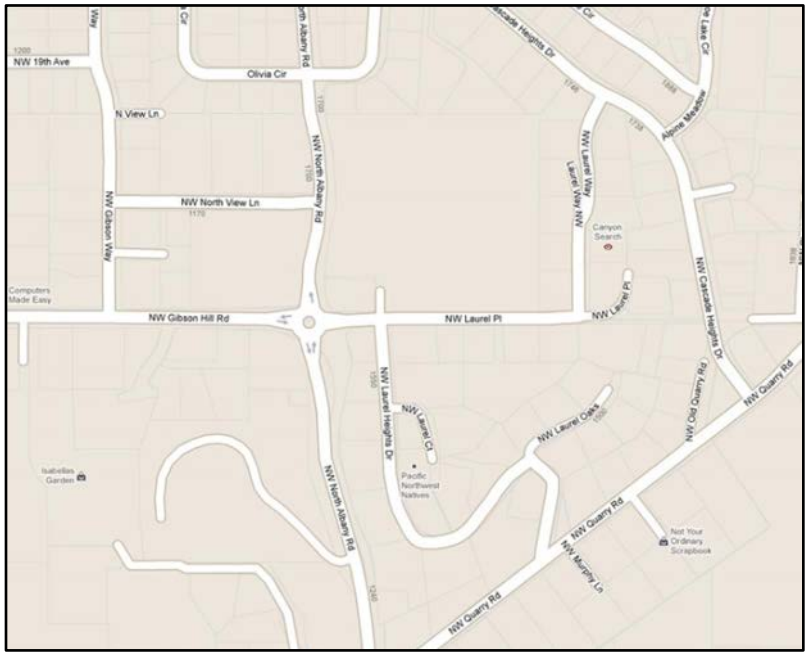
City	Intersection	# Legs	School	Inscribed Dia (ft)	Splitter Island Width (ft) (N, E, S, W)
Albany	NW Gibson Hill Rd and NW North Albany Rd	4	Yes	125	15, 15, 20, 20
Bend	Butler Market Rd and NE 8th Street	3	Yes	120	NA, 10, 10, 0
Bend	Franklin Ave and NE 8th Street	4	Yes	125	10, 10, 10, 10
Bend	NW Shevlin Park Rd/Newport Ave and NW College Way	4	No	135	10, 10, 15, 15
Happy Valley	Monteray Ave and Stevens Rd	4	Yes	135	20, 20, 15, 15
Happy Valley	Monteray Ave and Causey Ave	3	Yes	130	15, 15, 10, 15
Hillsboro	SE Alexander St and SE Brookwood Ave	4	Yes	160	15, 20, 10, 10
Eugene	Barger Dr and Green Hill Rd	3	Yes	125	10, 10, 10, NA
Lake Oswego	SW Stafford Rd and Rosemont Rd/Atherton Dr	4	Yes	135	15, 15, 15, 15
Sherwood/ Newberg	Crestview and Springbrook	4	Yes	200	25, 20, 25, 30
Springfield	Thurston Road and 58th Street	4	Yes	110	10, 10, 10, 10
Springfield	Jasper Road and 42nd Street	4	Yes	125	20, 20, 15, 15
Springfield	Corporate Way (Maple Island Farm Rd) and International Way	4	No	110	0, 10, 10, 10
Portland	SW Terwilliger and SW Palater Rd	4	Yes	125	20, 10, 15, 10
Tigard	Barrows Rd and Roshack Rd	4	No	115	15, 15, 15, 15

Appendix C – Site Descriptions

Albany, NW Albany Rd and NW Gibson Hill Rd

	Study Periods	Bikes	Peds
Bicyclists & Pedestrians	6:30 – 7:30 AM	0	0
	4:45 – 5:45 PM	0	0
# legs	4		
Heavy Veh.	Few		
Schools	North Albany Elementary North Albany Middle School Oak Grove Elementary Fairmont Elementary		

There are two heavy movements that are overlapping. There are no serious issues with the grade on approaches. Good restriction of plants in center.



Bend, Butler Market Rd and NE 8th Street

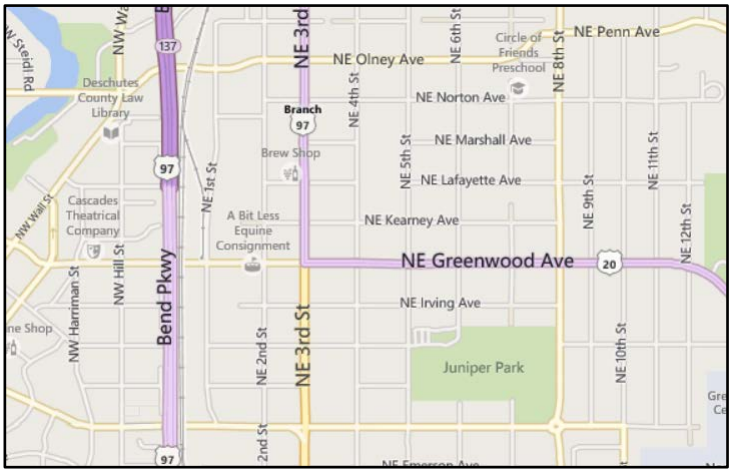
	Study Periods	Bikes	Peds
Bicyclists & Pedestrians	7:30 – 8:30 AM	4	0
	2:30 – 3:30 PM	4	0
	4:30 – 5:30 PM	4	0
# legs	3		
Heavy Veh.	Few		
Schools	Pilot Butte Middle School Juniper Elementary		

Somewhat transparent art object in the center. To the west, Butler Market Road connects with Mt Washington Drive, Bend Parkway, and US97. Continuing east, Butler Market Road is a major connector that intersects with 27th Street, Eagle Road, and Hamby Road. NE 8th Street to the South is a significant connector that parallels the Bend Parkway.

Bend, Franklin Ave and NE 8th Street

	Study Periods	Bikes	Peds
Bicyclists & Pedestrians	7:15 – 8:15 AM	3	0
	2:30 – 3:30 PM	5	6
	4:00 – 5:00 PM	9	12
# legs	4		
Heavy Veh.	Several		
Schools	Bend High School Marshal High School		

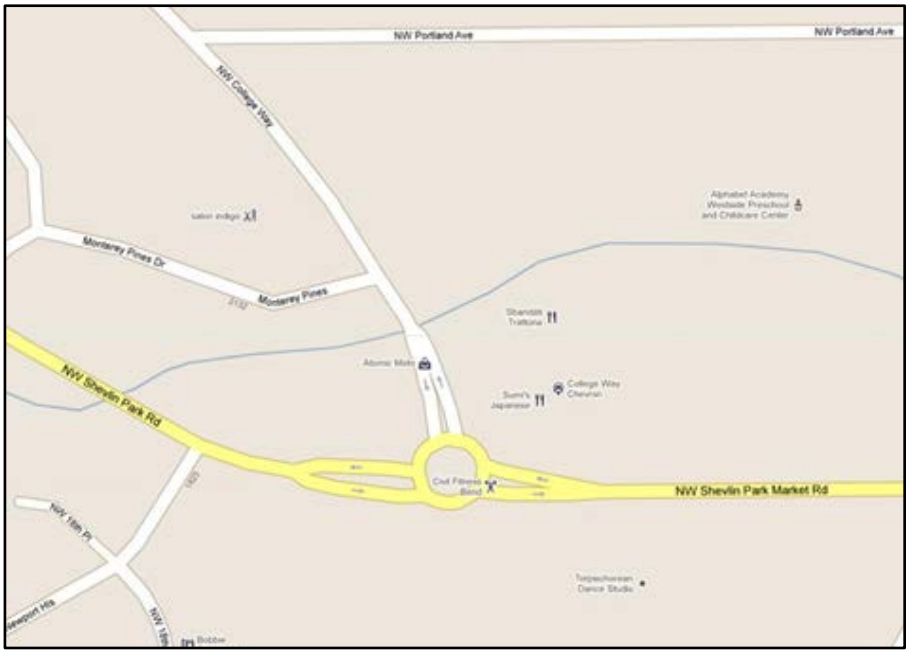
Placing drainage grates in the wheel path cases an undesirable additional stop by drivers. This is a nice place to slow traffic at the corner of a park.



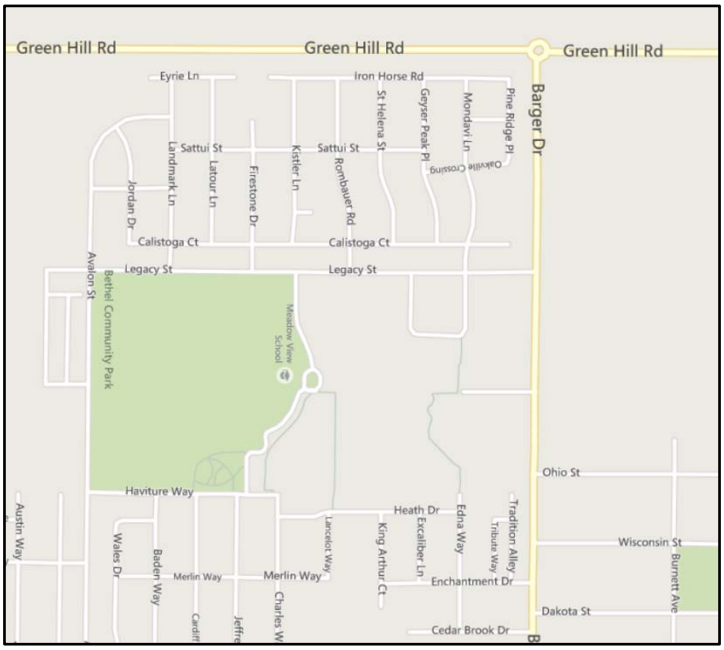
Bend, NW Shevlin Park Rd/Newport Ave and NW College Way

Bicyclists & Pedestrians	Study Periods	Bikes	Peds
	7:15 – 8:15 AM	6	4
	5:00 – 6:00 PM	4	3
# legs	4		
Heavy Veh.	Several		
Schools	N/A		

This is now a four leg roundabout. Large WB67 vehicles were seen competently crossing the median into the gas station. College Way has a very significant grade to it. Note how the city was able to easily add a fourth approach to this intersection.



Eugene, Barger Dr and Green Hill Rd



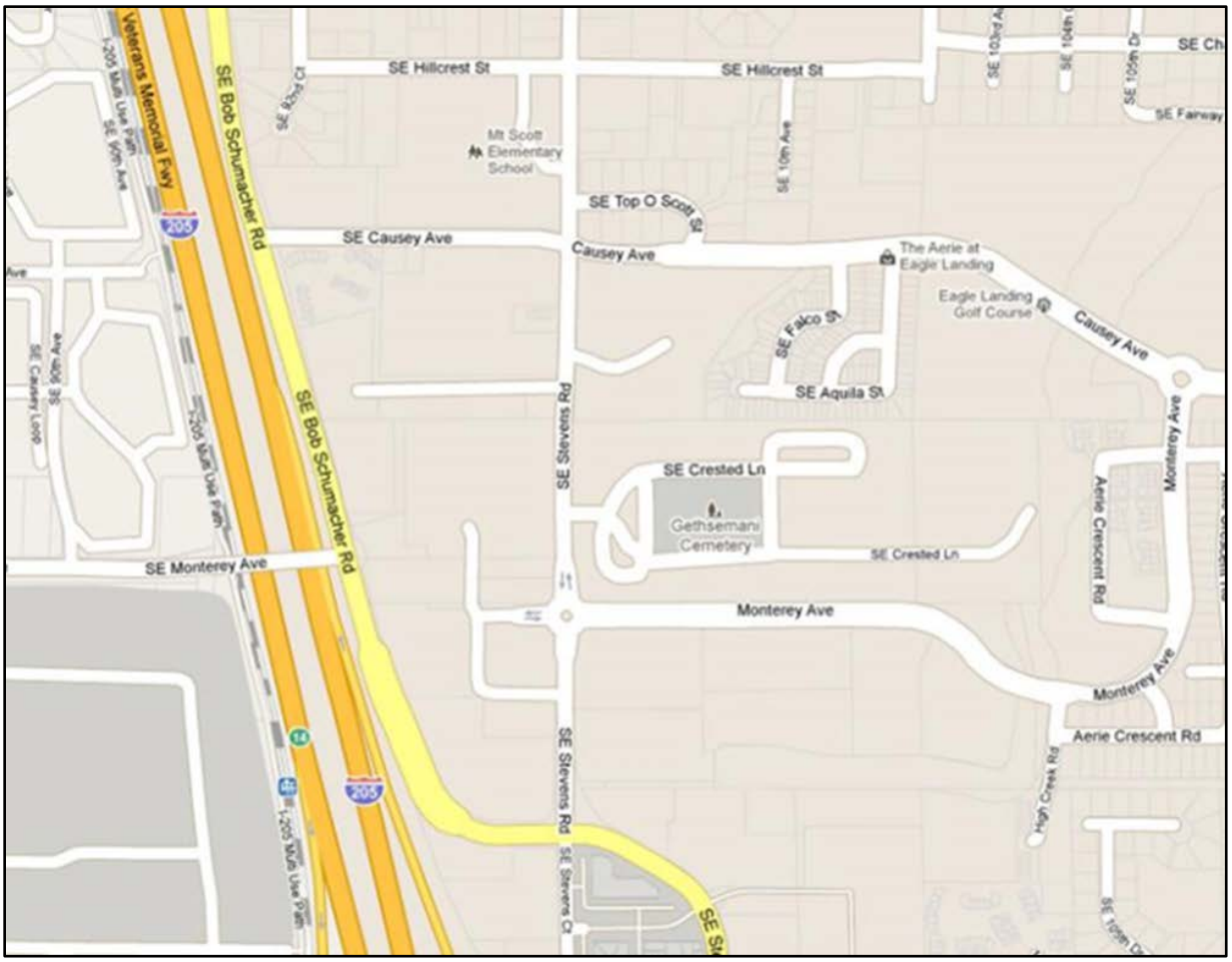
Bicyclists & Pedestrians	Study Period	Bikes	Peds
	4:45 – 5:45 PM	0	5
# legs	4		
Heavy Veh.	Moderate		
Schools	Witch Hazel Elementary Southern Meadows Middle School		

Note double yield signs. This roundabout functioned very well with a modest amount of items in the circular island. There are some utilities that seem close, but apparently has not been an issue to date. This roundabout is located on the east side of Eugene. Clear Lake Road is to the north, Royal Avenue is to the south.

Happy Valley, Monterey Ave and Stevens Rd

Bicyclists & Pedestrians	Study Period	Bikes	Peds
	6:15 – 9:00 AM	2	3
# legs	4		
Heavy Veh.	Few		
Schools	Mt Scott Elementary, Little Explorers Kindergarten		

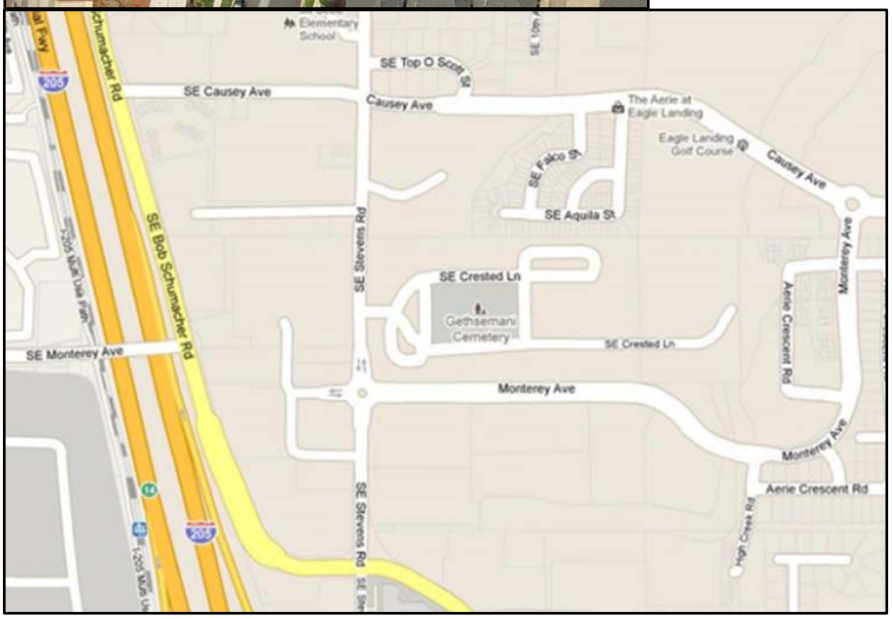
No queues beyond 2 cars. The 4th leg is Hope Community Church entrance. There is a significant grade difference to parking lot. Vehicle observed stopping and taking a picture from the circulatory roadway. One vehicle cut off another as they were staring at the eagle.



Happy Valley, Monterey Ave and Causey Ave

Bicyclists & Pedestrians	Study Period	Bikes	Peds
	7:00 – 7:45 AM	2	3
# legs	3		
Heavy Veh.	None		
Schools	Mt Scott Elementary Little Explorers Kindergarten		

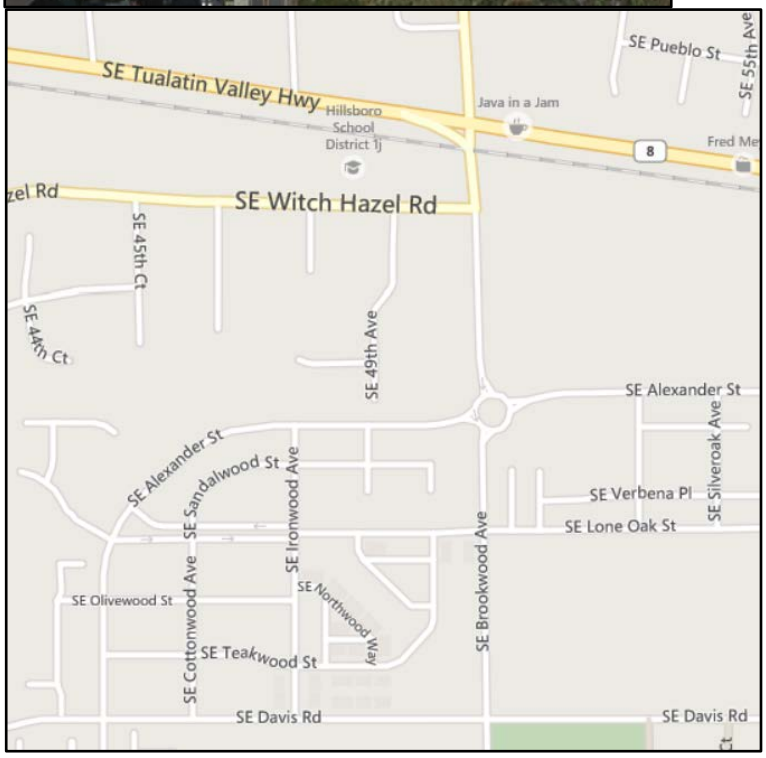
Golf course access is located nearby. Low volume, longest queue was one vehicle. No bicyclists or pedestrians in observed hours. Advertising sandwich signs were placed in the truck apron.



Hillsboro, SE Alexander St and SE Brookwood Ave

Bicyclists & Pedestrians	Study Periods	Bikes	Peds
	7:45 – 8:45 AM	0	2
	4:15 – 5:15 PM	0	5
# legs	4		
Heavy Veh.	Moderate		
Schools	Witch Hazel Elementary Southern Meadows Middle School		

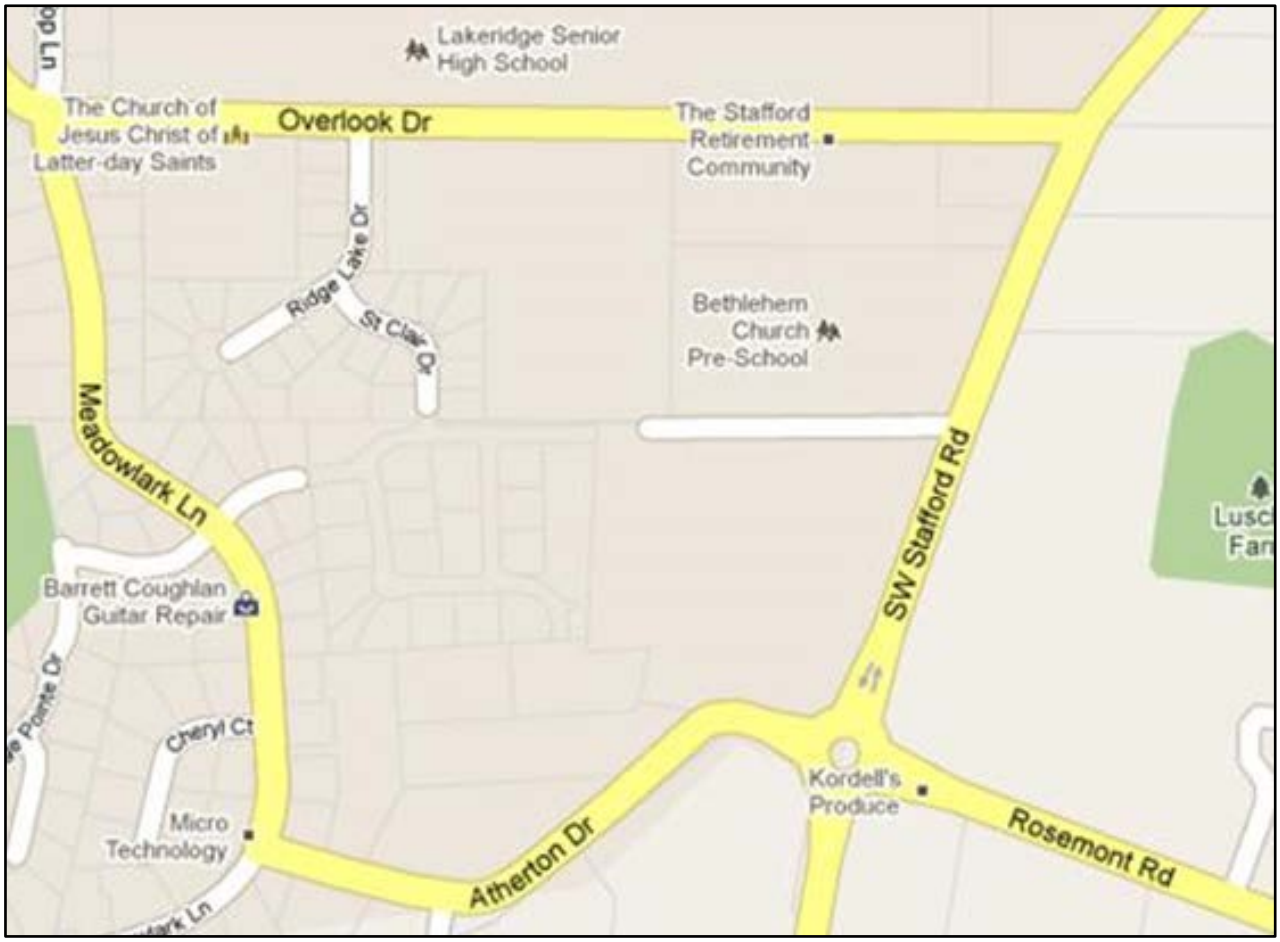
There is a railroad crossing just south of the Tualatin Valley Highway, OR8 to the north. With no obstructive feature, this roundabout operates very well. The bicycle ramps seem appropriate, where there are bicycle lanes.



Lake Oswego, SW Stafford Rd & Rosemont Rd/Atherton Dr

Bicyclists & Pedestrians	Study Periods	Bikes	Peds
	7:00 – 8:00 AM	0	0
	2:15 – 3:15 PM	0	1
# legs	4		
Heavy Veh.	Moderate		
Schools	Lake Ridge High School		

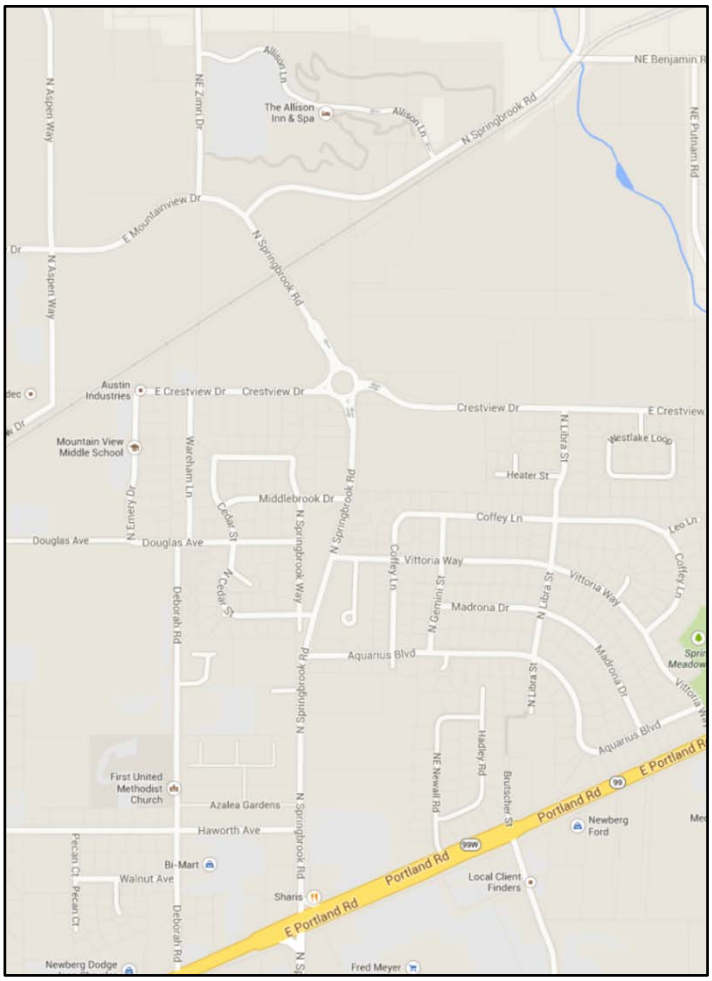
To the north Stafford Road leads to Lake Ridge High School, Lake Oswego Golf Course, and Lake Oswego. Stafford Road and Rosemont both eventually lead to I205. Where “sidewalk” exists, it is in the form of an asphalt multi-use path.



Newberg, Crestview Dr and Springbrook Rd

Bicyclists & Pedestrians	Study Periods	Bikes	Peds
	7:00 – 8:00 AM	0	0
	2:15 – 3:15 PM	0	1
# legs	4		
Heavy Veh.	Moderate		
Schools	Lake Ridge High School		

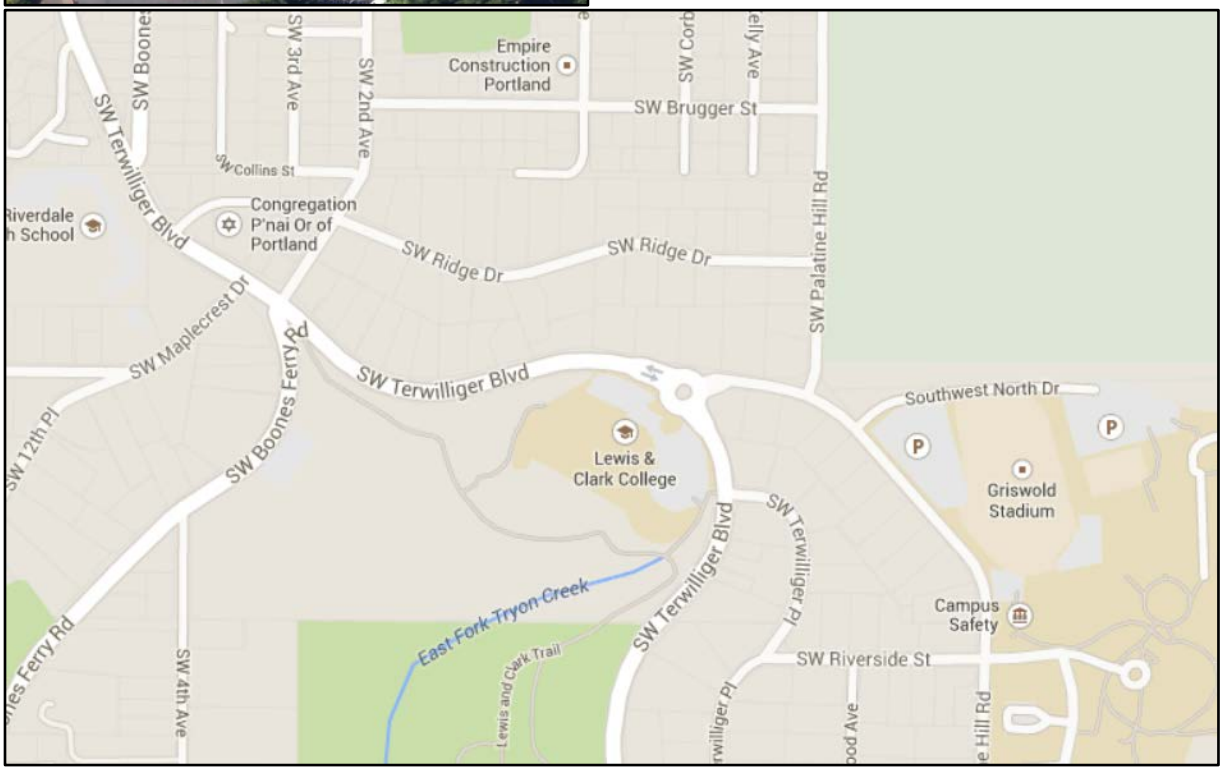
To the north Stafford Road leads to Lake Ridge High School, Lake Oswego Golf Course, and Lake Oswego. Stafford Road and Rosemont both eventually lead to I205. Where "sidewalk" exists, it is in the form of an asphalt multi-use path.



Portland, SW Terwilliger Blvd and Palater Rd

Bicyclists & Pedestrians	Study Periods	Bikes	Peds
	9:00 – 10:00 AM	9	16
	2:45 – 3:45 PM	10	4
# legs	3/4		
Heavy Veh.	Few		
Schools	Riverdale High School Lewis & Clark University		

This was a three leg intersection, with a fourth leg serving a law school. One leg serves as access to a park. The roundabout also serves two house driveway accesses. There were some heavy vehicles/buses. The truck apron is ineffective and not discernable by the travelling vehicles and is driven over regularly. This roundabout operates well with grades.

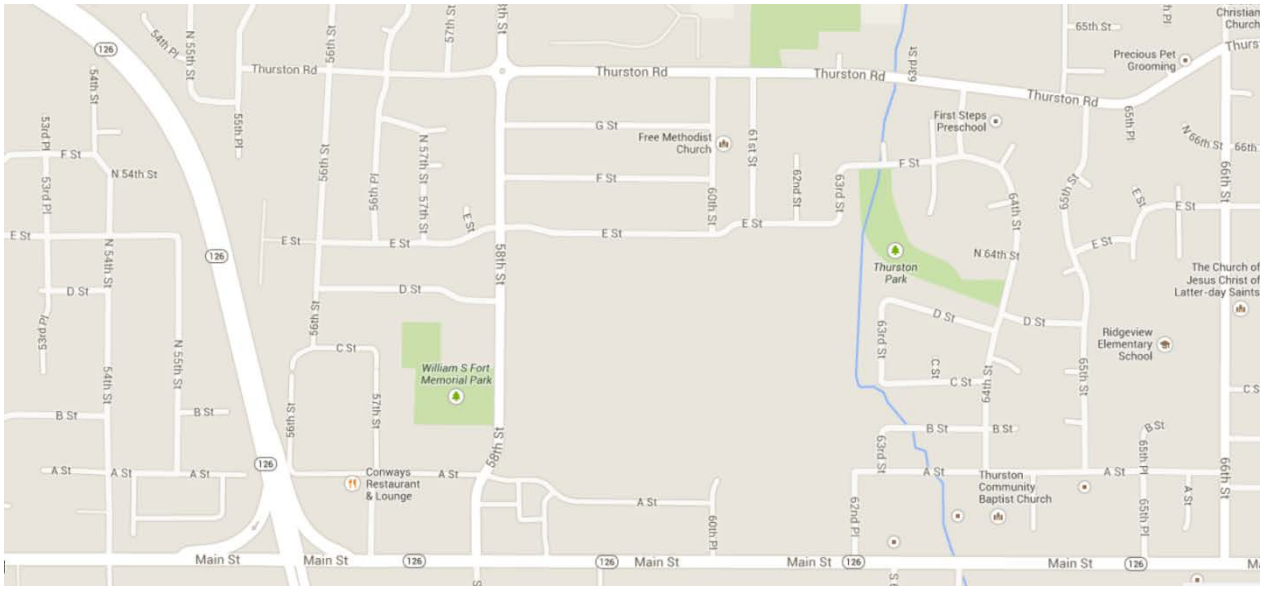


Springfield, Thurston Road & 58th Street

Bicyclists & Pedestrians	Study Periods	Bikes	Peds
	7:30 – 8:30 AM	1	6
	2:30 – 3:30 PM	0	5
# legs	4		
Heavy Veh.	Moderate (buses)		
Schools	Thurston High School		

This roundabout, built in 2001, is retrofit of a two-way stop. This roundabout helps prepare northbound drivers for the 10 mph curve beyond the roundabout. Bike lane ends sign is not common around roundabouts.

Thurston Road is one of few routes that parallels OR126/Main Street.

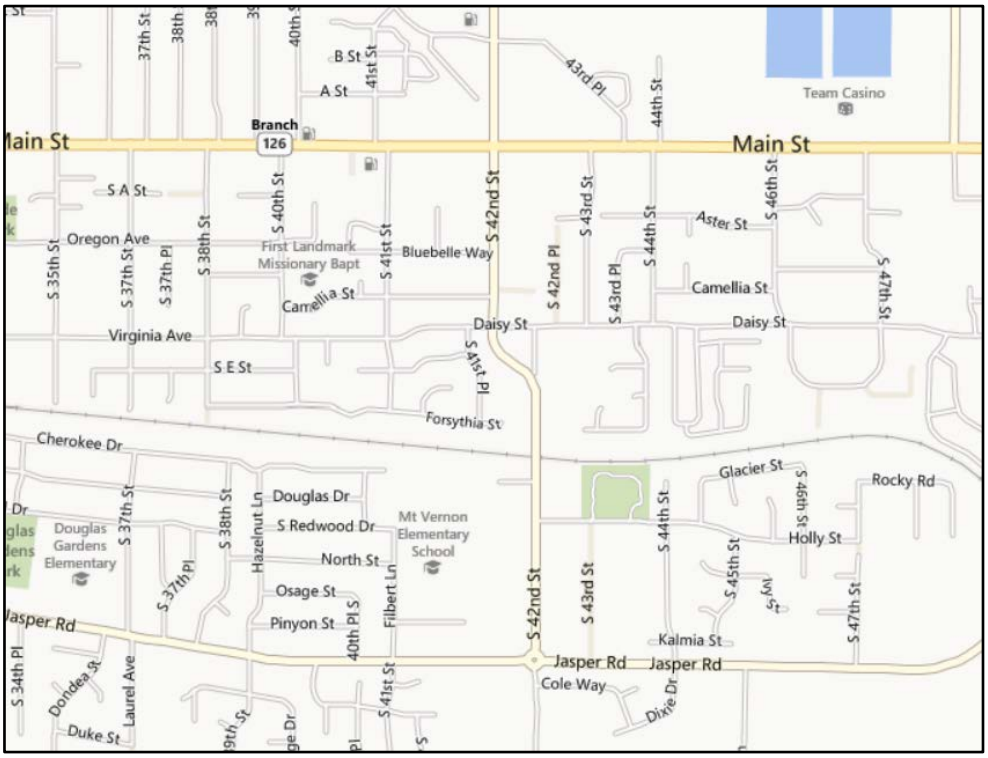


Springfield, Jasper Rd and 42nd

Bicyclists & Pedestrians	Study Periods	Bikes	Peds
	7:30 – 8:30 AM	0	0
	2:45 – 3:45 PM	0	0
# legs	4		
Heavy Veh.	Moderate (buses)		
Schools	Mt Vernon Elementary		

This is a roundabout on what is known as on OR222, the Springfield-Creswell Highway. The OR222 is marked on the north and east legs of this intersection. The customers used the convenience store in the northeast corner with ease.

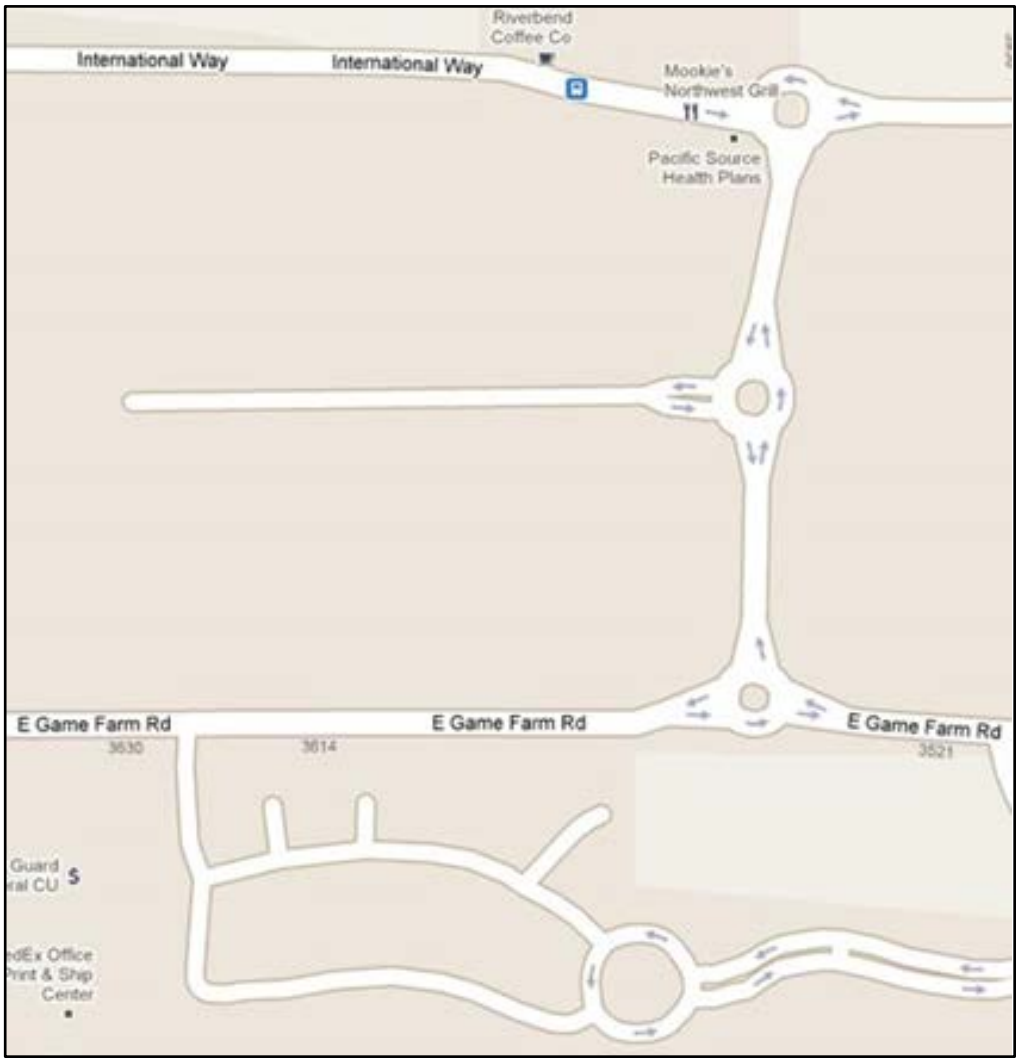
There is a neighborhood to the south. The northwest corner is a field that may develop at some point in the future.



Springfield, Maple Island Rd and International Way

Bicyclists & Pedestrians	Study Periods	Bikes	Peds
	11:30 AM – 12:30 PM	0	0
	4:45 – 5:45 PM	0	0
# legs	4, 3 splitter islands		
Heavy Veh.	Few (2 buses)		
Schools	N/A		

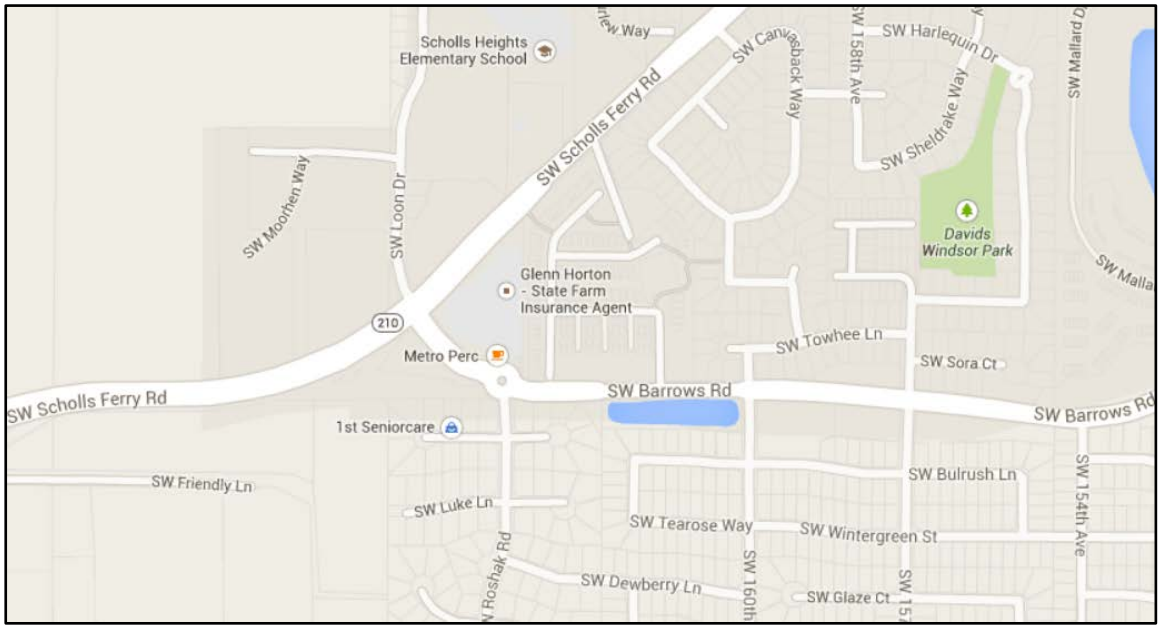
Note the double yield signs. The fourth leg is a shared access to a couple of businesses and a café. This is one of three roundabouts on Maple Island Road.



Tigard, Barrows Rd and Roshak Rd

Bicyclists & Pedestrians	Study Period	Bikes	Peds
	5:15 – 6:15 PM	15	2
# legs	4		
Heavy Veh.	Few		
Schools	N/A		

Note the double yield signs. SW Scholls Ferry Road, OR210, one block north, a business development to the east, a neighborhood to the west, and a gated fire access with mountable splitter island to the south. This roundabout operates well with grade. This roundabout has truck aprons like bulb outs on the corners between legs.



Appendix D – Data Collection Procedures

Procedures

Roundabouts were scoped for camera and observation locations. These were the procedures:

- Ensured all equipment from the materials list is packed in the car
- Double checked that PPE was packed for each person; class two vests and caps
- Scoped area for good location for tripod camera and station to count queues
- Located parking spot for state vehicle
- Set up tripod and telescoping pole/camera (sun glare)
- Ensured station was a safe location to measure queues
- Planned escape route from location if needed
- Measured distances of 50 feet, 100 feet, and 150 feet (50ft = 15.24m), placed metal/plastic flags at each distance
- With clip board, pen, and paper recorded queues

Materials List

These were the materials used.

- Procedures
- Roller Wheel
- Clip Boards
- Writing devices
- Paper/work sheets
- Plastic Flags, chalk for backup
- Red Hats
- Class 2 Vests
- Sunglasses
- Vehicle

Camera items

- Pole = 6.1 ft
- Tripod
- Battery Unit
- Charger (every night)
- Laptop and software
- Security cord, lock, and chain
- 9 - 20 lb. weights
- Ratchet strap