Turbo Roundabouts

Course No: C02-079

Credit: 2 PDH

Mark Rossow, P.E., PhD

Continuing Education and Development, Inc.
22 Stonewall Court
Woodcliff Lake, NJ 07677

P: (877) 322-5800
info@cedengineering.com

Informational Primer

Turbo Roundabouts

FHWA Safety Program

Cover images by Arcadis
Turbo Roundabouts, Netherlands

U.S. Department of Transportation
Federal Highway Administration

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CG	center point of turbo block
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
LED	Light Emitting Diode
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
OS/OW	oversize/overweight
Pcu/h	passenger cars per hour

Introduction

Implementing modern roundabouts saves lives and reduces serious injuries resulting from intersection and intersection-related crashes. As planned points of conflict, crashes attributed in some way to intersections contribute significantly to traffic fatality and injury numbers in the United States. Approximately half of all crashes and half of fatal and serious injury crashes occur at or near intersections. In the single year of 2018, 8,858 people were killed in intersection and intersection-related crashes.(1) In stark contrast, there were a total of 46 fatalities at roundabouts built in the United States over the nine-year period spanning 2005 to 2013, a time period in which the total number of roundabouts in the United States grew from a few hundred to a few thousand.(2) At the individual intersection level, converting a traditional at-grade signalized intersection to a modern roundabout is expected to reduce the number of injury crashes by 78 percent.(3) Converting a traditional at-grade minor-road stop control intersection to a modern roundabout is expected to reduce the number of injury crashes by 82 percent.(3)

Though most roundabouts in the United States are single-lane, multilane roundabouts have become more common. There is a tendency for some 2 x 2 multilane roundabouts[1] to experience higher than expected frequencies of sideswipe – same direction crashes.(4) Given that modern roundabout geometry reduces both the speed and angle of collisions, the sideswipe – same direction crashes in 2 x 2 multilane roundabouts tend to be low severity (i.e., crashes in which people are not injured, but where vehicles may be damaged).(4) Some other countries have implemented a modified version of a multilane roundabout, the turbo roundabout, with positive results. Characteristics of the turbo roundabout could potentially be effective at influencing driver behavior and reducing lane change conflicts in a way that would address the crash types occurring in 2 x 2 multilane roundabouts. First designed and implemented in the Netherlands in the 1990s, the turbo roundabout[2] (shown in figure 1) has the same general operating characteristics as modern roundabouts but utilizes notably different geometrics and applications of traffic control devices.(5) This informational primer seeks to describe the characteristics of turbo roundabouts, highlighting the design and traffic control features, operational capabilities, and potential safety benefits of these roundabout alternatives.

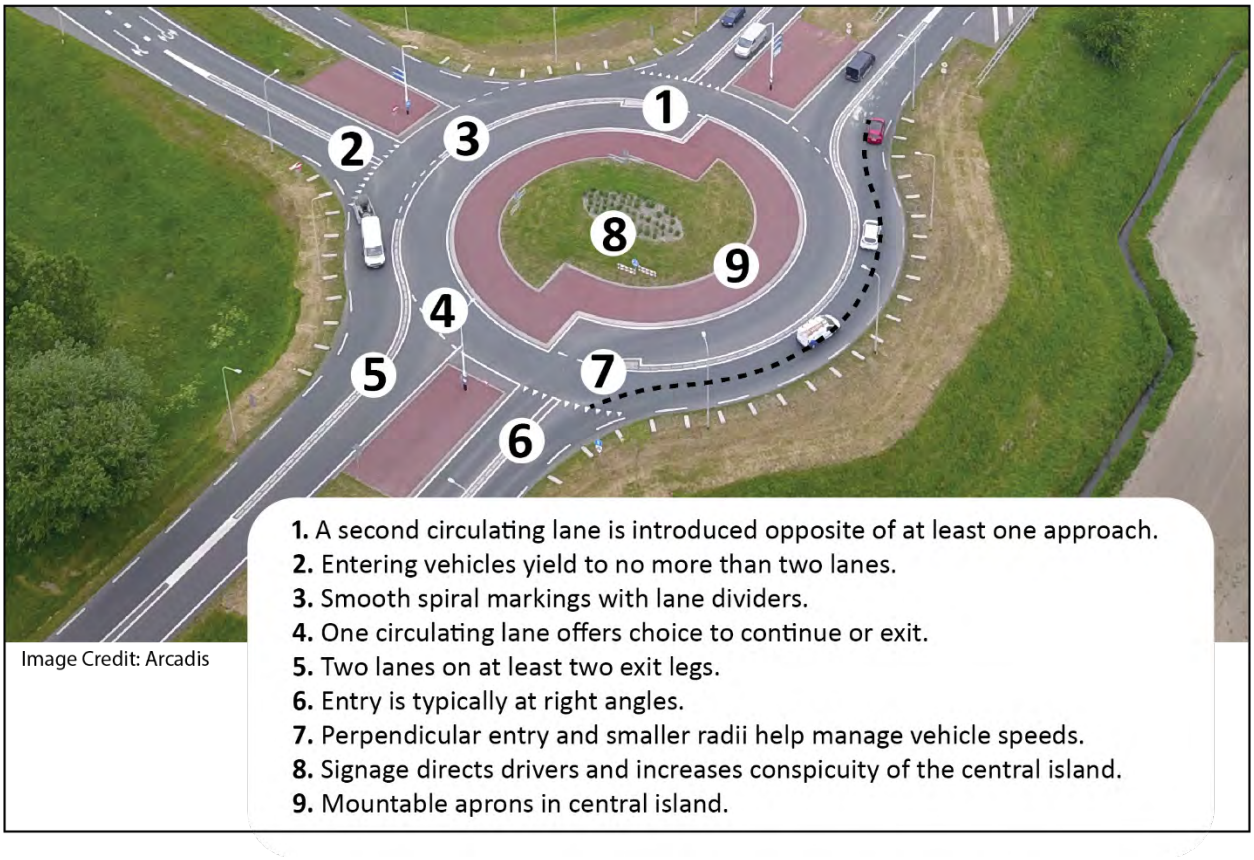
[1] A 2 x 2 roundabout is characterized by two entry lanes approaching two circulating lanes.
[2] The turbo roundabout was named by its inventor in the Netherlands in 1996. The descriptor “turbo” is meant to symbolize the geometric shape. It is not meant to convey faster vehicle speeds. In fact, its geometry was in part developed to reduce vehicle speeds below what might be observed during lower-volume hours of more traditional concentric multilane roundabouts.(6)

Figure 1. Photograph. Aerial view of turbo roundabout in Delft.[7]

Section 1: Characteristics of a Turbo Roundabout

Based on a review of international experience[8], features (illustrated in figure 2) that characterize turbo roundabouts include the following:[6]

- A second circulatory lane is inserted opposite of at least one entry lane.
- Traffic approaching the roundabout on at least one leg must yield to traffic in two, and no more than two, circulatory lanes in the roundabout.
- Smooth flow is encouraged by a spiral alignment.
- Lane dividers discourage lane changing within the roundabout. Drivers, therefore, select the proper lane prior to entering the roundabout. Internationally, options for lane separation have included raised, mountable lane dividers; flush lane dividers; or solid pavement markings.
- Each segment of the roundabout includes one circulatory lane from which drivers can choose whether to exit or continue around the roundabout.
- At least two exit legs are two-lane.
- The diameter of the roundabout is kept small to encourage lower speeds through the roundabout.
- Approach legs and entry are typically at right angles to the roundabout.
- Roundabout directional arrow signs direct drivers and increase conspicuity of the central island.
- Mountable aprons offer sufficient maneuvering space for longer vehicles.



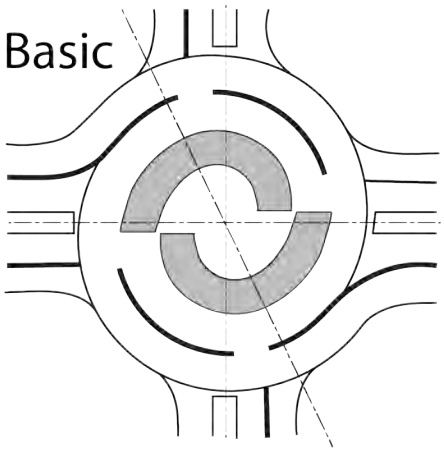
Source: FHWA.

Figure 2. Graphic. Turbo roundabout features. Image based on Fortuijn, 2009.[6]

There are different types of turbo roundabouts, including the basic, egg, knee, spiral, and rotor turbo roundabouts.[6] These options differ with respect to central island design, number of circulating lanes, and number of approach lanes, as described below:

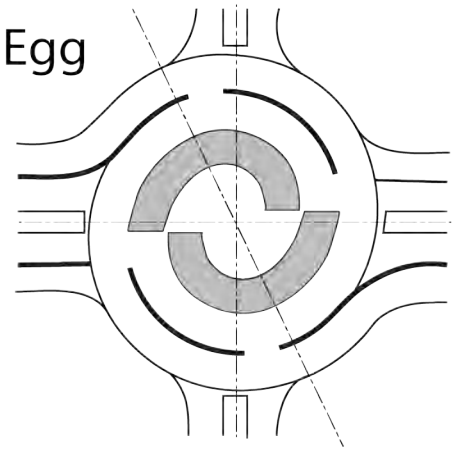
- Basic – inside lane added on major approaches, two lanes on each approach (see figure 3).
- Egg – similar to a basic turbo roundabout, but with only one approach lane on minor approaches (see figure 4).
- Knee – the inside lane is only added on one approach, two lanes on each approach (see figure 5).
- Spiral – three circulatory lanes, inside lane only added on two approaches, two approaches with three lanes and two approaches with two lanes (see figure 6).
- Rotor – three circulatory lanes, inside lane added on each approach, three lanes on each approach (see figure 7).

The variations in turbo roundabout designs differ in terms of total capacity available, so the type selected may be dictated by intersection demand. The capacity values provided in figure 3 through figure 7 represent capacity in the Netherlands and are not necessarily reflective of expected capacity values elsewhere.



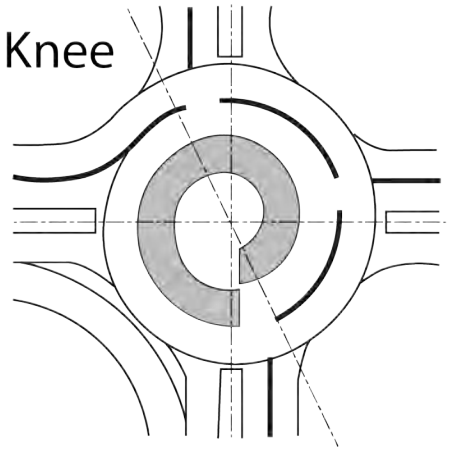
Source: FHWA.

Figure 3. Graphic. Basic turbo roundabout. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009.[6,9]



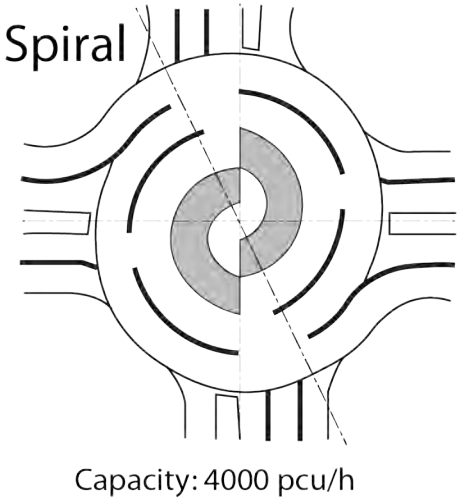
Source: FHWA.

Figure 4. Graphic. Egg turbo roundabout. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009.[6,9]



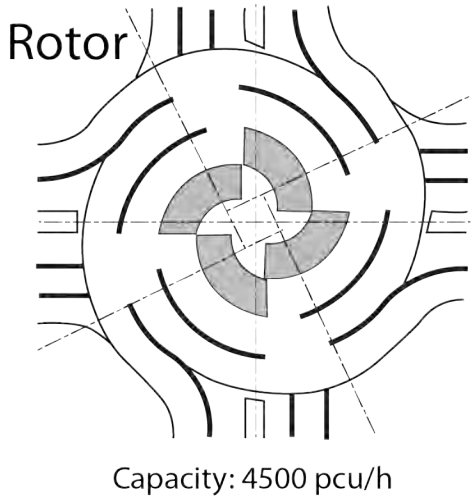
Source: FHWA.

Figure 5. Graphic. Knee turbo roundabout. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009.[6,9]



Source: FHWA.

Figure 6. Graphic. Spiral turbo roundabout. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009.[6,9]

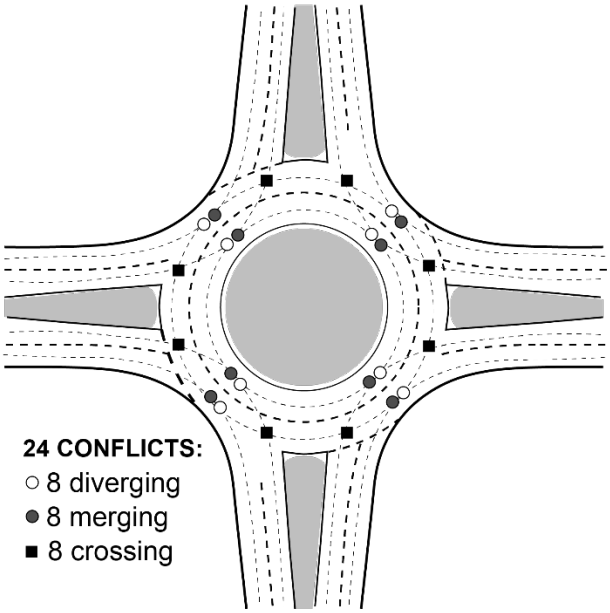


Source: FHWA.

Figure 7. Graphic. Rotor turbo roundabout. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009.[6,9]

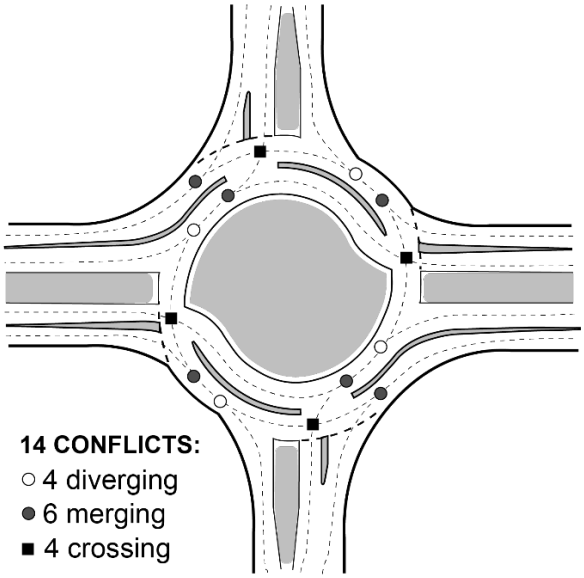
Section 2: Potential Benefits of Turbo Roundabouts

An international crash-based safety evaluation suggests conversion of an intersection from yield-control, signalized, or old-style rotary to a turbo roundabout is associated with a 76-percent reduction in injury crash frequency.[6] In addition, the geometric characteristics of the turbo roundabout result in operational outcomes that should help address lane selection, lane changing, and entering and exiting behaviors that can lead to the lower severity, multiple-vehicle crashes in 2 x 2 multilane roundabouts. The spiral road geometry and lane dividers of turbo roundabouts require drivers to choose the proper lane prior to entering the roundabout in order to leave the roundabout in the desired direction. Figure 8 and figure 9 show that the turbo roundabout eliminates some of the conflicts associated with the common crash types in modern 2 x 2 multilane roundabouts. At the two-lane exits of a turbo roundabout, drivers in the inside lane execute a "turn" to exit the roundabout, as in concentric roundabouts.[10] However, the turbo roundabout eliminates the requirement in concentric multilane roundabouts of exiting drivers in the inside lane having to first cross the outside lane. This is done by physically forcing drivers in the outside lane to exit.[6] The geometry of turbo roundabouts also helps to manage the speeds of vehicles entering, navigating, and exiting the roundabout. Operationally, the capacity of a turbo roundabout is expected to be similar to other modern multilane roundabouts.



Source: FHWA.

Figure 8. Graphic. Conflict point frequency for modern multilane roundabout. Image based on Vasconcelos et al., 2014.(11)



Source: FHWA.

Figure 9. Graphic. Conflict point frequency for turbo roundabout. Image based on Vasconcelos et al., 2014.(11)

Section 3: User Considerations

It is important to consider how various user groups are accommodated at turbo roundabouts given the intersection type's key features. Five primary user groups – motorists, pedestrians, bicyclists, motorcyclists, and freight/large vehicles – are discussed in this section.

3.1 Motorists

Turbo roundabouts rely on more direct entry geometry and enhanced delineation of lanes that can make it easier for motorists to successfully navigate them. Signage and supplemental pavement markings are provided in advance on approaches so drivers are given enough time to select their desired lane. When locating signs, designers should consider decision and stopping sight distance as well as potential queue lengths to provide drivers with adequate advance notice. At the entrance to the roundabout, drivers are required to identify acceptable gaps in no more than two conflicting lanes. A roundabout directional arrow sign placed directly in the drivers' field of view directs drivers to enter the circulatory roadway in the appropriate direction. Internationally, these signs are also recommended to increase the conspicuity of the central island and communicate to drivers the need to slow and turn into the roundabout.[6] The Roundabouts Informational Guide also recommends using landscaping to increase central island conspicuity.[12] Finally, the spiral geometry and enhanced delineation reinforce the appropriate maneuvers from each lane inside the roundabout.

One notable difference between turbo roundabouts and other modern roundabouts is the ability to complete U-turns. Modern roundabouts allow vehicles from all approaches to complete U-turn maneuvers. The lane arrangement of a turbo roundabout prohibits vehicles that enter on some approaches from completing U-turns. The approaches and lanes from which vehicles can and cannot perform U-turns vary based on the type of turbo roundabout. For instance, vehicles entering from the inside lane of the left and right approaches (the major road approaches) in figure 9 (a "Basic" turbo roundabout) can complete a U-turn; while vehicles approaching from the top and bottom approaches (the minor road approaches) cannot. As a result, it is important for analysts to consider the frequency of U-turn maneuvers at an intersection when evaluating turbo roundabouts as a potential alternative.

3.2 Pedestrians

The navigation through a turbo roundabout by a pedestrian does not differ from single-lane and multilane roundabouts. As a result, designers can follow guidance for pedestrian facilities at roundabouts proposed in the Roundabouts Informational Guide and National Cooperative Highway Research Program (NCHRP) Report 834:[12, 13]

- Keep sidewalks along the perimeter of the roundabout, separated from the edge of the circulatory roadway with a landscaped strip or buffer.
- Where crosswalks are provided, locate them for pedestrian convenience and safety, where drivers can be expected to yield the right-of-way, and where the crossing will be less likely to be blocked by queued vehicles.
- Provide a splitter island sufficiently wide to accommodate a crossing that is accessible to pedestrians with disabilities as well as wide enough for comfortable queueing.

3.3 Bicyclists

The decision of whether to provide separated bicycle facilities at turbo roundabouts depends on context, considering factors such as bicycle volume, the presence of existing bicycle facilities, motor vehicle volume, complexity of the roundabout, adjacent infrastructure and land use, and right-of-way availability. Bicycle features at turbo roundabouts are not expected to differ from traditional roundabouts, and features designers can consider to better accommodate bicyclists include:[12]

- Keeping radii small to reduce vehicle speeds, which can make bicyclists more comfortable if they ride in the roundabout.
- Terminating bicycle lanes before the edge of the circulatory roadway and crosswalks with enough length remaining for bicyclists to merge into traffic.
- Introducing bicycle lanes on exit legs downstream of crosswalks.
- If bicyclists are required to utilize the sidewalk, designing sidewalks to meet shared use path width requirements.
- If the intent is for bicyclists to cross at-grade on approaches, whether on a designated crossing or on a pedestrian crosswalk, a pavement-level cut-through of the splitter island can be provided.[14] The cut-through can be designed to include a chicane to encourage a two-stage crossing for bicyclists and provide more time for approaching drivers to identify crossing bicyclists. This is a commonly used treatment in the Netherlands.

3.4 Motorcyclists

While fatal crashes at roundabouts are much less likely than at traditional three- and four-leg intersections, motorcyclists are overrepresented in those fatal crashes. Motorcyclists were involved in 21 of the 46 fatal crashes that occurred at roundabouts in the United States between 2005 and 2013.[15] Roadway features that can have a significant impact on motorcycle safety performance at roundabouts include the presence and location of raised lane dividers and curbing, surface friction, pavement markings, drainage, sight distance (especially rider conspicuity), radii, the roadside environment, and surface conditions. Specific concerns for motorcyclists in turbo roundabouts are the truck apron and lane divider options that are raised. Sloped curbing with minimal vertical reveal can provide a more forgiving environment to motorcycles compared to vertical or rolled curbing. Designers can also provide supplemental signage alerting motorcyclists to these elements of turbo roundabouts. Potential alternatives to the raised lane dividers include striping and colorized and/or textured pavement, which are discussed in Section 7.1.4 Lane Divider.

3.5 Freight/Large Vehicles

The design of some turbo roundabout features is influenced by the physical dimensions and turning characteristics of the larger vehicles that will use the intersection. The lane widths of turbo roundabouts are determined with consideration of the design vehicle, typically the largest vehicle anticipated to regularly navigate the intersection. European turbo roundabout design guidance includes discussions on selecting lane widths so that design vehicles do not track into adjacent lanes.[9] However, the dimensions of European design vehicles are often smaller than design vehicle dimensions in the United States. Designing turbo roundabouts in the United States to prevent, for example, a WB-67 from tracking into an adjacent lane it not feasible within

a reasonably sized roundabout. However, this characteristic is not limited solely to turbo roundabouts. The Roundabouts Informational Guide states that "multilane roundabouts are designed either to allow large vehicles to track across more than one lane while entering, circulating, and exiting or to stay within their lane" [Pages 2-19].(12) This concept has also been adopted by some State departments of transportation as well. The Washington State Department of Transportation Design Manual informs designers to "assume a truck's travel path will [straddle] parts of two adjacent lanes" in multilane roundabouts [Pages 1320-18].(16) The South Carolina Department of Transportation allows large vehicles to "track across the whole width of the circulatory roadway to negotiate the roundabout" [Pages 9.7-11].(17) Given this allowance for multilane roundabouts, it is reasonable for agencies to allow design vehicles to track across multiple lanes within turbo roundabouts. In these situations, a raised lane divider is unlikely to be a sustainable option due to repeated strikes by the larger vehicles.

Starting the lane divider of a turbo roundabout as near as possible to the vehicle entry point is necessary to prevent vehicles circulating in the outside lane from changing to the inside lane at these locations. However, large vehicles entering the inside lane from an approach need a wider opening to account for their larger swept paths. Where a raised lane divider option is used, a traversable, demarcating feature can be provided at the origin of the raised divider to ease the entrance of larger vehicles.

A central truck apron is provided in turbo roundabouts to help accommodate larger vehicles that need to navigate the intersection. Aprons can also be provided on the perimeter of the roundabout to provide additional turning space for large vehicles. Finally, agencies can work with the State Oversize/Overweight (OS/OW) Load Permit Office to determine if the intersection is commonly used by OS/OW vehicles, and if so, obtain the applicable length and width requirements for those vehicles to develop strategies for accommodation.

Section 4: Location Considerations

Modern roundabouts can be among the safest feasible intersection alternatives in a wide variety of settings and contexts – low-speed urban, high-speed rural, at isolated intersections, as corridor treatments, and even at interchange ramp terminal intersections. Relevant site characteristics that can influence whether a roundabout is a feasible alternative include right-of-way limitations, intersection skew, winter maintenance needs, adjacent traffic generators or sites that require pre-emption, and downstream bottlenecks. Additional detail on roundabout applications commonly found to be feasible and advantageous can be found in the Roundabouts Informational Guide[3].(12)

Turbo roundabouts may be considered at any intersection where a roundabout is a potential alternative, particularly where traffic demand indicates the need for a multilane roundabout. Their design provides similar capacity to multilane roundabouts while reducing conflict points,

[3] At the time of publication of this informational primer, the 2nd Edition of the Roundabout Informational Guide was published under NCHRP Report 672. The 3rd Edition is being developed under NCHRP Project 03-130.

discouraging lane changes, and maintaining the speed reduction characteristics of single-lane roundabouts.

Section 5: Safety Analysis Methods and Results

Given the brief history of turbo roundabouts, international safety studies based on an analysis of crash data are limited, and not yet available in the context of a United States driving population. Dutch research analyzed crash data at seven intersections—including signalized, yield-control, and old-style rotary types—that were converted to a turbo roundabout and found a 76-percent reduction in the number of injury crashes.(6) Polish research found that turbo roundabouts with a raised lane divider experience a lower crash frequency than those with paint stripes only. However, the research observed lower severity crash outcomes in both cases. Only 7 percent of crashes on turbo roundabouts without a raised lane divider resulted in an injury, compared to 4 percent of crashes with a raised lane divider.(18) Safety surrogate measures resulting from microscopic traffic simulations or field observations (e.g., time-to-collision, vehicle speeds, vehicle conflicts, incorrect movements, and incorrect paths) have also indicated that turbo roundabouts are likely to experience less frequent and less severe crashes than multilane roundabouts due to the reduction of conflict points within the roundabout and the lower speeds required to navigate the smaller radii[4]. [See references 19, 20, 21, 22, and 23.]

Section 6: Operational Analysis

For a turbo roundabout to be successful, it is important to verify the design can accommodate the projected traffic volumes at the intersection. At modern multilane roundabouts in the United States, the capacity of one entry lane ranges from 300 to 1,100 passenger cars per hour (pc/h), depending on conflicting flow in the circulatory roadway, implying a total approach capacity ranging from approximately 600 to 2,200 pc/h for a two-lane approach.(12, 24) As with modern roundabouts, turbo roundabout capacity is measured at the approach level. Operational performance models for turbo roundabouts have not yet been developed for, or adapted to, the context of a United States driving population. International research suggests basic turbo roundabouts have similar capacities as multilane roundabouts with two entry and two circulating lanes. One such study from the Netherlands estimated a capacity for a basic turbo roundabout design of approximately 3,500 pc/h for all entries combined, assuming conflicting traffic volumes between 1,900 and 2,100 pc/h.(25) However, roundabout capacity in the Netherlands is likely to be higher than in the United States given broader driver familiarity with roundabouts.

Gap-acceptance models that consider critical headway, critical follow-up time, and conflicting traffic appear adequate for estimating turbo roundabout capacity. Research in Poland found the Highway Capacity Manual (HCM) capacity models for roundabouts produced capacity estimates for Polish turbo roundabouts that were comparable to estimates from Polish-specific turbo roundabout capacity models.(26) The roundabout capacity models of the HCM are likely to represent reasonable capacity estimates for turbo roundabout approaches with up to two lanes. As with single and multilane roundabouts, analysts would apply the HCM models to each lane of

[4] The ability to reliably link safety surrogates to crash frequency and severity remains a topic of ongoing research and debate.

each approach, given the specific characteristics of the lane and approach (e.g., number of entry lanes, number of conflicting lanes, conflicting flow).

Section 7: Design Considerations

The geometric design of a turbo roundabout is driven by the desired capacity and the desired characteristics of a design vehicle's horizontal swept path. The projected demand and cross sections on the approach roadways inform the number of lanes/lane arrangement decisions, which dictate the type of turbo roundabout to be built (see Section 1: Characteristics of a Turbo Roundabout). Once the type is selected, a horizontal swept path analysis of the design vehicle informs lane width decisions along with other lane width-related considerations (e.g., right-of-way, performance for all vehicle types and users). The turbo roundabout type and lane widths are combined to construct the turbo block, which guides the geometric design of the circulatory roadway.

7.1 Horizontal Design

7.1.1 Turbo Block

The spiral alignment of a turbo roundabout is generated from the "turbo block," a series of circular arcs with centers located at various points along a reference line known as a "translation axis." The turbo block consists of arcs that represent the inner and outer edges of each lane. The inner radius of the turbo block, which represents the radius of the central island, is selected based on the anticipated size of the turbo roundabout. The shift along the translation axis from the center is the width of the lane represented by the arc. The turbo block and angle of the translation axis differs for each turbo roundabout type. Figure 10 is a sample turbo block for a basic turbo roundabout with the major roadway oriented horizontally.

The turbo block is defined by the characteristics shown in figure 10. First is the center point (CG), which is the intersection of the approach centerlines. Second is the orientation of the translation axis, which is defined in relation to the major road approaches. Assuming the major road is oriented with the x-axis in figure 10, the right side of the translation axis is rotated 57.5 degrees around the center below the x-axis for a four-leg intersection, and the left side of the translation axis is rotated 65 degrees around the center below the x-axis for a three-leg intersection.[9,25] The angle of rotation for the translation axis can be tweaked to provide smooth, spiraled vehicle paths for all vehicle movements. Third are the radii of the circles (TR1, TR2, TR3, and TR4). TR1 defines the radius of the inside edge of the inside roadway. TR2 defines the outside edge of the inside roadway; with the difference between TR2 and TR1 equal to the width of the inside travel lane plus additional width for the edge lines delineating the raised lane divider. TR3 defines the inside edge of the outside roadway. The difference between TR2 and TR3 is the width of the lane divider. TR4 defines the outside edge of the outside roadway.

The fourth key set of dimensions defining the turbo block is the distances between the center points of the arcs. The circles corresponding to the four radii are split along the translation axis, and the resulting arcs are slid along the translation axis in opposing directions by half the distance defined as the *shift.* The shift is the distance between the centers of the arcs. The shift can differ for the TR1 centers and the TR2/3/4 centers if the inside roadway width is different than the outside roadway width. The shift for the TR1 centers ($\Delta\upsilon$ in figure 10) is equal to the

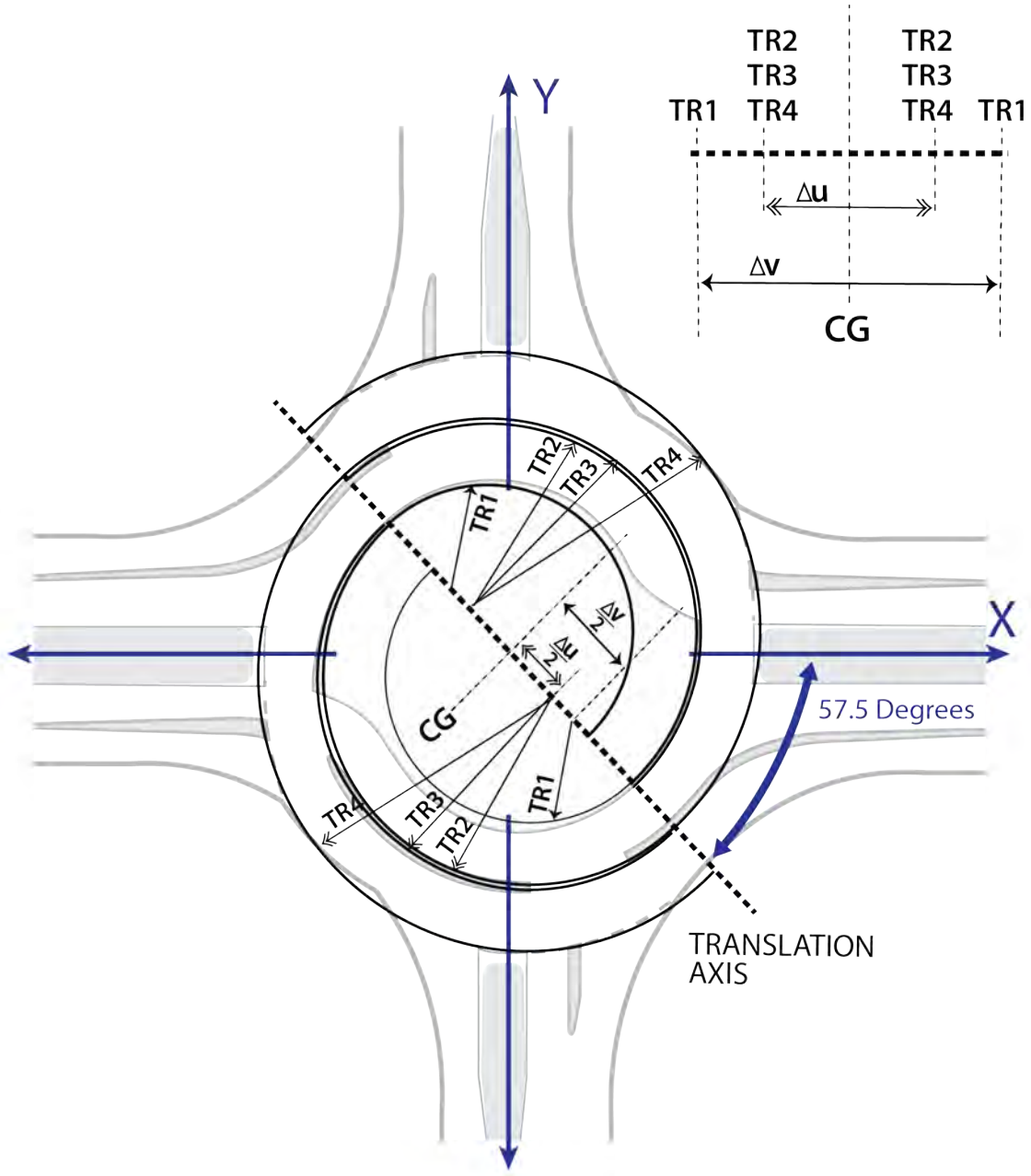
difference between the inside edge of the inside roadway and the inside edge of the outside roadway (also the difference between the values used for TR3 and TR1). The shift for the TR1 centers is achieved by sliding the two arcs defined by TR1 in opposing directions away from CG, each by $\Delta\upsilon/2$. In international practice, $\Delta\upsilon/2$ ranges from between 8.5 and 9.5 feet (for total shifts ranging between 17 and 19 feet), as shown in figure 10. The shift for the TR2/3/4 centers (Δu in figure 10) is the distance between the outside edge of the inside roadway and the outside edge of the outside roadway (also the difference between the values used for TR4 and TR2). The shift for the TR2/3/4 centers is achieved by sliding the arcs defined by TR2/3/4 in opposing directions away from CG by $\Delta u/2$, as shown in figure 10. This value ($\Delta u/2$) typically ranges from between 7.5 and 8.5 feet (for a total shift of 15 to 17 feet). If the inside and outside roadways are the same width, the shift value for all radii are the same ($\Delta\upsilon = \Delta u$).

Internationally, the radii (TR1, TR2, TR3, and TR4) for basic turbo roundabouts have ranges as follows:

- 34 to 66 feet for TR1.
- 52 to 82 feet for TR2.
- 53 to 83 feet for TR3[5].
- 70 to 100 feet for TR4.

With the offset arcs making up the turbo roundabout, the nominal diameter of the turbo roundabout is twice the value TR4 plus the width of the TR2/3/4 shift, Δu. Assuming a shift of 15 feet, the inscribed circle for basic turbo roundabouts ranges from 155 feet to 215 feet.

[5] The one-foot difference between the minimum and maximum TR2 and TR3 values implies an average width of one foot for the lane divider.



Source: FHWA.

Figure 10. Graphic. Sample turbo block. Image based on Overkamp & Van der Wijk, 2009 and Dzambas et al., 2017.[9,25]

7.1.2 Lane and Roadway Width

Determining the width of each lane of a turbo roundabout is informed by a horizontal swept path analysis of the design vehicle. The inside lane is often wider than the outside lane to compensate for the design vehicle maneuvering a smaller radius. Internationally, inside lane

width ranges from between 14 and 16 feet, while outside lane width ranges from between 13 and 14.5 feet. The inner roadway width, defined as the distance from the central island to the lane divider (TR2 minus TR1), including the inside and outside edge line pavement markings ranges from between 16 and 18 feet. The outer roadway width, defined as the distance from the lane divider to the outer edge of the roundabout (TR4 minus TR3), again including the inside and outside edge line pavement markings ranges from between 15 and 16.5 feet.[9, 25]

7.1.3 Central Island

The central island is defined by the innermost radius of the turbo block (TR1) and consists of a traversable portion (mountable apron) and a non-traversable portion. The non-traversable portion is typically used for signage, specifically a roundabout directional arrow sign. There are cutouts in the central island to introduce the inside lane of the turbo roundabout on the applicable approaches. There are two developed methods for design of these cutouts and beginning the inner lane. A curved entry, shown in figure 11, provides a smooth path for approaching vehicles, but may result in a greater chance of circulating vehicles entering the inside lane. A flat entry, shown in figure 12, helps to discourage this movement from circulating vehicles. Designers should check that objects on the central island do not restrict sight distance along the circulatory roadway.

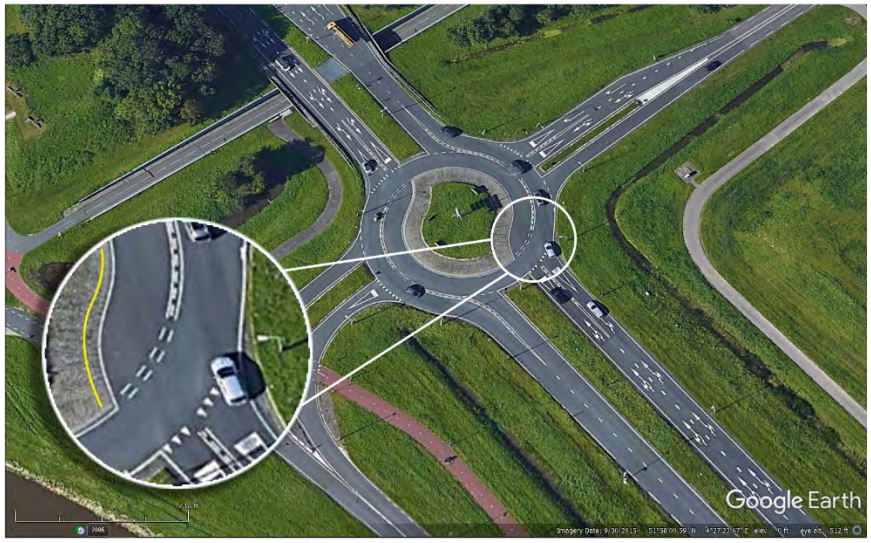


Figure 11. Photograph. Original design used in the Netherlands for introducing the inner lane.[27]

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Figure 12. Photograph. Revised design used in the Netherlands for introducing the inner lane.(28)

7.1.4 Lane Divider

One important feature of the turbo roundabout is a lane divider between each circulating lane. In the Netherlands, this lane divider is raised but mountable, designed with little vertical profile and a rather flat slope to provide forgiveness for errant vehicles (as shown in figure 13). Often, the raised lane divider is introduced with a traversable, demarcating feature to allow tracking by large vehicles (see figure 14). Some countries (including Poland, Germany, and Canada) have implemented turbo roundabouts without raised lane dividers, in part due to possible challenges these dividers present to motorcyclists and snow plowing operations.(9) In the United States, a roundabout in Alta, Utah[6] has a raised, mountable lane divider separating lanes for a two-lane portion of the roundabout.

Alternatives to the raised lane divider include striping and colorized or textured pavement, as shown in figure 15 from a turbo roundabout in Canada. While these options do not provide a physical barrier to lane changing, they still communicate this message to the driver both visually, and in the case of textured pavement, through audible and tactile mediums. Other alternatives to consider include:

- Milled rumble strips or rumble stripes, which provide more intense feedback to drivers than textured pavement.
- A double solid white lane, which the Manual on Uniform Traffic Control Devices (MUTCD) describes as a standard approach when crossing the lane lines are prohibited.(29) For one example, two roundabouts in Conway, Arkansas[7] use solid wide white thermoplastic lines to separate its two lanes within the circulatory roadway.
- Raised pavement markers which can provide visual and tactile feedback and be snow-plowable where needed.

[6] Located at Latitude 40.645758 Degrees North, Longitude 111.494956 Degrees West.
[7] Located at Latitude 35.066366 Degrees North, Longitude 92.414523 Degrees West.

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Figure 13. Photograph. Raised lane divider in a turbo roundabout in the Netherlands.

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Figure 14. Photograph. Example introduction of the raised lane divider.[30]

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Figure 15. Photograph. Lane divider for turbo roundabout at Victoria International Airport.[31]

7.1.5 Approach Geometry

Turbo roundabouts are constructed with radial approaches, which have the benefit of reducing changes to the alignment along the approach roadway and maintaining exit curvature that encourages drivers to maintain slower speeds through the exit of the roundabout. Additionally, turbo roundabouts are built with little or no flare or deflection and smaller entry radii. The angle between entering traffic and circulating traffic is therefore larger (closer to a perpendicular entry) for a turbo roundabout than for other modern multilane roundabouts. These approach features differ from modern multilane roundabouts in the United States, which typically include flare to gain some capacity increase and deflection to align entering vehicles "to the right of" the central island in the desired direction of travel. The entry geometry of a turbo roundabout generally does not channelize drivers into the circulatory roadway to the right of the central island and the splitter islands generally do not have enough curvature to block a direct path of approaching vehicles to the central island. This approach geometry is based on the premise that it will be clearer to drivers that they are approaching an intersection that should be negotiated at lower speeds.[6] Potential disadvantages include drivers errantly hitting the central island, making wrong-way left turn maneuvers to enter the roundabout, and making wrong-way exit maneuvers into entrance approach lanes.[12] International literature emphasizes the importance of a roundabout directional arrow sign, placed in the central island in the line of sight of approaching drivers, that directs drivers to turn right and increases the conspicuity of the central island (discussed in Section 7.3). It also emphasizes the need for a forgiving design of the central island and sign in the case that either is struck.

Internationally, turbo roundabout entry radii range from 39 to 50 feet.[9, 25] For comparison, modern multilane roundabouts in the United States are designed with entry radii exceeding 65 feet, and even single-lane roundabouts have entry radii ranging from 50 to 100 feet.[12]

7.2 Sight Distance and Visibility

Adequate stopping and decision sight distance should be provided for all users of the turbo roundabout. Stopping and intersection sight distance should be provided at all approaches. The Roundabouts Informational Guide provides guidelines for evaluating sight distance and visibility at roundabouts.[12]

7.3 Signage and Pavement Markings

There are a few differences in the traffic control devices within the circulatory roadway of turbo roundabouts compared to modern multilane roundabouts. For modern multilane roundabouts, lanes are separated using either a single dashed or solid white line. As discussed in section 7.1.4 Lane Divider, these are replaced with lane dividers in turbo roundabouts. Potential advantages of the lane divider compared to single dashed or solid white lines include less ambiguous and more intuitive messaging to drivers on lane selection, lane keeping, and the appropriate maneuvers from each lane.

Given the operational characteristic of prohibited lane changes within the circulatory roadway of a turbo roundabout, signage and pavement markings on the approaches, especially for lane selection, are critical for motorists to identify and select their desired lane before entering the roundabout. Chapter 2 of the MUTCD, as well as the Roundabouts Informational Guide, describe applications of lane control signage for roundabout approaches.[12, 29] Lane control signage can be supplemented using pavement marking arrows.

A version of the roundabout directional arrow sign (R6-4, R6-4a, or R6-4, as shown in figure 16) in the central island directs drivers to the right and increases the conspicuity of the central island. Signage can also direct pedestrians and bicyclists to designated facilities, drivers to their desired lanes, and communicate the presence of raised curbing, such as a raised lane divider (if one is used). If the lane divider includes grooved, textured, or brick pavements, consideration can be given to including sign W8-15 to warn road users of its presence. Pavement markings shall be used to delineate the edges of the approach and circulatory lanes. Additionally, supplemental delineation can be achieved using reflectors or light emitting diodes (LEDs) to illuminate the edges of the apron and lane dividers.[29] Finally, given the important role signage and pavement markings play for all users of turbo roundabouts, it is important that all traffic control devices are compliant with the MUTCD and for agencies to establish consistent maintenance practices that sustain the visibility and retroreflectivity of traffic control devices.

Source: FHWA.

Figure 16. Graphic. Roundabout directional arrow sign (R6-4b) for central island.[29]

7.4 Pedestrian Design Treatments

Pedestrian accommodations for turbo roundabouts do not differ from modern roundabouts. Crossings should be kept at the perimeter of the intersection, with crosswalks and splitter islands on the approaches to provide two stage crossings. All sidewalks, crosswalks, and curb ramps should be accessible to and usable by pedestrians with disabilities. The crosswalk should be placed far enough (minimum of 20 feet, or one vehicle-length) from the circulatory roadway so a motorist can exit the roundabout and then stop before reaching any potential pedestrians in the crosswalk.[12]

7.5 Bicycle Design Treatments

Bicycle guidance for turbo roundabouts is the same as for modern roundabouts. A bicyclist can either mix with motor vehicle traffic or, when available, utilize separated facilities. The decision as to which treatment is adopted is based on context, weighing factors such as bicyclist volume, motor vehicle volume, complexity of the roundabout, adjacent infrastructure and land use, and available right-of-way. In the Netherlands, separate bicycle paths outside of the roundabout are recommended where possible, including for turbo roundabouts.[25] Dutch guidance recommends adding curb cuts with chicanes in splitter islands for bicycle crossings (figure 17). The curb cuts encourage bicyclists to use the crossing, while the chicane encourages the crossing to be taken in two stages.

Figure 17. Photograph. Example of a chicane in a splitter island at a turbo roundabout in the Netherlands to provide additional time for approaching drivers to identify the bicyclist and to encourage bicyclists to perform a two-stage crossing.(32)

7.6 Vertical Design

Vertical alignment considerations are the same as other modern roundabouts. The geometry should not restrict sight distance throughout the intersection area, including decision sight distance on the approaches when selecting lanes, stopping sight distance on the approach and on the circulatory roadway, and intersection sight distance at the entrances to the circulatory roadway.

7.7 Lighting

The use of proper lighting is encouraged to improve the visibility of the middle island and raised lane divider.(25) Lighting should also be provided to give adequate visibility for pedestrian and bicycle facilities, especially crossings, though it is important that designers are careful to avoid creating negative contrast lighting and shadowing.(12)

7.8 Landscaping

Landscaping should be limited to the non-traversable portion of the central island and not hinder stopping sight distance around the circulatory roadway. If sprinklers are used to maintain landscaping, designers should consider the impacts of irrigation runoff onto the circular roadway, as unexpected wet pavement can introduce another potential risk to users of the intersection.(33)

7.9 Other Design Considerations

Other design considerations, such as bypass lanes, access management, at-grade rail crossings, evacuation routes, and bus stops, should be addressed the same as they are for modern roundabouts. Specific guidelines for these issues are available in the Roundabout Informational Guide.[12]

7.10 Comparison to United States Roundabout Design Principles

The Roundabouts Informational Guide describes six overarching principles that inform the design of roundabouts.[12] Table 1 describes the principles and the manners in which they are addressed in turbo roundabouts.

Table 1. Roundabout design principles.

Design Principles from the Roundabout Informational Guide[12]	Addressed in Turbo Roundabouts
"Provide slow entry speeds and consistent speeds through the roundabout by using deflection."	International practices of a perpendicular entry and smaller radii of the right turns on entry are intended to slow vehicle entry speeds.
"Provide the appropriate number of lanes and lane assignment to achieve adequate capacity, lane volume balance, and lane continuity."	Turbo roundabout variants are available for a range of traffic demand. International research suggests basic turbo roundabouts have similar capacities as multilane roundabouts with two entry and two circulating lanes.
"Provide smooth channelization that is intuitive to drivers and results in vehicles naturally using the intended lanes."	The spiral lane markings and lane dividers provide intuitive messaging to drivers on lane selection, lane keeping, and the appropriate maneuvers from each lane.
"Provide adequate accommodation for the design vehicles."	As with modern multilane roundabouts, lane width decisions for turbo roundabouts are informed by a horizontal swept path analysis of the design vehicle along with other lane width-related considerations (e.g., right-of-way, performance for all vehicle types and users). Additionally, aprons are provided on the central island and as necessary on the perimeter of the roundabout to provide additional space.
"Design to meet the needs of pedestrians and cyclists."	Pedestrian and bicycle accommodations for turbo roundabouts do not differ from modern multilane roundabouts.
"Provide appropriate sight distance and visibility for driver recognition of the intersection and conflicting users."	Signage is placed far enough in advance of the roundabout so road users are aware of the approaching intersection and the need to select their lane before entering the roundabout. The roundabout directional arrow sign on the central island increases driver recognition of the roundabout.

Section 8: Costs

As of this writing, no turbo roundabouts have been constructed in the United States, meaning there is no local data related to turbo roundabout costs. However, turbo roundabouts are similar to multilane roundabouts, and are therefore expected to have similar types and magnitudes of costs. Turbo roundabouts may vary slightly from multilane roundabouts in required right-of-way. A radial entry with no flare and smaller entrance radii requires a larger swept path for large vehicles. The circular roadway may therefore be wider in some cases than for a comparable multilane roundabout. However, significant changes to the alignment of the approach roadway are generally unlikely given the entry geometry of the turbo roundabout.

Section 9: Education and Public Involvement

Given the unique geometry and limited knowledge of turbo roundabouts in the United States, traditional public outreach methods for roundabouts will need to be modified for educating the public about turbo roundabouts. Below is a discussion on various messages and approaches that may benefit education efforts, drawing on successful methodologies used in Europe and other roundabout strategies implemented in the United States.

9.1 Key Messages

During initial public outreach, agencies may find it helpful to place emphasis on the safety benefits of roundabouts in general, along with additional emphasis on the reduction of conflict points and the intuitive lane selection and channelization associated with turbo roundabouts. Agencies can also emphasize the key differences between multilane roundabouts and turbo roundabouts, including the lane divider and the spiral lane markings.

As the project develops, highlighting previous turbo roundabouts can be important to demonstrate the positive impact made on traffic flows and to create a greater sense of familiarity with how to navigate the roundabout. These messages can reemphasize the importance of lane selection on the approach and the principle of no lane changing in the circulatory roadway. The lack of a track record for turbo roundabouts in the United States may present challenges to convey these key messages in the short term; international success can be discussed here instead. As turbo roundabouts are opened throughout the United States, it is important to incorporate feedback from those projects into messaging on future projects. After installation, agencies can continue providing information on how specific user types are intended to navigate the turbo roundabout.

9.2 Educational Media

Real-time video or simulations are appropriate media for educating engineering audiences and the public alike at the beginning of a project, as they provide a clear depiction of how users are meant to navigate the turbo roundabout. Though video will be difficult to obtain until after early United States installations, agencies can take this form of media into consideration as more turbo roundabouts are built. Other suggested media include social media, flyers and fact sheets, slide decks, and educational guides.

9.3 Audiences

It is important for agencies to consider all relevant audiences for public involvement and education efforts, not just the general driving population. Other important target audiences include:

- New/young drivers.
- Large vehicle/freight drivers.
- Motorcyclists.
- Bicyclists and pedestrians.
- Local and State roadway personnel, including maintenance crews and land use planners.

9.4 Decision Matrix

Transportation agencies need to consider the audience's key needs and issues, the appropriate method for reaching the targeted audience, and the agency's capabilities and budget to implement the selected education/awareness approaches. A decision matrix, similar to that in table 2, can be useful for identifying audiences and developing appropriate marketing and communication materials.

Table 2. Target audience educational/awareness media.

Audience	Organization	Informational Primer	Real-time Video/Simulatio	Signage	Slide Decks	Social Media	Education Guide	Fact Sheets and Flyers	Webinars
Local and State Transportation Agencies	Roadway Designers & Engineers	X	X		X		X	X	X
	Maintenance Crews	X					X		X
	Land Use Planners	X	X		X		X	X	X
User Groups	Drivers		X	X	X	X	X	X	
	Large Vehicle/Freight Drivers		X	X	X	X	X	X	
	Motorcyclists		X	X	X	X	X	X	
	Bicyclists & Pedestrians		X	X	X	X	X	X	

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FHWA, Office of Safety

Jeffrey Shaw
jeffrey.shaw@dot.gov
202-738-7793

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