Operations and Safety of Separated Bicycle Facilities at Single Lane Roundabouts

David Stanek, PE
Fehr & Peers
1001 K Street, 3rd Floor, Sacramento, CA 95814
Tel: (916) 329-7332; Fax: (916) 773-2015; Email: D.Stanek@fehrandpeers.com

ABSTRACT

Cycle tracks, also known as protected bike lanes, are becoming increasingly popular in the United States. These facilities provide separation from motor vehicle and pedestrian traffic resulting in increased comfort and convenience for bicyclists. Accommodating cycle tracks at intersections can be complex at a conventional intersection due to conflicting flows of motor vehicles and pedestrians. A roundabout intersection may provide a superior solution for operational and safety concerns.

This paper will assess the operational and safety aspects of the following options for accommodating separated bicycle facilities at a single lane roundabout.

- Merge bicycles with the motor vehicle travel lanes
- Direct bicycles onto a pathway shared with pedestrians
- Provide bicycle paths separated from motor vehicle travel lanes and pedestrian paths

Current guidance (*Roundabouts: An Informational Guide, 2nd Edition*) recommends that bicycles use the motor vehicle travel lanes at single lane roundabouts. The design speed for motor vehicles typically ranges from 15 to 20 mph, which is near to the typical speed for bicyclists, 8 to 15 mph. However, riding with traffic may be uncomfortable for some bicyclists, so the improved travel environment provided by the cycle track is offset by the intersection treatment.

To preserve the separation from motor vehicles, bicycles could be directed to a shared-use path at the roundabout. Current guidance recommends this treatment for multi-lane roundabouts due to the higher design speed for motor vehicles. However, the shared pathway has longitudinal conflicts with pedestrians and results in a lower bicycle travel speed.

Providing a separate bicycle path through the intersection has been employed at intersections in the Netherlands. This design provides pedestrian crosswalks for both motor vehicle travel lanes and the bicycle lanes. Keeping bicycles separate from other modes better matches the cycle track's concept of operations as a separate facility. And, this option can accommodate two-way cycle tracks.

Using a simulation analysis model, the operational performance of the three options for accommodating separated bicycle facilities at a typical design for a single lane roundabout were analyzed. The options were evaluated using motor vehicle volumes that generate a moderately busy (that is, Level of Service C/D) intersection. The analysis results report travel time and delay for motor vehicles, bicycles, and pedestrians. To assess safety, the conflict points among the travel modes were identified, along with the speed of conflicting traffic streams.

INTRODUCTION

Separated bicycle facilities, also known as cycle tracks, are an emerging bikeway type in the United States. Popular in bicycle-friendly European countries such as the Netherlands and Denmark, cycle tracks are exclusive bikeways that combine the user experience of a separated path with the on-street infrastructure of a conventional bike lane. Cycle tracks often feature vertical separation between the bikeway and the adjacent travel lane such as bollards, planters, raised curb, or on-street parking. When properly designed, cycle tracks are associated with a higher level of user comfort that attracts a broader cross-section of users (*1*) and an overall lower crash rate when compared with the crash rate for roadways without cycle tracks (*2*).

While the roadway design is straightforward, intersection design is a key challenge for the implementation of separated bicycle facilities. Research from Montreal, Canada showed that bicyclists are more likely to suffer an injury or fatality at an intersection than at other locations, and the traffic movement that resulted in the greatest number of bicyclist crashes at intersections was the right turn (*3-4*). Traditional bike lane design, which places bike lanes immediately adjacent to a travel lane to encourage merging within an area in advance of the intersection, generally seeks to minimize conflicts between right-turning drivers and through bicyclists to avoid "right hook" collisions. Without a defined merging area at intersections, the separation between the cycle track and the adjacent travel lane introduces potential turn conflicts at intersections.

At signalized intersections, the *Separated Bike Lane Planning and Design Guide* from FHWA recommends signing and striping treatments (such as prohibiting right turns on red and installing bike boxes) and providing mixing zones so that bicycles and motor vehicles can merge and/or cross paths upstream of the intersection (*5*). A new intersection design, called a protected intersection or Dutch junction, has recently been introduced, and at least two have been constructed in Davis, California and Salt Lake City, Utah. In this design, bicycles have a separate path through the intersection and use corner refuge islands to increase their visibility to right-turning vehicles. While options for signal operations at protected intersections will have variable effects on intersection capacity (*6*), the comfort and safety benefits to bicyclists by providing a facility separate from both motor vehicles and pedestrians is clear.

The roundabout as an intersection design is much less frequent than other designs in the United States. However, roundabouts have important advantages for transportation operations and safety over all-way stop control and, to a more limited extent, signal control. As a result, roundabouts are likely to continue to increase in popularity. So, accommodating cycle tracks at roundabouts needs to be addressed by roadway designers.

BACKGROUND

Roundabouts: An Informational Guide, 2nd Edition recommends two options for accommodating bicycles at roundabouts (*7*). **Figure 1** shows a single lane roundabout design at the intersection of two roadways that includes design features for both options.

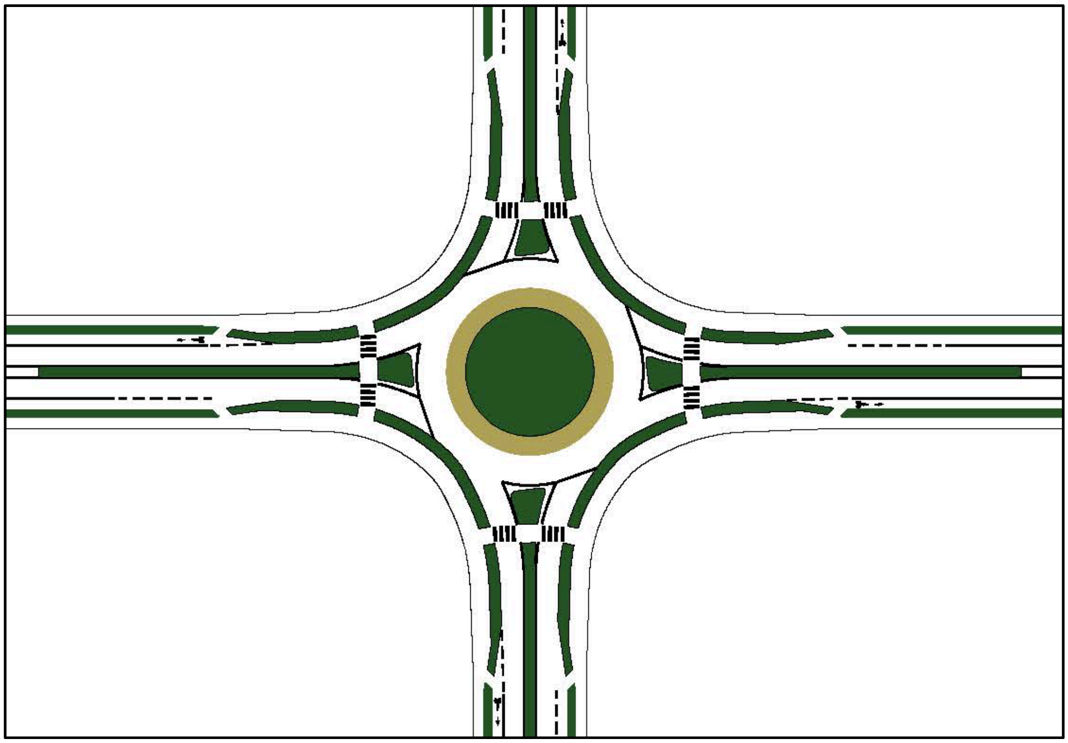

FIGURE 1 Typical roundabout design

For confident riders, bicycles traveling on the shoulder or in a bicycle lane merge with motor vehicles on the roundabout approach, travel as a motor vehicle through the roundabout – including yielding to circulating vehicles, and return to the shoulder or bicycle lane on the departure leg. Due to the horizontal deflection, motor vehicle speed is reduced through the roundabout so that the speed differential between bicycles and motor vehicles is lower. As a result, bicycles do not impede motor vehicle traffic as much as on a straight roadway segment, and bicycles are more likely to merge smoothly with motor vehicle traffic.

For concerned (less confident) riders, bicycles are provided with a ramp to the shared path for bicycles and pedestrians that circles the roundabout. This path is wider than a typical sidewalk so that both pedestrians and bicycles can be accommodated. Bicycles use the path and associated crosswalks and then return to the roadway downstream of the intersection using another ramp. The slower speed of pedestrians results in a slower bicycle speed on the shared path. The setback of the crosswalk from the intersection causes a longer travel distance for bicycles compared with traveling via the circulatory roadway. However, bicycles on this route only cross paths with motor vehicles at crosswalks where motor vehicles are required to yield.

Providing a bicycle lane on the circulatory roadway of the roundabout is not recommended (*7*). When a motor vehicle and a bicycle travel side-by-side, the bicycle is not easily visible to the driver. As a result, a driver exiting the roundabout may fail to yield to a bicycle that is continuing through the roundabout (also known as a right-hook collision).

The Dutch roadway design manual (*8*) provides another option to accommodate bicycles at roundabouts. The design is similar in concept to the signalized protected intersection described above. Bicycles are provided a pathway separated from both motor vehicles and pedestrians through the roundabout. The Massachusetts Department of Transportation's separated bikeway guidelines provide an American adoption of this design (*9*). **Figure 2** shows an example of a protected intersection design for a single lane roundabout.

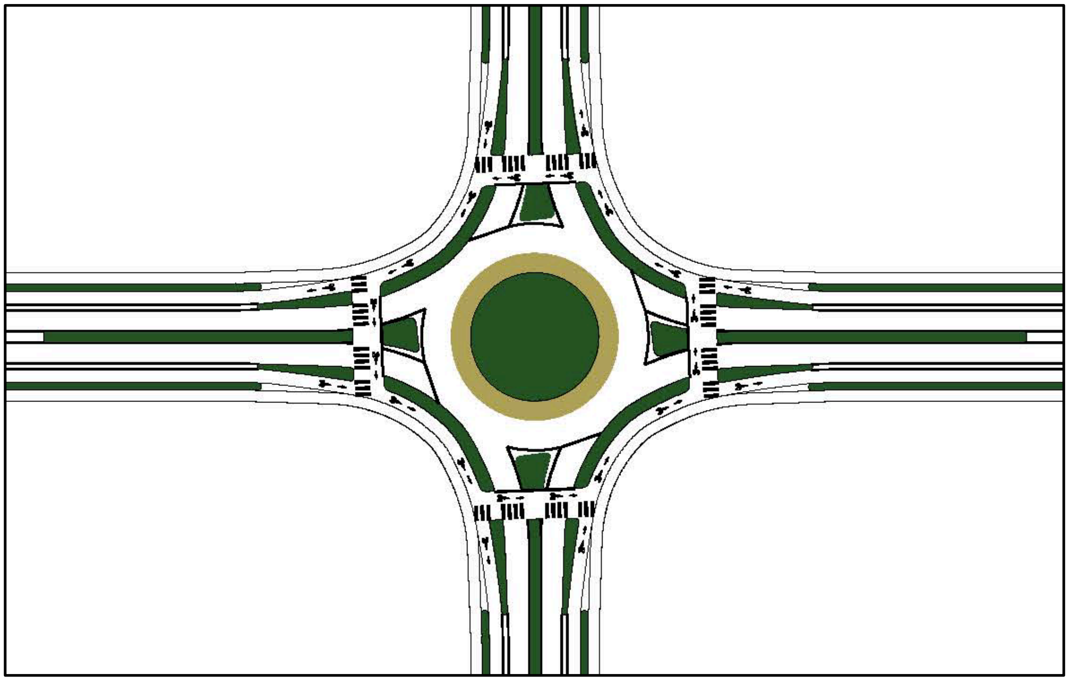

FIGURE 2 Protected roundabout design

With this design, bicyclists traveling in a cycle track (or bike lane) remain in a separate facility while traveling through the roundabout. Bicycles circulate counter-clockwise, like motor vehicles, in a pathway adjacent to the pedestrian sidewalk and crosswalks. Bicyclists yield to pedestrians at crosswalks, but drivers yield to bicycles (and pedestrians) at crosswalks. This conceptual design for the protected roundabout has a larger footprint (about 2 to 4 feet from the center line to the edge of traveled way) than the typical design to account for the buffer separation between motor vehicles and bicycles on the approaches and between pedestrians and bicycles at the roundabout.

OPERATIONS ANALYSIS

The *Highway Capacity Manual* method for roundabout capacity accounts for the presence of bicycles and pedestrians on motor vehicle performance (*7*). Bicycles traveling in the roadway have a recommended passenger car equivalent (PCE) value of 0.5. This factor can be used when converting the observed vehicle flow rate of passenger cars, heavy vehicles, and bicycles to the equivalent passenger car flow rate. Pedestrians traveling in the crosswalks impede vehicle entry to the roundabout when pedestrians have priority. The methodology provides a capacity adjustment factor based on the pedestrian volume and the conflicting circulating flow rate. Bicycles traveling in the crosswalks or in a cycle track adjacent to the crosswalk can be treated as pedestrians to estimate their effect on intersection capacity.

These adjustments for bicycles and pedestrians can be used to evaluate motor vehicle performance for the typical and protected single lane roundabout designs presented in **Figures 1 and 2**. However, the methodology has limitations including not accounting for vehicle delay due to pedestrians in the crosswalks on the exiting legs. Additionally, the *Highway Capacity Manual* does not provide analysis methods to estimate bicycle and pedestrian performance. As a result, a simulation analysis model was selected to evaluate operations of the typical and protected roundabout designs.

OPERATIONS MODELING

To determine operational performance of the roundabout designs, a Vissim (version 9.00-04) microsimulation model was constructed. Screen captures of the model networks are shown in **Figure 3**. In the figure, bicycle-only links are shown in green, pedestrian-only links are shown in white, and shared use (bicycle and pedestrian) links are shown in red. The models were built using the conceptual roundabout designs from **Figures 1 and 2**. In both designs, the single lane roundabout has a 130-foot inscribed circle diameter with pedestrian/bicycle crossings located 20 feet from the circulating roadway.

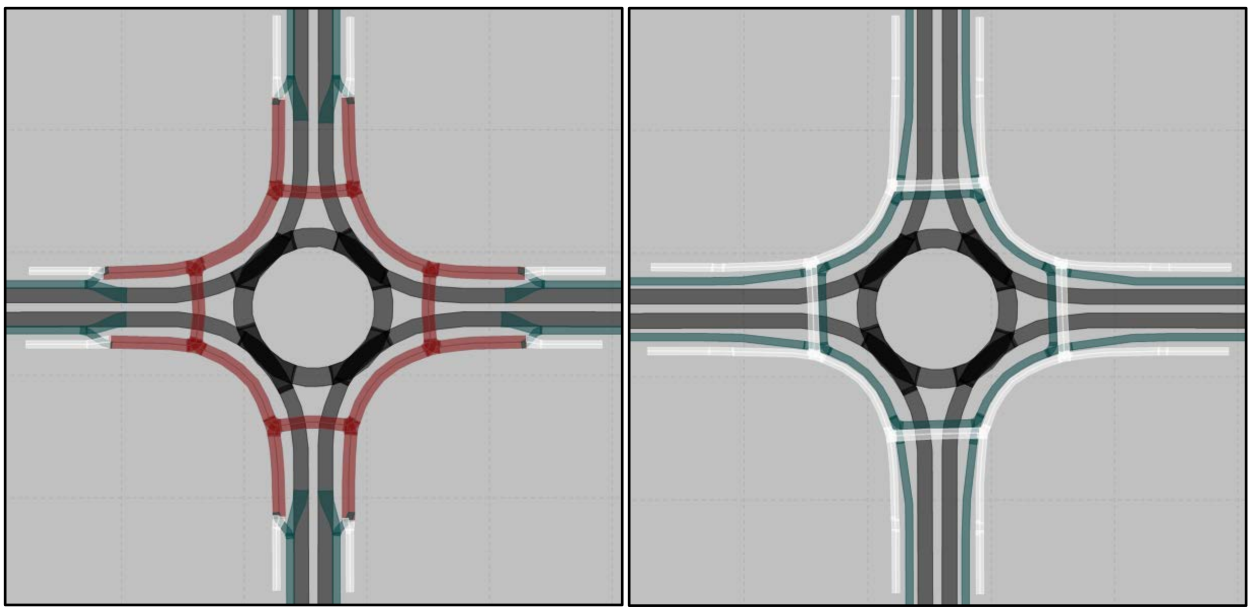

FIGURE 3 Typical (left) and protected (right) roundabout designs in Vissim

The roundabout model was calibrated to provide a capacity curve similar to the California adjustment to *Highway Capacity Manual* methodology (*10*). **Figure 4** shows the comparison of capacity for three entering flow rates with the default and California Adjustment versions of the HCM capacity equation. Capacity was determined using the modeled approach delay to select the entering volume that would yield a volume-to-capacity ratio of approximately 1.0 when the HCM delay equation was applied (*11*). A Vissim priority rule with a minimum gap time of 2.9 seconds generated a capacity curve that was closest to the California adjustment curve although the capacity is higher for lower entering flow rates and lower for higher entering flow rates. Despite this difference, the modeled capacity curve is well within the capacity variation in the observed data used to develop the HCM roundabout capacity parameters (*10*).

The modeling assumptions for the test case are described below.

- Seeding interval of 15 minutes and four 15-minute analysis intervals for a one-hour period

- Peak hour factor of 0.95
- Truck volume of 3 percent for all turning movements
- Pedestrian volume of 20 pedestrians per hour in the crosswalks
- Average speed of 35 mph (40.2 kph) for motor vehicles, 11.5 mph (18.5 kph) for bicyclists, and 2.5 mph (4.0 kph) for pedestrians
- An average speed of 20 mph (32.2 kph) for motor vehicles at the roundabout and an average speed of 5.5 mph (8.9 kph) for bicycles on the shared path

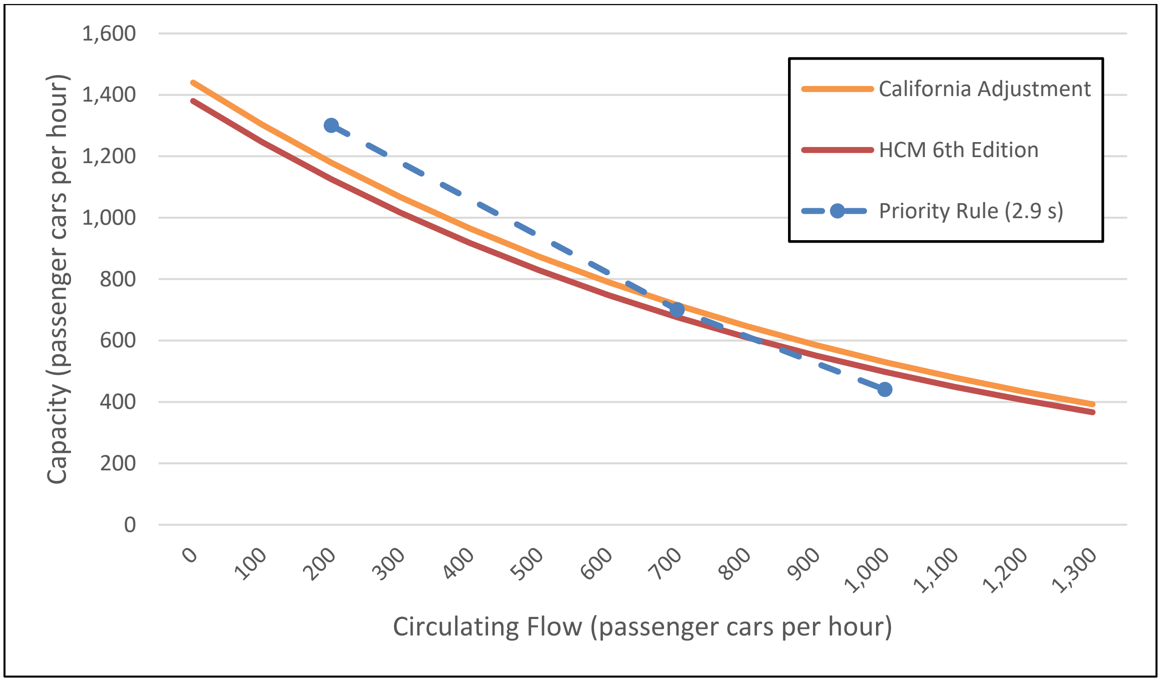

FIGURE 4 Vissim model roundabout calibration

The following volume assumptions were used to represent a typical urban or suburban environment with relatively high bicycle and pedestrian volume. The motor vehicle volume was set to 2,100 vehicles per hour, and the distribution was 70 percent on the major street and 60 percent in the peak direction. The turning percentages for the major street were set as follows.

- 2 percent U turns
- 18 percent left turns
- 60 percent through
- 20 percent right turns

For the minor street, 10 percent each was shifted from the through movement to the left and right turns so that 30 percent were U and left turns, 40 percent were through, and 30 percent were right turns. The bicycle volume was set to 80 vehicles per hour with 50 percent on the major street and 50 percent in the peak direction. The distribution among bicycle turning movements is the same as for motor vehicles on the major street. **Figure 5** shows the resulting turning movement volumes for motor vehicles and bicycles with the percentages applied.

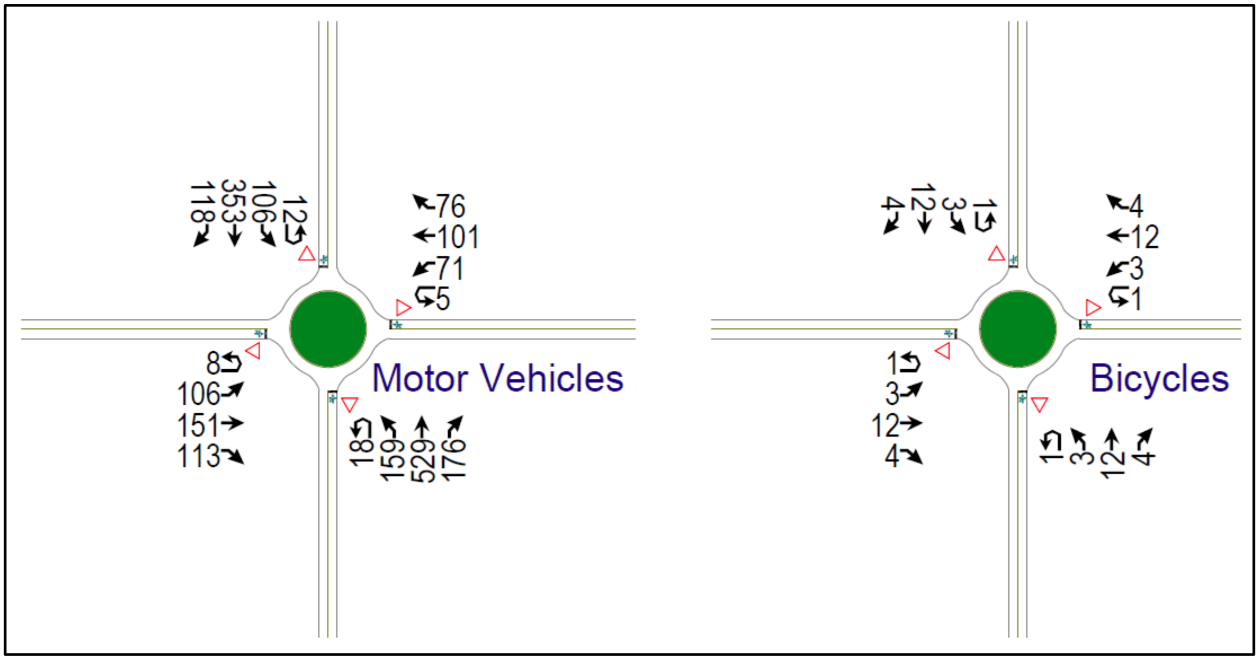

FIGURE 5 Motor vehicle and bicycle volumes

For the typical roundabout, bicyclists have the option to travel through the roundabout as a vehicle or take the shared path, as described above. To test the operational effect, the percentage of bicycles taking the shared path was varied from 0 to 100 percent. When bicycles transition from the bike lane to the roadway, the model requires motor vehicles yield to them. Bicycles were assumed to have the same yielding behavior on entry to the roundabout as motor vehicles. Bicycles traveling on the shared path were assumed to yield right-of-way to pedestrians and were allowed to pass them on the path.

For the protected intersection scenario, all bicycles use the separated bicycle facilities rather than the roadway. Motor vehicles were required to yield to both bicycles and pedestrians at crosswalks, and bicycles were required to yield to pedestrians at crosswalks. (Dutch guidance recommends that motor vehicles yield to bicycles in urban areas, which is consistent with the assumptions for this test case, but that bicycles should yield to motor vehicles in rural locations (*8*)).

ANALYSIS RESULTS

Table 1 presents the intersection operations analysis results under five scenarios: four with the typical roundabout design and one with the protected roundabout design. The average intersection delay is reported in seconds per vehicle for the vehicles that travel through the circulating roadway of the roundabout. The total network-wide delay and travel time for bicycles is also reported.

For the given total demand of 2,100 motor vehicles per hour, 80 bicycles per hour, and 80 pedestrians per hour, the typical roundabout configuration provides an average of 26.5 seconds of delay when no bicycles use the shared path. This value corresponds to Level of Service (LOS) D conditions according to the *Highway Capacity Manual*. When bicycles shift to using the path, the average intersection delay decreases because motor vehicles are less likely to be delayed by the slower moving bicycles. The scenarios with 50 and 100 percent bicycles using the path results in an average delay less than 25 seconds per vehicle, which corresponds to LOS C conditions.

TABLE 1 Roundabout Operational Performance

Scenario	Average Intersection Delay[1]	Average Network Delay for Bicycles	Total Travel Time for Bicycles
Typical, 0% Path	26.5 sec/veh	5.20 sec/veh	1.57 hr
Typical, 25% Path	25.1 sec/veh	3.94 sec/veh	1.69 hr
Typical, 50% Path	23.5 sec/veh	2.98 sec/veh	1.77 hr
Typical, 100% Path	21.8 sec/veh	1.20 sec/veh	2.00 hr
Protected	23.9 sec/veh	1.83 sec/veh	1.57 hr

Note: 1. Average intersection delay reported in seconds per vehicle for motor vehicles and bicycles traveling through the roundabout.

The average intersection delay for the protected roundabout is about the same as the typical roundabout scenario with 50 percent of bicycles on the shared path, which is about 24 seconds per vehicle. The delay value is not as low as the 100 percent path scenario because slower-moving pedestrians tend to impede bicyclists on the shared path such that pedestrians and bicycles occupy the crosswalk at about the same time. This grouping of conflicting traffic at crosswalks results in less delay for motor vehicles.

Total bicycle delay in the network is highest when all bicycles use the street to travel through the roundabout. When traveling as a vehicle, bicycles experience the same approach delay due to conflicting vehicles in the circulating roadway that motor vehicles experience. Bicycle delay is lowest when all use the shared path since only conflicts with pedestrians impede travel. In the protected design, the bicycle delay is higher than the 100 percent path scenario due to more pedestrian crossing conflicts. In contrast, the shared path allows bicycles to overtake pedestrians rather than cross paths, which results in lower delay.

Although bicycle delay decreases with the shift to path riding, bicycle travel time increases. In the model, delay is measured in relation to the desired speed, which is lower for bicycles on the shared path compared to bicycles on the roadway. So, bicycles take more time to travel through the intersection on average when using the path versus the roadway. In addition, the path route is longer than the roadway route, which leads to longer travel times. With the separate facility, bicycles are able to maintain a higher desired speed through the intersection. As a result, the bicycle travel time is as low or lower than the typical roundabout design scenarios.

The five scenarios presented above were also analyzed using a total entering motor vehicle volume of 2,200 vehicles per hour, which is 100 vehicles per hour higher than the original scenario, with all other inputs unchanged. The average intersection delay ranged from 38 to 57 seconds per vehicle for the typical roundabout design (LOS E to F conditions) and was 45 seconds per vehicle for the protected roundabout design. Similar relationships were found among the scenarios for bicycle delay and travel time.

SAFETY ASSESSMENT

To assess safety of the typical and protected roundabout designs, the number and type of conflict points were determined. As described above, bicyclists in a bicycle lane or on the shoulder have two options for traveling through the roundabout in the typical design as shown in **Figure 6**. Bicycles traveling on the roadway must merge with vehicles, cross pedestrians at the crosswalks, merge and diverge with vehicles in the circulatory roadway, and diverge with vehicles back to the bicycle lane. Bicycles traveling on the shared path cross pedestrians at the sidewalk, and merge and diverge with other bicycles and pedestrians before returning to the bicycle lane. When both options are provided, bicycles also merge and diverge with other bicycles where the bicycle lane ends/starts at the roundabout. With the protected roundabout design as shown in **Figure 7**, bicycles cross pedestrians at crosswalks, merge and diverge with other bicycles, and cross paths with vehicles in the crosswalks.

The number of conflict points by mode and conflict type are tabulated according to the bicycle route and roundabout design in **Table 2**. Bicycles traveling through the typical roundabout design shown in **Figure 6** have 32 conflict points, half of which are with larger, faster-moving motor vehicles. Bicycles traveling via the shared path have 8 more conflict points than traveling via the roadway, but only 8 of the conflict are with motor vehicles. Bicycles traveling through the protected roundabout design have the fewest conflict points, 24. Like the shared path route, only 8 of the conflicts are with motor vehicles. Additionally, the separate bicycle facility through the roundabout eliminates 8 pedestrian conflicts.

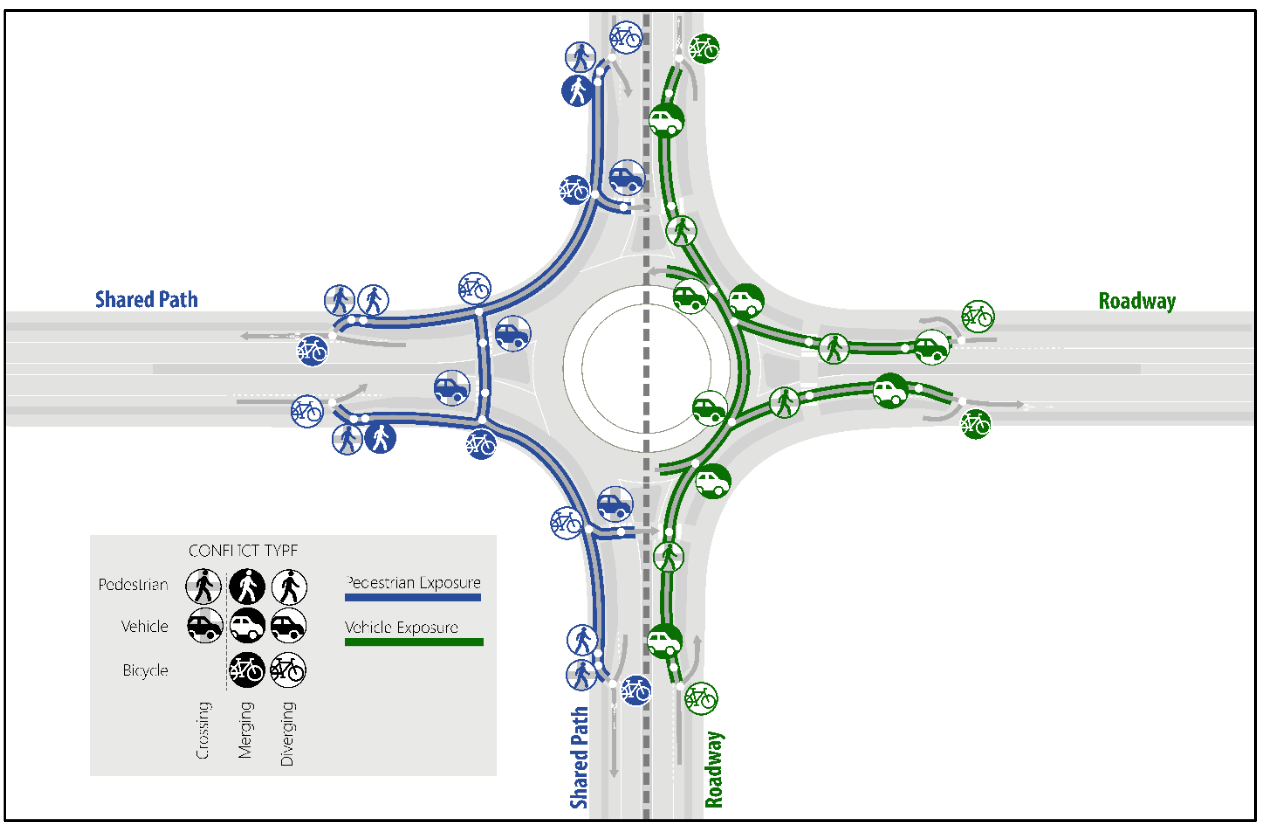

FIGURE 6 Bicycle conflict points for typical roundabout design

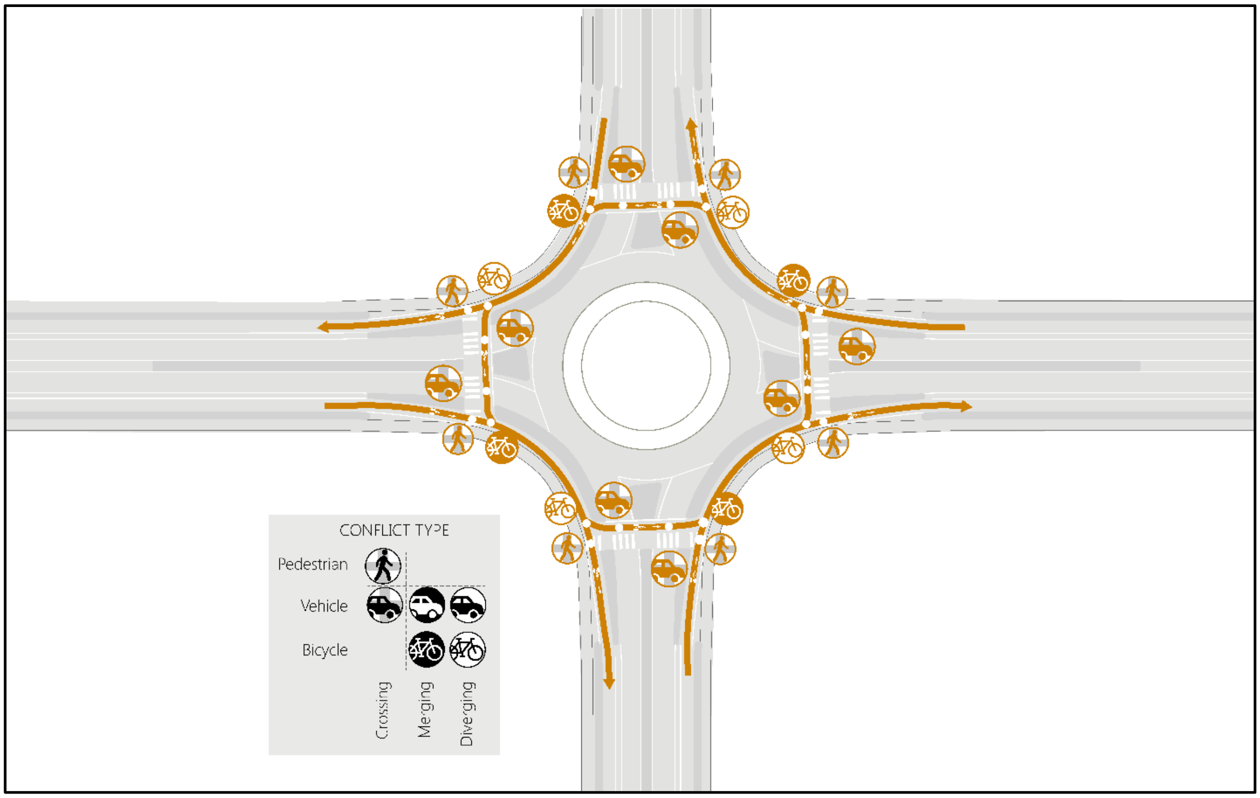

FIGURE 7 Bicycle conflict points for protected roundabout design

TABLE 2 Bicycle Conflict Points

Conflict Points		Typical Design		
Mode	**Type**	**Roadway**	**Shared Path**	**Protected Design**
Motor Vehicle	Crossing	-	8	8
	Merging	8	-	-
	Diverging	8	-	-
Bicycle	Crossing	-	-	-
	Merging	4	8	4
	Diverging	4	8	4
Pedestrian	Crossing	8	8	8
	Merging	-	4	-
	Diverging	-	4	-
Total		32	40	24

In addition to conflict points, exposure to other traffic modes can affect safety and comfort of users. When traveling on the roadway, bicycles must travel with larger, heavier, and faster motor vehicles. Collisions between motor vehicles and bicycles, even at low motor vehicle speeds, are usually insignificant to drivers but are likely to be serious for bicyclists. When traveling on the shared path, bicycles must travel with slower-moving and potentially erratic pedestrian traffic. Even a pathway that is wider than a typical sidewalk does not necessarily improve bicycle safety (*12*). As shown in **Figure 6**, bicycles traveling in the roadway and on the shared path are exposed to other travel modes for significant portions of their route through the roundabout. Such exposure contradicts the cycle track's goal of improved bicycle safety and comfort. In contrast, the protected roundabout design provides the separation of travel modes through the intersection so that safety and comfort are closer to the level that bicyclists experience on the cycle track between intersections.

CONCLUSIONS AND RECOMMENDATIONS

The operations and safety of typical and protected designs for a single lane roundabout intersection were compared. The typical design either directs bicycles to share the roadway with motor vehicles or to share a pathway with pedestrians to travel through the intersection. The protected design provides a bicycle-only route through the intersection that is located between the motor vehicle roadway and pedestrian sidewalks and crosswalks.

The simulation analysis of multimodal operations shows that roundabout intersection delay is higher when more bicycles use the roadway and lower when more use the shared use path. For the relatively high bicycle volume in the test case (80 bicycles per hour), this shift between roadway and path routes yielded a range of about 5 seconds per vehicle for LOS C/D conditions and nearly 20 seconds per vehicle for LOS E/F conditions. The protected design provided an intersection delay for motor vehicles that was similar to that for the typical design with 50 percent bicycles on the roadway. Importantly, the protected design had lower bicycle delays and travel time for most of the typical design scenarios.

The safety benefits of the protected design for bicycles is clearer. The protected design reduces the number of conflict points with other modes compared to both the roadway and shared path routes in the typical design. The protected design has the same number of motor vehicle conflict points as the shared path route for the typical design, and it has fewer pedestrian conflict points. Unlike the typical design, the protected design keeps bicycles separate from other modes that have different speeds and other characteristics to provide a more comfortable experience.

The simulation model approach presented here could be applied to investigate improvements to the *Highway Capacity Manual* method for roundabout capacity analysis. Further research could be conducted to refine the estimate of 0.5 passenger cars per bicycle conversion value, and potentially to determine a relationship between this value and the volume of motor vehicles and bicycles. The pedestrian capacity adjustment could also be investigated to determine how the effect of bicycles in crosswalks differ from pedestrians due to their different speed and operational characteristics. These further refinements would provide evidence for when the protected roundabout design should be selected over the typical roundabout design.

REFERENCES

1. Monsere, C. M., McNeil, N., and J. Dill. Multiuser Perspectives on Separated, On-Street Bicycle Infrastructure. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2314,* Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 22-30.

2. Lusk, A. C., Morency, P., Miranda-Moreno, L. F., Willett, W. C., and J. T. Dennerlein. Bicycle Guidelines and Crash Rates on Cycle Tracks in the United States. *American Journal of Public Health,* Vol. 103, No. 7, 2013, pp. 1240-1248.

3. Zahabi, S. A. H., Strauss, J., Manaugh, K., & L. F. Miranda-Moreno. Estimating Potential Effect of Speed Limits, Built Environment, and Other Factors on Severity of Pedestrian and Cyclist Injuries in Crashes. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2247,* Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 81-90.

4. Miranda-Moreno, L. F., Strauss, J., & P. Morency. Disaggregate Exposure Measures and Injury Frequency Models of Cyclist Safety at Signalized Intersections. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2236,* Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 74-82.

5. *Separated Bike Lane Planning and Design Guide*. FHWA, U.S. Department of Transportation, 2015, p. 132.

6. Stanek, D. and C. Alexander. Simulation Analysis of Intersection Treatments for Cycle Tracks. Presented at the Transportation Research Board 95th Annual Meeting, Washington, DC, 2016.

7. Rodegerdts, L., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B. Crown, B. Guichet, and A. O'Brien. *NCHRP Report 672: Roundabouts: An Informational Guide, 2nd Edition*. Transportation Research Board of the National Academies, Washington, DC, 2010.

8. CROW. *Design Manual for Bicycle Traffic*, 2007.

9. *Separated Bike Lane Planning & Design Guide*. Massachusetts Department of Transportation, 2015, pp. 76-77.

10. *Highway Capacity Manual 6th Edition: A Guide for Multimodal Mobility Analysis*. Chapter 33 – Roundabouts: Supplemental. http://hcmvolume4.org. Accessed November 22, 2016.

11. Stanek, D. Comparing Roundabout Capacity Analysis Methods, or How the Selection of Analysis Method Can Affect the Design. Presented at the Transportation Research Board 91st Annual Meeting, Washington, DC, 2012.

12. American Association of State Highway Transportation Officials. *Guide for the Development of Bicycle Facilities*, 1999, p. 58.