CITY OF BEND

# T R A N S M I T T A L

**To:** Eric King, City Manager

**From** Nick Arnis, GMD Director and Robin Lewis, Transportation Engineer

**Re:** Assessment of Reed Market/15th Street intersection

**Date:** 4/7/2017

---

Please include this memo in the weekly City Managers report.

At the request of the Old Farm Neighborhood Association Board about pedestrian safety, and the City desire to evaluate the 15th and Reed Market roundabout, an assessment was done of the SE 15th Street and Reed Market Road roundabout. The roundabout was constructed in 2014 as a part of the Transportation General Obligation Bond to replace the existing traffic signal that had a high number of injury crashes and was not up to City standards. The study reviewed safety and operations at the intersection.

The complete study is found at:
http://www.bendoregon.gov/government/departments/growth-management/transportation-planning-program

**Summary and Findings:**

- Crashes reduced by 84%
- Vehicles approach speeds are slow and within design speeds
- Drivers have high yield rates for pedestrians; there is no need for a signalized crosswalk at this time.
- Limited analysis but capacity is about 30% higher than national average

| **Evaluation** | **Findings** |
|---|---|
| Is the intersection safer? Yes | Average crashes per year decreased<br>from 18 to 2 |
| Is the crosswalk safe? Yes | <u>Approaches (2 lanes to cross)</u><br>95 to 100% cars yielding to pedestrians and;<br><u>Exits (single lane to cross)</u><br>75% yielding (lower if biking in crosswalk) |
| Are drivers using correct lanes? Yes | 94 to 100% (few people use the wrong lane) |
| Are the speeds within the design? Yes | 15 mph entering: consistent with design<br>17 mph circulating: consistent with design<br>22 mph exiting: consistent with design |
| Is it efficient? Yes –with limited data | Measured capacity is 29% higher than national average |

**Next Steps**

The study identifies additional signing and messaging for people biking through crosswalks. While the number of drivers using the correct lane to navigate the roundabout is very high, there is room for improvement and the study identifies lane assignment signs and pavement markings.

720 SW Washington St.
Suite 500
Portland, OR 97205
503.243.3500
www.dksassociates.com

# FINAL MEMORANDUM

**DATE:** March 20, 2017

**TO:** Robin Lewis, City of Bend

**FROM:** Steve Boice, P.E., PTOE
Chris Maciejewski, P.E, PTOE
Randy Johnson, P.E., PTOE
Sina Vadaei, EI

**SUBJECT:** **City of Bend Roundabout Assessment**
Task 4 Data Evaluation P16172-001

## Introduction

The purpose of this memorandum is to present the evaluation results of the field data collected at the study roundabout of 15th Street/Reed Market Road in Bend, Oregon. This roundabout was constructed as a multi-lane hybrid to meet immediate travel demand needs while allowing for phasing of additional lanes if needed in the future. It is also one of five newer roundabouts that have been constructed with the City's updated roundabout design standards. The analysis aims to address citizen concerns of driver confusion, higher travel speeds, and potentially higher crash rates compared to other single lane roundabouts within the City. It also considers the impacts these factors may have on roundabout operations and capacity.

## Evaluation Criteria and Results

To evaluate the operation and safety of the roundabout, six criteria were analyzed as presented previously as part of the methodology memorandum. A summary of the results of each of the criteria is given below.

### Crash Data

Table 1 shows the total reported collisions at the intersection of 15th Street/Reed Market Road as well as the calculated observed crash rates for both before and after the construction of the roundabout[1]. Typically observed crash rates approaching or exceeding 1.0/million entering vehicles (MEV) are flagged for further review. As shown in the table the crash rate per MEV at the intersection prior to the roundabout, under traffic signal control, exceeded 1.0, which indicates there was a need for investigation into potential safety improvements. A roundabout was constructed at this intersection largely due to operational and safety benefits. After the

[1] City of Bend crash records, 2010-2015, provided by Jovi Anderson, City of Bend

construction of the roundabout, the average number of crashes per year and crash rate per MEV was reduced. The average number of total crashes per year was reduced from 18.2 to 2, which is an 84-percent decrease in reported crashes per year.

**Table 1: Reported Crashes and Observed Crash Rates**

| Year | Reported Crashes | | | | Average Crashes/ Year | Observed Crash Rate/Million Entering Vehicle (MEV) | % Total Reduction |
|---|---|---|---|---|---|---|---|
| | Fatal | Injury | PDO[2] | Total | | | |
| Before (2010 to 2014)[1] | 0 | 26 | 65 | 91 | 18.2 | 1.9 | 84 |
| After (2015)[1] | 0 | 2 | 1 | 2 | 3 | 0.3 | |

Notes:
1. Before refers to the time before the roundabout was built. After refers to the time after the roundabout was built. The roundabout was opened November 21, 2014 and the "After" crash data is available only for the year 2015. The 2015 data is preliminary and subject to change.
2. PDO = Property Damage Only crashes

This is a significant reduction in crashes, therefore the comparison of crash rates for other single lane and multi-lane roundabouts were conducted. Table 2 shows the average annual crash rates at 11 U.S intersections that were converted to roundabouts[2]. The average crash rate of the study roundabout is much less than other U.S large sized roundabouts, however the available crash data is limited to one year.

**Table 2: Average Annual Crash Rates at 11 U.S. Intersections Converted to Roundabouts**

| Size | Sites | Before Roundabout | | | Roundabout | | | % Total Reduction |
|---|---|---|---|---|---|---|---|---|
| | | Injury | PDO | Total | Injury | PDO | Total | |
| Small/Moderate[1] | 8 | 2.0 | 2.4 | 4.8 | 0.5 | 1.6 | 2.4 | 50 |
| Large[2] | 3 | 5.8 | 15.7 | 21.5 | 4.0 | 11.3 | 15.3 | 29 |

Notes:
1. Mostly single-lane roundabouts with an inscribed circle diameter of 30 to 35 m (100 to 115 ft).
2. Multilane roundabouts with an inscribed circle diameter greater than 50 m (165 ft).

Additionally, the crash rate reduction from this study was compared to the crash reduction factor (CRF) from Crash Modification Factors Clearing House[3]. A crash reduction factor (CRF) is the percentage crash reduction that might be expected after implementing a given countermeasure at a specific site.

---

[2] Roundabouts: An Informational Guide. Washington, D.C.: U.S. Dept. of Transportation, Federal Highway Administration, 2000. June 2000. Web.
[3] "Crash Modification Factors Clearinghouse." Crash Modification Factors Clearinghouse. N.p., n.d. Web. 24 Feb. 2017.

Table 3 shows the CRF for converting a signalized intersection into a roundabout. As listed, the CRF for the study roundabout is also greater than other studies and is comparable with that used by the Oregon Department of Transportation (ODOT).

**Table 3: Crash Reduction Factors for Converting a Signalized Intersection into Single or Multi-Lane Roundabout**

| | Crash Reduction Factor (%) |
|---|---|
| Single-Lane[4] | 26 |
| Multi-Lane[3] | 19 |
| ODOT Roundabout[5] | 48-78* |
| Study Roundabout (Hybrid) | 89 |

*Note: This CRF does not include PDO's

## Count Data

Existing volumes were collected for three different days at the study roundabout using a combination of video and road tubes. Figure 1 through Figure 3 show the peak hour turn movement counts for each respective day of count data. The volumes were found to be relatively consistent over the study period. Table 4 shows the peak hour times and total entering volume. The highest p.m. peak hour volume occurred on September 21, 2016 (Wednesday) beginning at 4:30 p.m. The current peak hour volumes are consistent with the previously forecasted peak hour volumes for the intersection (current 2016 p.m. peak 2,594 versus projected 2020 p.m. peak 2,585, current 2016 a.m. peak 2,166 versus projected 2020 a.m. peak 2,079)[6].

Figure 4 shows the trend of existing average daily eastbound traffic volumes given the three days of count data over the 24-hour period. As illustrated the volumes peak in the morning from 7 a.m. to 9 a.m. and in the afternoon from 4 p.m. to 6 p.m. The right lane of the west leg approach has lower volumes than the left lane since the right lane is a right turn only lane. This makes the left lane of the west leg approach the critical lane, a concept that is important when modifying the capacity model later in this memorandum.

[4] Gross, Frank, Craig Lyon, Bhagwant Persaud, and Raghavan Srinivasan. "Safety Effectiveness of Converting Signalized Intersections to Roundabouts." Accident Analysis & Prevention 50 (2012): n. pag. Web.
[5] ODOT HSIP Countermeasures and Crash Reduction Factors, January 2015.
[6] G.O. Bond Reed Market Intersection Evaluation Report, DKS Associates, October 2012.

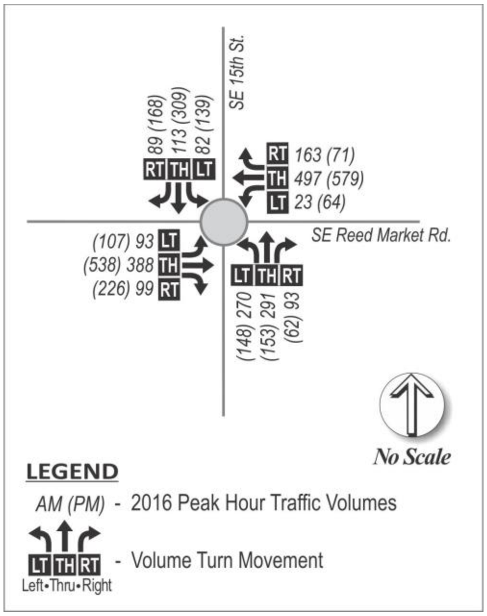


**Figure 1: Peak Hour Volumes for 9/20/2016**

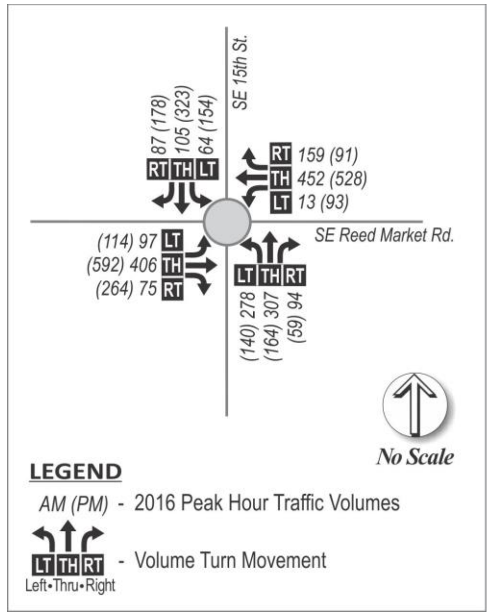


**Figure 2: Peak Hour Volumes for 9/21/2016**

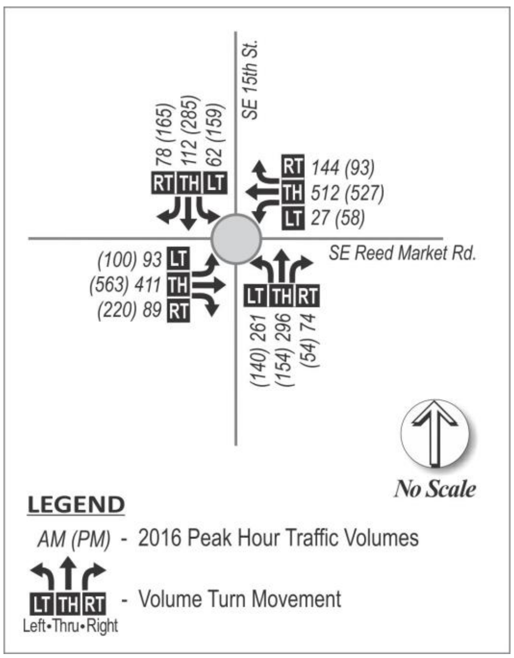


**Figure 3: Peak Hour Volumes for 9/22/2016**

**Table 4: Peak Hour Times and Total Volumes for Collected Data**

| Date | a.m. Peak Hour (p.m. Peak Hour) | Total a.m. Volume (Total p.m. Volume) |
|---|---|---|
| September 20, 2016 | 7:10 to 8:10<br>(4:50 to 5:50) | 2,201<br>(2,564) |
| September 21, 2016 | 7:10 to 8:10<br>(4:30 to 5:30) | 2,137<br>(2,700) |
| September 22, 2016 | 7:05 to 8:05<br>(4:40 to 5:40) | 2,159<br>(2,518) |

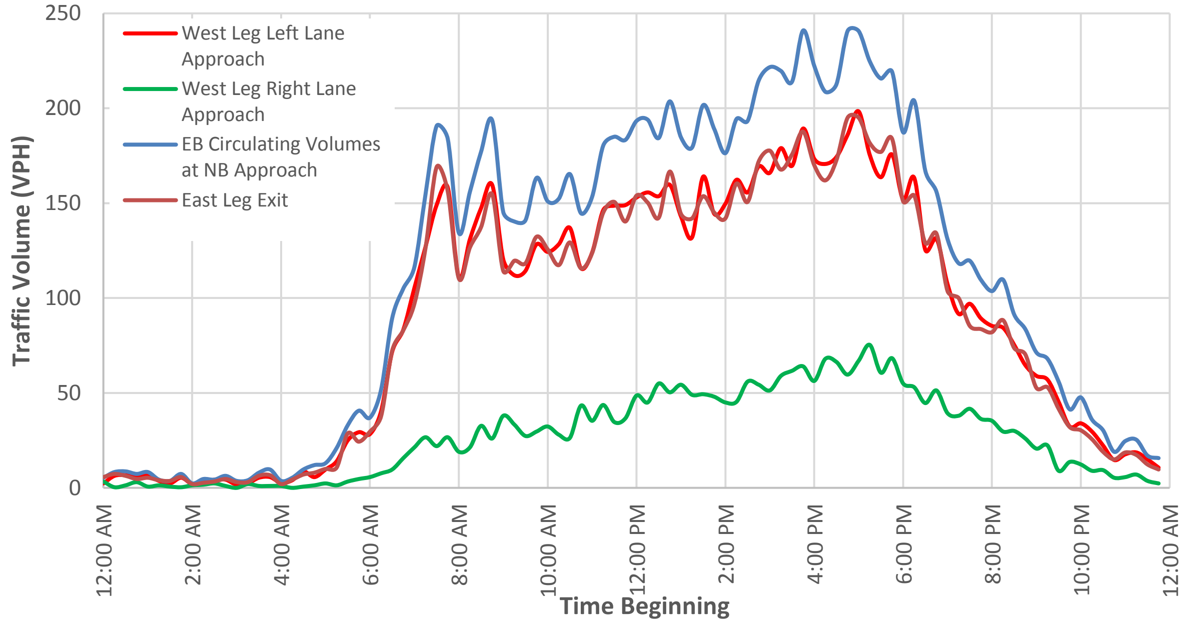


**Figure 4: Average Daily Volumes at 15th Street/Reed Market Road**

## Pedestrian Yielding Compliance

Table 5 shows the yielding compliance rate of all vehicles during a pedestrian or bicyclist crossing event at the marked crosswalk on the east leg of the study roundabout.

The pedestrian/bicyclist yielding rates of eastbound entering vehicles is high (95-percent to 100-percent), however the exiting vehicles along the west leg have a much lower pedestrian yielding compliance rate (65-percent). In comparison, roundabouts across the country showed an average yield rate of 76 to 79-percent on the entry side and 54 to 69-percent on the exit side[7]. Therefore, the yielding rate for entering vehicles at this roundabout is higher than average, and within average for exiting vehicles.

[7] Rodegerts, Lee, et al. (2007), Roundabouts in the Unites States. NCHRP Report 572. National Cooperative Highway Research Program. Transportation Research Board. Washington, DC. 2007Rouphail et al., 2005

It is important to note that pedestrian volumes at this roundabout were low during the traffic count periods and almost half of the crossing events were bicyclists using the crosswalk. All the bicyclists using the crosswalk biked across rather than getting off their bikes prior to the crossing[8]. Drivers could be more likely to yield to pedestrians than bicyclists because drivers could interpret bicyclists as vehicles.

**Table 5: Pedestrian/Bicyclist Yielding Compliance Rate on the East Leg of the Study Roundabout**

| Date | Time | # of Crossing Events | Sample Size (# of Vehicles) | Yielding Compliance[1] | | |
|---|---|---|---|---|---|---|
| | | | | Exiting Vehicles | Entering Vehicles (Left Lane) | Entering Vehicles (Right Lane) |
| September 20, 2016 | 6 a.m. – 8 p.m. | 8 | 23 | 60% | 85% | 100% |
| September 21, 2016 | 6 a.m. – 8 p.m. | 12 | 24 | 63% | 100% | 100% |
| September 22, 2016 | 6 a.m. – 8 p.m. | 10 | 13 | 100% | 100% | 100% |
| **Total Yielding Compliance[2]** | | **30** | **60** | **65%** | **95%** | **100%** |
| **Nationwide Comparison** | | | | **54% – 69%** | **76% to 78%** | |

Notes:
1. Yielding compliance is calculated by dividing the number of vehicles that yielded by the total number of vehicles that had the opportunity to yield or not yield during the crossing events on a given day. A motorist is in compliance when they slowed or stopped/remained stopped for a crossing pedestrian/bicyclist waiting on the curb or splitter island to cross.
2. Total yielding compliance is calculated by dividing number of vehicles that did not yield by the total number of vehicles that had the opportunity to yield or not yield during the crossing events over the three days of the study.

To further understand the nature of yielding compliance Table 6 summarizes the pedestrian/bicyclist yielding compliance rate of pedestrians/bicyclists that walked/biked from the curb towards the island. As indicated, the percentage drops slightly. In comparison, roundabouts across the country showed an average yield rate of 76-percent on the entry side and 54-percent on the exit side[9].

---

[8] ORS 814.410 states that a bicycle may operate on sidewalk or entering crosswalk if operating at a speed that is similar to an ordinary walk.
[9] Rodegerts, Lee, et al. (2007), Roundabouts in the Unites States. NCHRP Report 572. National Cooperative Highway Research Program. Transportation Research Board. Washington, DC. 2007Rouphail et al., 2005

**Table 6: Pedestrian/Bicyclist Yielding Compliance Rate on the East Leg of the Study Roundabout for pedestrians/bicyclists walking/biking towards the island**

| Date | Time | # of Crossing Events | Sample Size (# of Vehicles) | Yielding Compliance | | |
|---|---|---|---|---|---|---|
| | | | | Exiting Vehicles | Entering Vehicles (Left Lane) | Entering Vehicles (Right Lane) |
| September 20, 2016 | 6 a.m. – 8 p.m. | 5 | 14 | 43% | 50% | N/A |
| September 21, 2016 | 6 a.m. – 8 p.m. | 9 | 15 | 56% | 100% | N/A |
| September 22, 2016 | 6 a.m. – 8 p.m. | 6 | 3 | N/A | 100% | 100% |
| **Total Yielding Compliance** | | **20** | **32** | 50% | 83% | 100% |
| **Nationwide Comparison** | | | | **54%** | **76%** | |

Table 7 summarizes the yielding compliance rate for pedestrians and bicyclists separately. The yielding compliance rate increases for exiting vehicles when there is a pedestrian present compared to bicyclist.

**Table 7: Pedestrian Versus Bicyclists Yielding Compliance Rate on the East Leg of the Study Roundabout**

| Date | Time | # of Crossing Events | Sample Size (# of Vehicles) | Yielding Compliance | | |
|---|---|---|---|---|---|---|
| | | | | Exiting Vehicles | Entering Vehicles (Left Lane) | Entering Vehicles (Right Lane) |
| **Total Bicyclist Yielding Compliance** | | 14 | 30 | 55% | 100% | 100% |
| **Total Pedestrian Yielding Compliance** | | 16 | 30 | 75% | 90% | 100% |
| **Nationwide Comparison** | | | | 54% – 69% | 76% to 78% | |

Table 8 summarizes the yielding compliance rate for pedestrians and bicyclists that traveled from the curb towards the island separately. Again, the yielding compliance rate increases for exiting vehicles when there is a pedestrian present compared to a bicyclist.

**Table 8: Pedestrian Versus Bicyclists Yielding Compliance Rate on the East Leg of the Study Roundabout for pedestrians/bicyclists walking/biking towards the island**

| Date | Time | # of Crossing Events | Sample Size (# of Vehicles) | Yielding Compliance | | |
|---|---|---|---|---|---|---|
| | | | | Exiting Vehicles | Entering Vehicles (Left Lane) | Entering Vehicles (Right Lane) |
| **Total Bicyclist Yielding Compliance** | | 11 | 14 | 38% | 100% | N/A |
| **Total Pedestrian Yielding Compliance** | | 9 | 18 | 63% | 80% | 100% |
| **Nationwide Comparison** | | | | 54% – 69% | 76% to 78% | |

Based on the given data, the entry pedestrian compliance rate exceeds the national average. The high compliance rate on entry may be attributed to adequate sight distance, crosswalk marking visibility and driver expectancy to yield at entry to the roundabout. Exiting vehicles tend to increase their speed in the roundabout and increase their speed even more as they exit the roundabout. While the exiting pedestrian yielding compliance rate is lower, adequate sight distance is available, operating speeds are below the design speed, and the rate is comparable to national averages. One possible factor to lower rates at the exit could be driver expectancy to not yield after entering an intersection.

Based on the low number of observed natural pedestrian crossings further analysis with a larger sample size is recommended (staged crossings) to assess yielding compliance for both pedestrians and bicyclists.

## Lane Assignment Compliance

Table 9 shows the lane assignment compliance rate of all vehicles along the west and south leg approaches while Figure 5 shows a graphical representation of the total correct lane assignment compliance rate by approach leg. To measure compliance, each vehicle was observed through video to see whether they used the correct lanes from the point of entry to where they exit.

**Table 9: Lane Assignment Compliance Rate by Leg Approach**

| West Leg Approach | | | | | |
|---|---|---|---|---|---|
| Date | Time | Volume | | Lane Compliance Rate | |
| | | Left Lane | Right Lane | Left Lane | Right Lane |
| September 20, 2016 | 4 p.m. – 6 p.m. | 1,412 | 590 | 100% | 98% |
| September 21, 2016 | 4 p.m. – 6 p.m. | 1,487 | 521 | 100% | 97% |
| September 22, 2016 | 4 p.m. – 6 p.m. | 1,353 | 454 | 100% | 95% |
| **Total** | | **4,252** | **1,565** | **100%** | **97%** |
| **South Leg Approach** | | | | | |
| **Date** | **Time** | **Volume** | | **Lane Compliance Rate** | |
| | | **Left Lane** | **Right Lane** | **Left Lane** | **Right Lane** |
| September 20, 2016 | 4 p.m. – 6 p.m. | 295 | 113 | 93% | 96% |
| September 21, 2016 | 4 p.m. – 6 p.m. | 293 | 103 | 92% | 91% |
| September 22, 2016 | 4 p.m. – 6 p.m. | 264 | 108 | 97% | 98% |
| **Total** | | **852** | **324** | **94%** | **95%** |

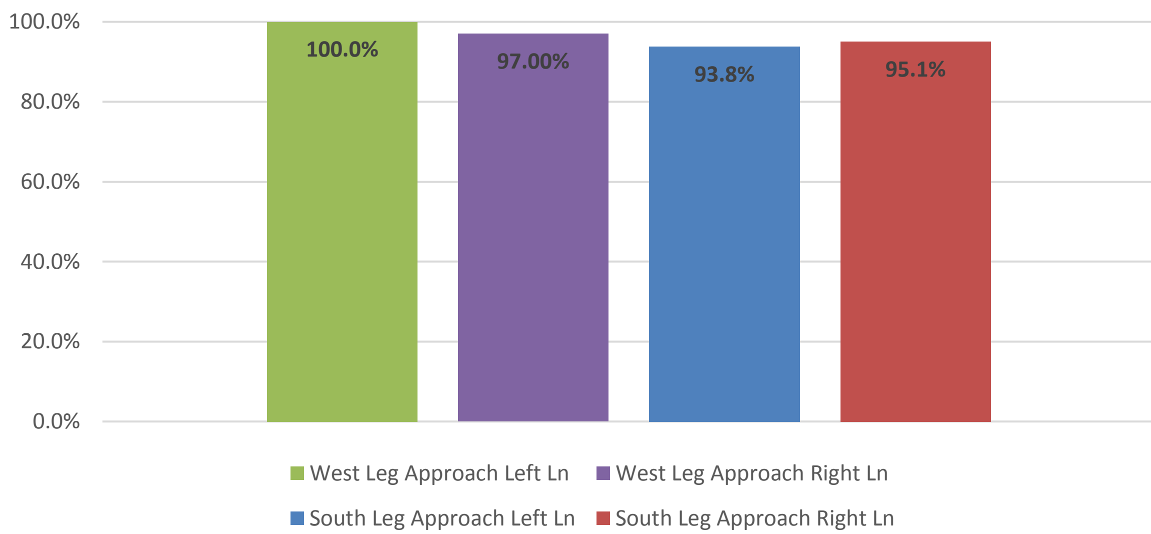


**Figure 5: Total Lane Assignment Compliance Rate by Leg Approach**

Overall, the lane assignment compliance rate at this roundabout is high. The south leg approach has a slightly lower compliance rate than the west leg, but was still observed to have a lane assignment compliance of over 90-percent. The slightly lower compliance for the south leg could be because the lane-use configuration at this approach is different than the other three legs. The eastbound, westbound, and southbound approach have a thru-left turn lane as well as a dedicated right turn only lane, while the northbound approach has a thru-right turn lane and a left turn only lane. Table 10 which shows the origin to destination rates for both the west and south leg confirms that almost all the vehicles that incorrectly used the left lane (left turn only) coming from the south leg approach proceeded to go straight (north leg). For the west leg approach, most vehicles that were non-compliant were the vehicles using the right lane (right turn only) as they proceeded straight (east leg).

**Table 10: Origin to Destination Rates of Vehicles using the Roundabout during P.M. Peak Hours**

| | Origin | Destination | | | |
|---|---|---|---|---|---|
| | | South Leg | North Leg | West Leg | East Leg |
| West Leg | Left Lane | (0.02%) | 17.17% | 0.00% | 82.81% |
| | Right Lane | 97.06% | (0.06%) | (0.00%) | (2.88%) |
| South Leg | Left Lane | 0.00% | (6.10%) | 93.78% | (0.12%) |
| | Right Lane | (0.00%) | 69.85% | (4.94%) | 25.21% |

Notes:
1. (X.XX%) Represents percent of vehicles that have a destination that is non-compliant with the assigned lane utilization
2. X.XX% Represents percent of vehicles that have a destination that is compliant with the assigned lane utilization

### Vehicle Speed

Table 11 shows the measured 85th percentile speeds at the west leg entrance, middle of circulating roadway at the south leg, and the east leg exit of the roundabout. Figure 6 indicates the locations at which speeds were measured. The measured 85th percentile speeds at each location were all below the design speed.

**Table 11: 85th Percentile Speed by Vehicle's Location at the Roundabout**

| Location | Sample Size (Vehicles) | 85th % Speed (MPH) | Design Speed (MPH) |
|---|---|---|---|
| Entrance (Left Lane) | 22,845 | 15 | 27.6 |
| Entrance (Right Lane) | 7,218 | 14 | 27.6 |
| Mid-Circulating | 43,291 | 17 | 18.8 |
| Exit | 25,661 | 22 | 34.8 |

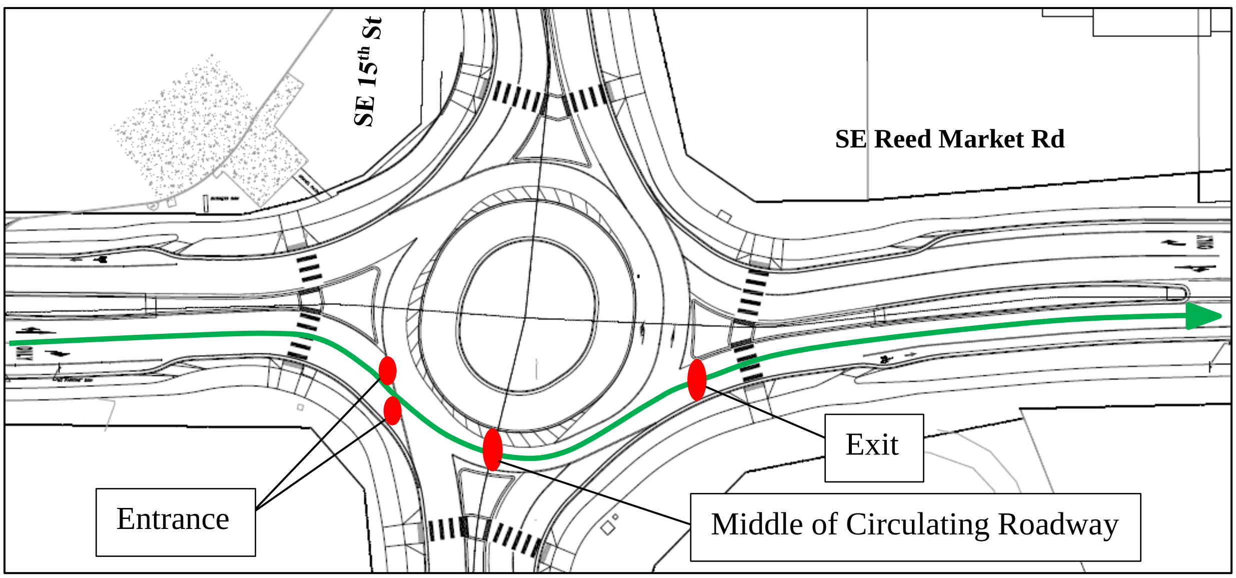


**Figure 6: Speed Measuring Locations**

Figure 7 illustrates the percent distribution of speeds at the three different points of the roundabout. There is a small percentage of vehicles that drive above the design speed as listed in Table 12.

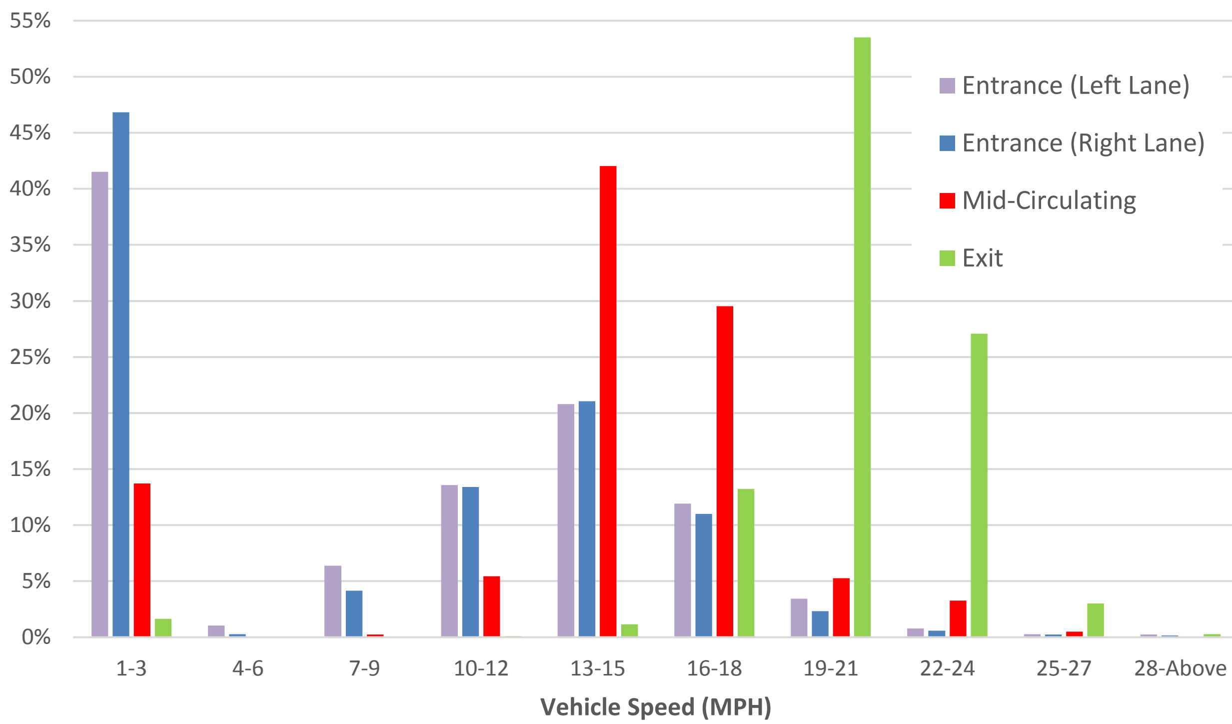


**Figure 7: Percent Distribution of Speed by Vehicle's Location at the Roundabout**

**Table 12: Percent of Vehicles Driving Above the Design Speed**

| Location | Percent of Vehicles Driving Above the Design Speed |
|---|---|
| Entrance (Left Lane) | 0.5% |
| Entrance (Right Lane) | 0.3% |
| Mid-Circulating | 9.1% |
| Exit | 0.0% |

As provided in the figures and tables above, vehicles tend to enter the roundabout with lower speeds and speed up continuously as they exit the roundabout. The 85$^{th}$ percentile speeds at all locations of the roundabout are below the design speed.

## Gap Acceptance Analysis

This section presents the estimates of critical gap and follow up headway. These values are then used to develop a new specific capacity model for the multi-lane hybrid study roundabout.

### *Critical Headway (Gap)*

As discussed in the methodology memorandum, the critical gap is the minimum gap an entering driver would find acceptable. The critical gap was evaluated using the maximum likelihood technique[10], a method that estimates the average critical gap of all drivers by assuming that a single driver's critical gap ranges between their largest rejected gap (or lag) and the accepted gap. Two different methodologies were used for estimating critical gap as follows:

- **Method 1:** Does not include observations that contains accepted gaps larger than 10 seconds.
- **Method 2:** Includes observations that contains accepted gaps larger than 10 seconds.

Both methods do not include observations that do not have a rejected gap/lag or had an accepted gap that was smaller than the largest rejected gap. Exiting vehicles were also not included in this study.

Table 13 shows the results of the critical gap for the west approach (eastbound) of the roundabout during the p.m. peak hour. As listed, Method 2 has a higher mean critical gap since all accepted gaps were included. Method 2 also shows a higher standard deviation because of that reason. Since NCHRP 572 recommends multi-lane capacity analysis to be conducted on a lane by lane basis and reported for the most critical lane (lane with the highest volume) on each approach, this study separated out mean critical gap by lane. The critical lane for the eastbound approach of the study roundabout is the left lane. Therefore, the mean critical gap for this study is between 3.80 to 4.10 seconds. It is recommended that Method 1 be used for this study due to the lower standard deviation.

Table 14 shows a reference of critical gaps found in other studies. The critical gap found in this study is lower than the national average. However, the critical gap is similar to the City of Bend's current standard (4.1 seconds) for a single lane roundabout. It is important to note that the City of Bend's standard for critical gap is based on a single lane roundabout and not for a hybrid roundabout, as is the case with this roundabout.

**Table 13: Critical Gap Results for the West Approach of Study Roundabout**

| West Leg Approach | Method 1 | | | Method 2 | | |
|---|---|---|---|---|---|---|
| | Sample Size | Mean Critical Gap (s) | Standard Deviation (s) | Sample Size | Mean Critical Gap (s) | Standard Deviation (s) |
| Left Lane | 217 | 3.80 | 0.63 | 350 | 4.10 | 0.81 |
| Right Lane | 87 | 3.32 | 0.83 | 127 | 3.49 | 0.86 |
| Total | 304 | 3.62 | 0.77 | 477 | 3.91 | 0.90 |

[10] Rodegerts, Lee, et al. (2007), Roundabouts in the Unites States. NCHRP Report 572. National Cooperative Highway Research Program. Transportation Research Board. Washington, DC. 2007Rouphail et al., 2005

**Table 14: Mean Critical Gap Comparison**

| Reference | Mean Critical Gap (s) | | |
|---|---|---|---|
| | Single | Left | Right |
| HCM 2010[11] | 5.19 | 4.29 | 4.11 |
| NCHRP 572[12] | 5.10 | 4.50 | 4.20 |
| 2010 Bend Study[13] | 4.10 | N/A | |

***Follow-Up Headway***

As discussed in the methodology, the follow-up headway is defined as the headway maintained by two consecutive entering vehicles using the same gap in the conflicting stream. The follow-up headway was observed for the west leg (eastbound approach) of the study roundabout during the p.m. peak hour. Figure 8 illustrates the frequency of the follow-up headway for the left and right lane. For the left lane, very few follow-up headways exceed six seconds. Approximately 2-percent of the data exceed a follow-up headway of six seconds. Therefore, a follow-up headway threshold of six seconds was established for the left lane, assuming that it would indicate a queued condition. Similarly, a follow-up headway threshold of eight seconds was established for the right lane. Approximately 6-percent of the data exceed a follow-up headway of eight seconds. Using these thresholds, the mean follow-up headways for each lane of the west leg approach were calculated and are shown in Table 15.

The mean follow-up headway is approximately 2.86 seconds for the left lane (critical lane) of the study approach while the right lane is slightly higher at 3.27 seconds. Table 16 shows a reference of follow-up headways found in other studies. It can be seen that the follow-up headway found in this study is similar to the national average. However, the follow-up headway is slightly higher than the City of Bend’s current standard (2.7 seconds) for a single lane roundabout. Again values are expected to be different from the City of Bend’s current standard as this study analyzes a multi-lane hybrid roundabout and not a single lane roundabout.

[11] TRB, Highway Capacity Manual, Chpt. 21 and supplemental 33, N.R.C., Washington DC, 2010.
[12] Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. J. Troutbeck, W. Brilon, and Others. *National Cooperative Highway Research Program Report 572: Roundabouts in the United States*, Transportation Research Board of the National Academic, Washington, D.C, 2007.
[13] Roundabout Evaluation and Design Guidelines, Kittleson & Associates, Inc., April 2010

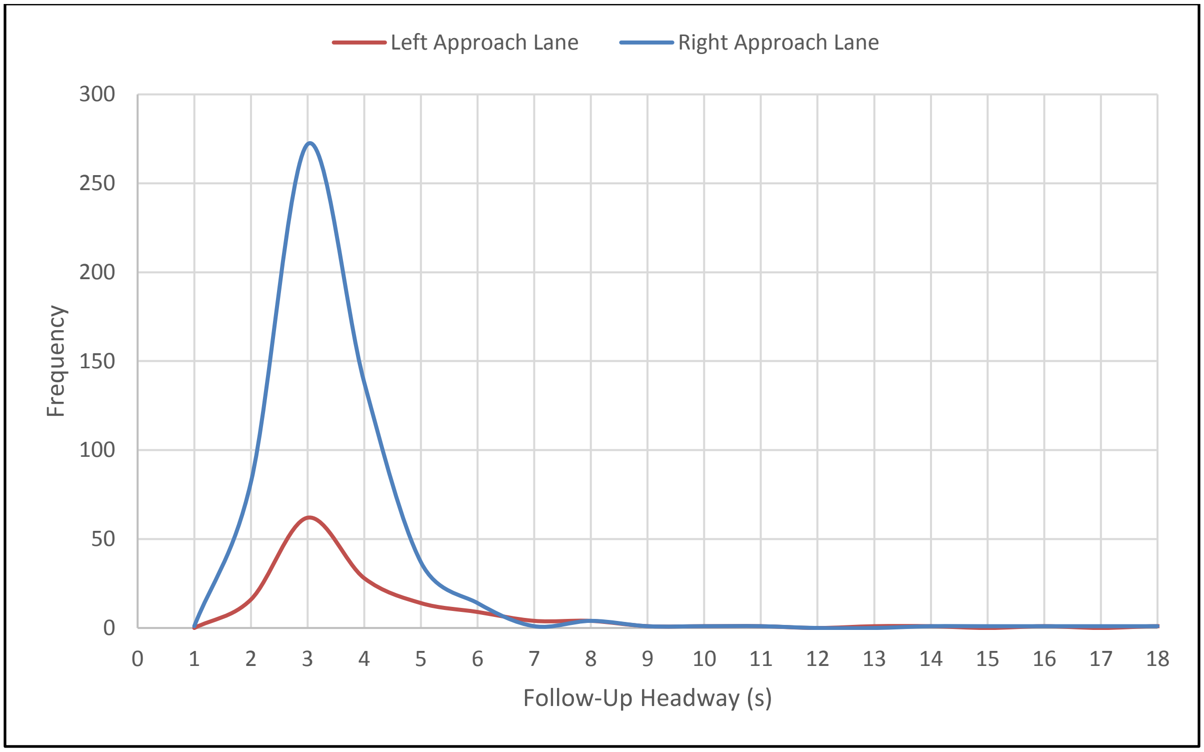


**Figure 8: Follow-Up Headway Frequency for the West Leg Left and Right Approach Lane**

**Table 15: Follow-Up Headway Estimates for the West Leg Approach of Study Roundabout**

| Left Lane | | | Right Lane | | |
|---|---|---|---|---|---|
| Sample Size | Mean Follow-Up Headway <6 s (s) | Standard Deviation (s) | Sample Size | Mean Follow-Up Headway < 8 s (s) | Standard Deviation (s) |
| 544 | 2.86 | 0.85 | 137 | 3.27 | 1.38 |

**Table 16: Mean Follow-Up Headway Comparison**

| Reference | Mean Follow-Up Headway (s) | | |
|---|---|---|---|
| | Single | Left | Right |
| HCM 2010[14] | 3.19 | 3.19 | 3.19 |
| NCHRP 572[15] | 3.20 | 3.40 | 3.10 |
| 2010 Bend Study[16] | 2.7 | N/A | |

[14] TRB, Highway Capacity Manual, Chpt. 21 and supplemental 33, N.R.C., Washington DC, 2010.
[15] Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. J. Troutbeck, W. Brilon, and Others. *National Cooperative Highway Research Program Report 572: Roundabouts in the United States*, Transportation Research Board of the National Academic, Washington, D.C, 2007.
[16] Roundabout Evaluation and Design Guidelines, Kittleson & Associates, Inc., April 2010

### *Capacity*

The parameters in the capacity model (Equation 1[17]) can be calibrated to account for the driver's behavior found in this study.

$$c_{pce} = A * \exp\left(-B * v_{c,pce}\right) \qquad \text{Equation 1}$$

Where

$c_{pce} = lane\ capacity\left(\frac{pc}{h}\right)$

$A = \frac{3600}{t_f}$

$B = \frac{t_c - t_f/2}{3600}$

$v_c = conflicting\ circulating\ flow\ rate, adjusted\ for\ heavy\ vehicles\ \left(\frac{pc}{h}\right)$

$t_f = follow - up\ headway\ (s)$

$t_c = critical\ headway\ (s)$

The values that will be evaluated for this study are the A and B variables. The calibrated capacity model for the study roundabout as well as the existing HCM 2010 and City of Bend standard capacity models are shown in

Table 17.

**Table 17: Calibrated Capacity Model for the Study Roundabout vs Existing Capacity Models**

| | $t_f$ (s) | $t_c$ (s) | A | B | $c_{pce}$ (pc/h) |
|---|---|---|---|---|---|
| **Study Roundabout** | | | | | |
| West Leg Left Lane (Critical Lane) | 2.86 | 3.80 | 1259 | 0.0007 | $1259 * \exp(-0.0007 * v_{c,pce})$ |
| West Leg Right Lane | 3.27 | 3.32 | 1101 | 0.00047 | $1101 * \exp(-0.00047 * v_{c,pce})$ |
| **National Average (HCM 2010 & NCHRP 572)** | | | | | |
| Single Lane | 3.2 | 5.1 | 1125 | 0.001 | $1130 * \exp(-0.0010 * v_{c,pce})$ |
| Multi-Lane (Critical Lane) | 3.2 | 4.2 | 1125 | 0.0007 | $1130 * \exp(-0.0007 * v_{c,pce})$ |
| **City of Bend Existing Standards** | | | | | |
| Single Lane | 2.7 | 4.1 | 1333 | 0.0008 | $1333 * \exp(-0.0008 * v_{c,pce})$ |
| [18]Multi-Lane (Critical Lane) | 3.2 | 4.2 | 1125 | 0.0007 | $1130 * \exp(-0.0007 * v_{c,pce})$ |

[17] Roundabout Evaluation and Design Guidelines, Kittleson & Associates, Inc., April 2010

[18] There no calibrated City of Bend model for multi-lane roundabouts therefore NCHRP 572 values are reported.

Table 17 compares the study roundabout's west leg lane capacity using the different capacity models based on the p.m. peak hour traffic volumes at the study intersection. When comparing the study roundabout's capacity model for the left or right lane to the existing capacity models, the study roundabout's calibrated capacity model provides a similar lane capacity to the City's existing single lane roundabout model. The measured capacity is approximately 29-percent higher than national averages.

The results indicate that although there are two approaching lanes for both the study approach and adjacent approach (right turn lane and through/left lane) the lane capacity is similar to a single lane due to the single circulating lane. Note that a multi-lane roundabout refers to when entry lanes are conflicted by two circulating lanes. The right turn lane along the adjacent approach (north leg) does not appear to affect the left lane capacity. It is recommended that additional legs of the study roundabout be evaluated in addition to other roundabouts for further comparison to better understand the distribution of critical gap and follow-up headway for a larger sample size.

**Table 18: Study Roundabout West Leg Lane Capacity Comparison**

| Reference | Conflicting Flow | $c_{pce}$ (pc/h) | % Difference from Study Roundabout's $c_{pce}$ |
|---|---|---|---|
| **Study Roundabout** | | | |
| Left Lane (Critical Lane) | 607 | 824 | N/A |
| Right Lane | 607 | 828 | N/A |
| **Single Lane** | | | |
| NCHRP 572/HCM 2010 | 607 | 616 | -29% |
| Existing City of Bend Standard | 607 | 820 | -1% |
| **Multi-Lane** | | | |
| NCHRP 572/HCM 2010/ Existing City of Bend Standard | 607 | 740 | -11% |

## Findings

Based on the findings presented above, the safety and operations of the study roundabout is within or above national averages. Data collected at the roundabout indicate that drivers are generally complying with lane assignments, yielding to pedestrians, and operating within expected operating speeds. While enhancements could be considered in some areas, such as yielding at the roundabout exit, results indicate a high level of overall compliance. The following sections describe key findings and recommendations where appropriate by performance measure.

## Crash Data

Comparing crash data from before and after the roundabout was constructed, it is evident that crash rates have improved compared to traffic signal operations. The crash rate is lower when compared to other roundabouts within the U.S., however the after data is limited to one year. While crash records should continue to be evaluated, there is no apparent safety issue at this time.

## Pedestrian Yielding Compliance

The observed yielding compliance rate to pedestrians and bicyclists at the study hybrid multi-lane roundabout is higher than the national average, but may be lower than expected compared to other locations in Bend (e.g., single lane roundabouts and mid-block crossings of 2 to 3 lane facilities). For example, the yielding compliance rate for exiting vehicles was found to be lower than the rate for entering vehicles, although still comparable to national averages. From this study, there are no immediate concerns that likely necessitate an active pedestrian crossing treatments such as a rectangular rapid flashing beacon (RRFB) at the roundabout approaches. Per NCHRP Report 562, the need for an active pedestrian crossing treatment is a function of pedestrian volumes (minimum of 20 pedestrians per hour is needed for any sort of treatment recommendation), speeds, surrounding area's population, major road volumes, pedestrian crossing distance, and expected motorist compliance at pedestrian crossings. Results from this study show that pedestrian counts are low (1 pedestrian/hr), speeds at the roundabout are below the design speeds, pedestrian crossing distance is short due to the splitter island, and the pedestrian yielding compliance rates are comparable to national averages (if not higher).

However, there was an observed reduction in yielding compliance for bicycle movements utilizing the pedestrian crossing areas. Low cost improvements to improve yielding compliance rates at the study roundabout exits for this condition can include additional signing, enforcement, and driver education. Additional signing can include a "DISMOUNT BIKES" sign for bicyclists using the crosswalk. This allows the bicyclist to behave like a pedestrian so that motorists may be more likely to observe the desired crossing movement (i.e., the bicycle would then approach the roundabout at a lower speed, increasing the time for a driver to see them) and comply with the crosswalk laws. Another option to further promote yielding behavior could be a sign for exiting vehicles. This sign could say EXITING VEHICLES stop FOR bike and pedestrians (See Figure 9). However, this sign is not currently approved in the Manual on Uniform Traffic Control Devices[19] (MUTCD) and would need further research and approval from FHWA for implementation. Furthermore, oversized pedestrian crossing signs could be installed at the roundabout exits.

[19] "Manual on Uniform Traffic Control Devices for Streets and Highways - 2009 Edition." (n.d.): n. pag. FHWA. U.S Department of Transportation, Federal Highway Administration, Dec. 2009. Web.


**Figure 9: Potential Sign for Exiting Vehicles at the Roundabout**

Due to a small sample size of natural pedestrian crossings (the majority of observed crossings were bicycles), it is recommended further data to be gathered to capture a larger sample size of pedestrian crossings before implementing enhancements other than the “DISMOUNT BIKES” signage. A larger sample size can be can be accomplished through staged crossing events.

## Lane Assignment Compliance

The observed lane assignment compliance rate is also high (above 90%) and no major improvements appear to be needed. The only recommendations at this time are to maintain the existing pavement markings as some of the existing pavement legends and striping are fading away. Figure 10 shows the existing lane-use arrow in the left lane fading away, making it look like the left lane is a left turn only lane. To maintain the effectiveness of the paint currently used, restriping of the roundabout on a yearly basis could be part of the City maintenance program. This maybe most useful after the winter season when snow and ice have cleared. For longer lasting durable striping, thermoplastic and methyl methacrylate inlayed could be installed; however, this should be reviewed with the City’s maintenance practices including snowplowing and street sweeping. Continued driver education could also improve lane assignment compliance rate over time as drivers become more accustomed to navigating roundabouts of various types and aware of visual cues such as signing/striping.

Furthermore, if additional enhancement is desired at a later time to improve the south leg lane assignment compliance, installing lane-use arrows in advance and at the approach of the roundabout (downstream of crosswalk) is optional per the MUTCD[20]. This can provide additional direction for drivers. Larger lane use signs could also help or installing them on both sides of the roadway (in median and along curb).

[20] "2009 Edition Chapter 3C. Roundabout Markings." Chapter 3C - MUTCD 2009 Edition - FHWA. U.S Department of Transportation, Federal Highway Administration, 8 July 2015. Web.

**Figure 10: Existing Lane-Use Arrows Fading Away**

### Vehicle Speed

Vehicle speed at the study roundabout was not found to be a significant issue. Vehicles enter the roundabout at approximately 14-15 mph, circulate at 17 mph, and exit at 22 mph. While there are no advisory speed signs along the roundabout approaches, these speeds are consistent with the design speeds.

### Critical Gap and Follow-Up Headway

Results of the critical and follow-up headway for the west leg show a similar lane capacity for a hybrid multi-lane approach with a single conflicting yielding lane and the City's current model for a single lane roundabout. The measured capacity is approximately 29-percent higher than national averages. The right turn lane along the adjacent approach (north leg) does not appear to affect the left lane capacity along the west leg approach. Due to the limited sample size, it is recommended that further data be gathered to provide a larger sample size before calibrating the capacity model (as shown in
Table 17) for a multi-lane hybrid roundabout. Additional legs of the study roundabout in addition to other legs of roundabouts with similar hybrid lane configuration should be assessed to better understand the distribution of critical gap and follow-up headway.
.