Turbo Roundabouts:

A Review of Practices in the Czech Republic, the Netherlands, and Poland

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FHWA Global Benchmarking Program Report
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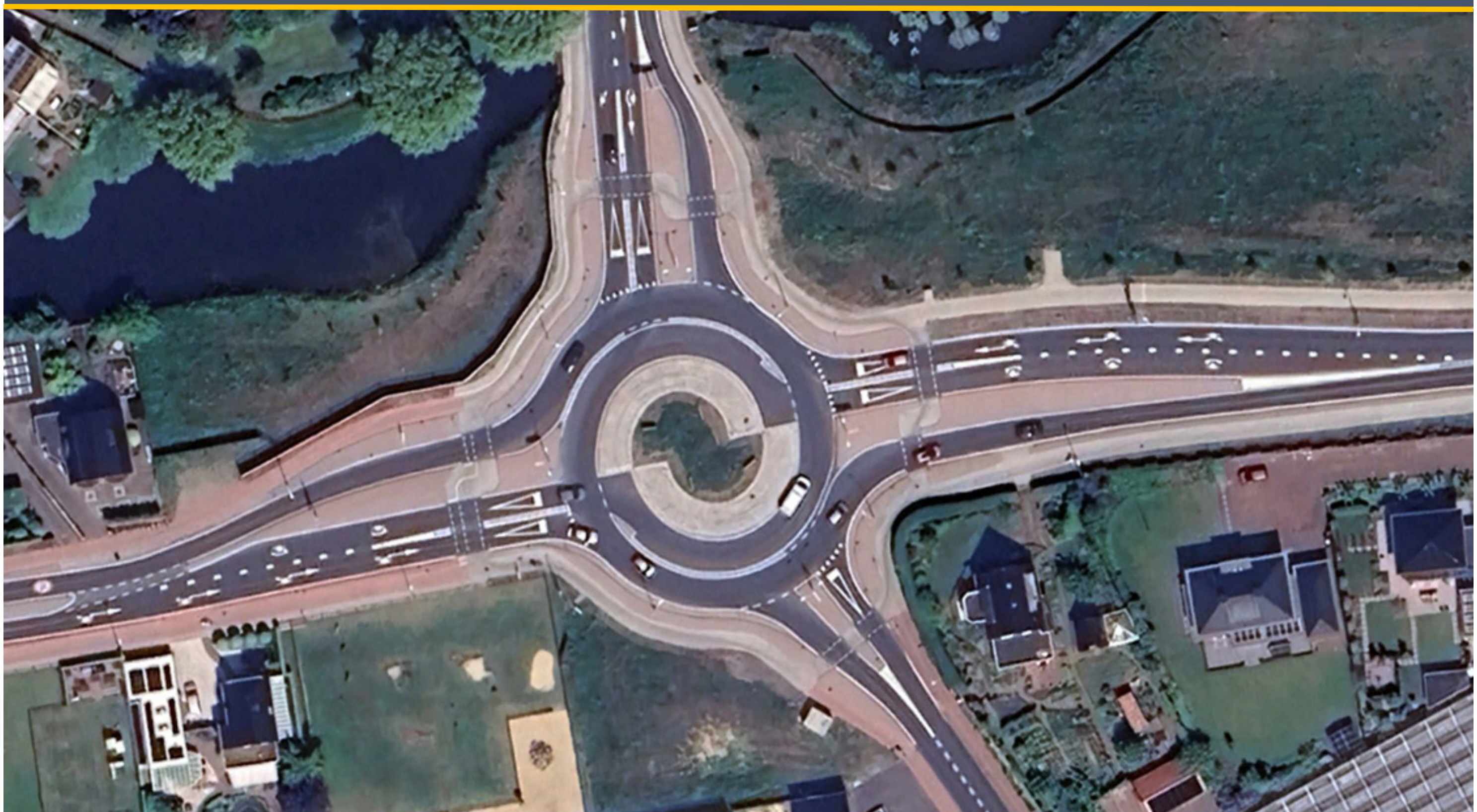

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16. Abstract

This report documents the findings from an international study on turbo roundabouts undertaken as part of the Federal Highway Administration's Office of International Program's Global Benchmarking Program. The study was motivated by the growing domestic interest in and installation of turbo roundabouts to combat the disproportionate number of property damage only (PDO) crashes at some U.S. multi-lane roundabouts. The report summarizes international experiences with turbo roundabouts to provide information on the benefits and challenges of their implementation, to determine the availability and applicability of design guidance, and to identify opportunities for further turbo roundabout implementation in the U.S. The study identified many examples where the visited countries implemented turbo roundabouts with positive results that will inform implementation in the U.S.

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List of Abbreviations

Abbreviation	Term
CDV	Transport Research Center
DOT	Department of Transportation
EU	European Union
FGSV	Road and Transportation Research Association
FHWA	Federal Highway Administration
GBP	Global Benchmarking Program
GDDKiA	General Directorate for National Roads and Motorways
PDO	Property Damage Only
RSD	Road and Motorway Directorate
SWOV	Institute for Road Safety Research
TU Delft	Delft University of Technology
U.S.	United States

Executive Summary

Study Overview

The Federal Highway Administration (FHWA) conducted this study under its Global Benchmarking Program (GBP).[1] The GBP serves as a tool for accessing, evaluating, and implementing proven global innovations that have the potential to significantly improve highway transportation in the United States (U.S.). Instead of recreating advances already developed by other countries, the program focuses on acquiring and adopting technologies and best practices already available and used abroad.

The purpose of this study was to learn about international experiences with turbo roundabouts to better understand the benefits and challenges of their implementation, to determine the availability and applicability of design guidance, and to identify opportunities for further turbo roundabout implementation in the U.S based on growing domestic interest.

Turbo roundabouts are a modified version of multi-lane roundabouts and operate similarly. The term "turbo" refers to the turbine-style geometric shape of the roundabout and not the speed of vehicles traveling through the roundabout. The distinct geometric design characteristics of turbo roundabouts were developed to mitigate conflict points within the roundabout as a means toward improved safety performance relative to conventional multi-lane roundabouts.[2]

Research has shown that some multi-lane roundabouts with two entering lanes and two circulating lanes, commonly known as 2x2 roundabouts, are overrepresented for higher rates of property damage only (PDO) crashes.[3] Several countries have deployed turbo roundabouts to reduce these crashes while maintaining or increasing capacity and balancing user needs.

As of late 2023, there were four operational turbo roundabouts in the U.S. located in Jacksonville, Florida; Fort Lewis, Kansas; Delaware County, Ohio; and Hollister, California. Additionally, a conventional roundabout was retrofitted to a turbo roundabout in Bonita Spring, Florida in 2022. Some States have begun to incorporate turbo roundabout design guidance into their design manuals, but there are still challenges and knowledge gaps, especially with regard to the radial entrance alignment and circulating geometry, the use of channelization (raised and flush) between lanes, accommodation of large vehicles such as trucks, pedestrian and bicyclist considerations, and weather-related maintenance concerns.

The U.S. study team included representatives from the FHWA Office of Safety Technologies; FHWA Office

[1] FHWA Global Benchmarking Program: https://international.fhwa.dot.gov/programs/mrp/gbp.cfm
[2] Throughout this report, "modern roundabouts," "conventional roundabouts," and "modern conventional roundabouts" are used interchangeably to refer to roundabouts that feature channelized, curved approaches that reduce vehicle speed, entry yield control that gives right-of-way to circulating traffic, and counterclockwise flow around a central island that minimizes conflict points.
[3] Reasons for Drivers Failing To Yield at Multi-Lane Roundabout Exits: Transportation Pooled Fund Study Final Report: https://rosap.ntl.bts.gov/view/dot/66498

of Technical Services, Resource Center; Minnesota Department of Transportation (DOT); North Carolina DOT; and the City of Hilliard, Ohio.[4] The first phase of the study consisted of desk-based research and interviews to better understand the safety, design, and implementation of turbo roundabout in countries that have deployed them on a significant scale or that have unique implementation circumstances of interest to the U.S. This research identified Poland, the Czech Republic, and the Netherlands as locations for in-person site visits and technical meetings in the second phase of the study. The findings from these activities are summarized in this report.

Key Findings and Observations

The study findings are organized into the following categories:

- **Safety Performance**
    - Deployment of turbo roundabouts shows a similar **reduction in fatal and injury crashes** to the deployment of conventional roundabouts.
    - Newly constructed turbo roundabouts or roundabouts retrofitted with turbo roundabout features have the potential to **reduce PDO crashes.**
    - The right-angle or rounded inner lane design in the center island results in **slower speeds** at the entry to the turbo roundabout.
    - Raised channelization results in **fewer conflict points**.
- **Operational Performance**
    - Turbo roundabouts facilitate **efficient movement of all users and vehicle types** including pedestrians, bicyclists, freight, transit, and motor vehicles.
- **Methods and Effectiveness of Lane Separation**
    - **Robust channelization** is essential. Raised channelization is generally more effective in keeping vehicles in their lanes than the use of flush markings. However there are certain trade-offs for such use.
    - Routine (daily and seasonal) and long-term **maintenance practices** for turbo roundabouts are widely accepted throughout the Czech Republic, Poland, and the Netherlands. Specification and design of the channelization materials and layout is done with maintenance consultation.
- **Signing and Pavement Marking Practices**
    - **Proper lane selection** on the approaches is more critical for turbo roundabouts due to the channelization (raised or flush) that discourages lane changing. This is facilitated by a series of **reinforcing signing and markings** in advance of the entry.
- **User Considerations and Experiences**
    - **Pedestrian and bicyclist** movements are not markedly different at the observed turbo roundabouts when compared to conventional roundabouts. Additionally, there are no special or different treatments present at turbo roundabouts than at other intersections.
    - **Large vehicles** such as buses and tractor-trailer trucks consistently clear turbo

[4] The information contained in this report do not necessarily reflect the opinions or policies of the North Carolina DOT, Minnesota DOT, or the City of Hilliard, Ohio.

roundabouts with little difficulty in the countries studied. However, these vehicles are typically smaller and potentially more maneuverable than the U.S. equivalents, which may influence the transferability of this finding. Mountable truck aprons are provided within the circulatory roadway and between adjacent legs.

- **Design Guidance**
    - A **radial entry alignment** is more typical for turbo roundabouts than a tangential alignment, with no observed or reported issues with speed transition and control.
    - The **inner lane in the circulatory roadway** has two typical design options: right-angled and rounded. These designs result in differences in observed lane discipline due to their impact on sight lanes and lane selection.
- **Retrofitting Modern Conventional Roundabouts to Turbo Roundabouts**
    - **Reducing lanes and conflict points** improves safety and operations.
    - **Low-cost modifications** can be made using marking, signing, and curbing.

Report Audience

This report is intended to inform U.S. practitioners and policymakers interested in assessing the applicability and suitability of turbo roundabouts within a transportation system. The findings contained in this report could be applicable to all levels of government: Federal, State, Tribal, regional, and local.

Introduction

Study Background and Context

The Federal Highway Administration (FHWA) conducted this study under the Global Benchmarking Program (GBP). The GBP serves as a tool for accessing, evaluating, and implementing proven global innovations that have the potential to significantly improve highway transportation in the United States (U.S.). The purpose of this study was to learn about international experiences with turbo roundabouts, a modified version of a multi-lane roundabout, to better understand the benefits and challenges of their implementation, to determine the availability and applicability of design guidance, and to identify opportunities for further turbo roundabout implementation in the U.S.

Study Motivation

FHWA undertook this study in response to the growing domestic interest in and installation of turbo roundabouts to combat the disproportionate number of property damage only (PDO) crashes at some U.S. multi-lane roundabouts. As of late 2023, there were four operational turbo roundabouts in the U.S. located in Jacksonville, Florida; Fort Lewis, Kansas; Delaware County, Ohio; and Hollister, California. Additionally, a conventional roundabout was retrofitted to a turbo roundabout in Bonita Spring, Florida in 2022. Some States have started to incorporate turbo roundabout design guidance into their design manuals, but more information is needed to determine best practices for entry alignment, circulating geometry, the use of channelization between lanes (raised and flush), accommodation of large vehicles such as commercial trucks, pedestrians and bicyclist features and use, and weather-related maintenance practices. A comprehensive understanding of best practices and lessons learned from countries with extensive turbo roundabout experience can help better assess when and how to implement turbo roundabouts in the U.S.

Study Team

The FHWA study team included the following members:

- **Jeffrey Shaw, Study Lead** – Intersections Program Manager, Safety Operations Team, Office of Safety Technologies, FHWA
- **Hillary Isebrands, Implementation Lead** – Senior Safety Engineer, Safety and Design Technical Services Team, Resource Center, Office of Technical Services, FHWA
- **Douglas Carter** – State Geometric Engineer, Minnesota Department of Transportation
- **Joseph Hummer** – State Traffic Management Engineer, North Carolina Department of Transportation
- **Letty Schamp** – Director of Transportation and Mobility, City of Hilliard, Ohio
- **Renée Blackburn, Report Lead** – Policy Analyst, U.S. DOT Volpe Center

See **Appendix A: U.S. Study Team Members** for additional information on the study team members.

Study Focus Areas

Focus areas for the study included the following:

- **Evaluation (Safety)** of how turbo roundabouts affect the frequency and types of crashes and other safety metrics.
- **Evaluation (Operations)** of the impact of turbo roundabouts on capacity, delay, and queuing.
- **Diverse User Needs**, including considerations for large trucks, motorcyclists, bicyclists, pedestrians, and those with additional accessibility needs.
- **Weather-Related Concerns and Maintenance**, particularly regarding the impact of raised features on snow removal and drainage.
- **Design Guidance** that incorporates contextual factors such as driving conditions and maintenance requirements.
- **Driver Education**, including traffic control devices, literature, and videos.
- **Conversions from Modern Conventional Roundabouts**, including cost considerations and impact on safety and operations.

A full list of the questions used to guide the study effort can be found in **Appendix B: Focus Questions**

Status of Roundabouts in the U.S.

The United Kingdom implemented the first modern roundabouts in the 1960s. In the U.S., the construction of roundabouts has grown steadily since the mid-1990s due to their safety record in reducing fatal and serious injury crashes.[5] Despite this growth, roundabout implementation in the U.S. has generally lagged that of many other countries. An analysis of roundabout data from 2014 found that the U.S. had one roundabout per 1,118 intersections, compared to Germany (one roundabout per 313 intersections), the United Kingdom (one roundabout per 127 intersections), and France (one roundabout per 45 intersections).[6] However, construction of roundabouts has been increasing over the last two decades. As of 2021, there were approximately 8,800 roundabouts in the U.S., and that number was estimated to surpass 10,000 in 2023.[7]

In general, single-lane roundabouts, which account for roughly 75% of the total roundabouts in the U.S., have been overwhelmingly successful in terms of safety and operational performance.[8] The success of multi-lane roundabouts, which account for the remaining 25% of the total roundabouts, has been less consistent. Multi-lane roundabouts have reduced fatal and serious injury crashes, which is the aim of the Safe System approach and the focus of Safety Performance Management in the U.S. , but an increase in

[5] "NCHRP Research Report 1043: Guide for Turbo Roundabouts" Retrieved from: https://nap.nationalacademies.org/catalog/27069/guide-for-roundabouts
[6] "Metcalfe, J. Why Does America Hate Roundabouts?" Retrieved from: https://www.bloomberg.com/news/articles/2016-03-10/mapping-america-s-resistance-to-traffic-roundabouts
[7] "Status of Roundabouts in North America, 2022 Edition" Retrieved from: https://trb.secure-platform.com/a/gallery/rounds/52/details/3462
[8] Ibid.

PDO crashes at some multi-lane roundabouts has hampered implementation in several jurisdictions. Research has shown that some multi-lane roundabouts with two entering lanes and two circulating lanes, commonly known as 2x2 roundabouts, are overrepresented for higher PDO crashes.[9] Examples of the types of crashes common at these roundabouts can be seen in **Figure 1** below.

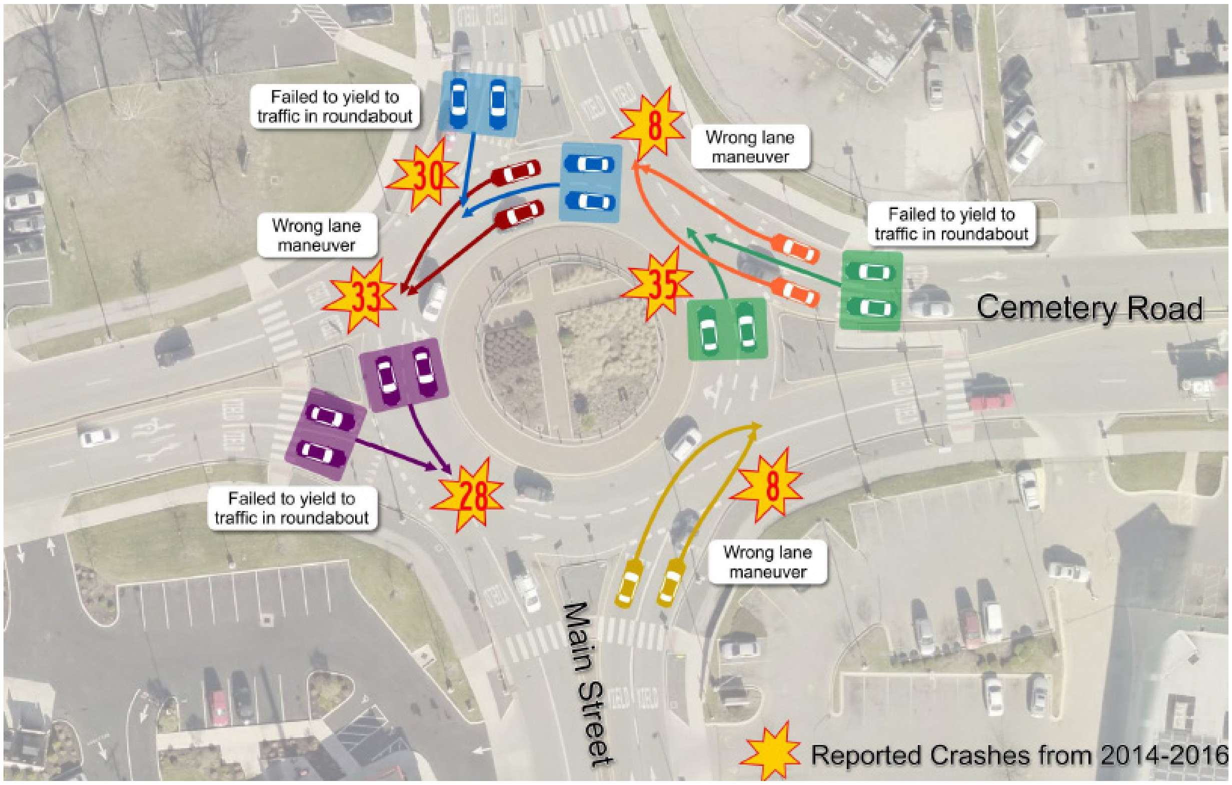


Figure 1: *Example 2x2 roundabout configuration (Hilliard, OH) (Source: City of Hilliard, OH)*

A high number of PDO crashes does not translate to poor safety, but it can erode public acceptance and threaten the implementation of highly successful roundabout designs that contribute to a safer transportation system. Some agencies have mitigated the "2x2 crash problem" by converting through lanes to turn-only lanes, reducing the number of lanes, enhancing pavement markings, and installing raised crosswalks. While these practices reduce conflict points and attempt to simplify a driver's decision-making, turbo roundabouts could offer a more efficient solution.

Overview of Turbo Roundabouts

Around 2000, when the U.S. published its first Roundabout Guide[10] and began more regularly implementing modern roundabouts, the Netherlands began modifying their designs to address, among other issues, the high frequency of crashes with multi-lane roundabout designs. The turbo roundabout evolved from the European radial roundabout entry design that mitigated the common crash types

[9] "Reasons for Drivers Failing to Yield at Multi-Lane Roundabout Exits: Transportation Pooled Fund Study Final Report." Retrieved from: https://rosap.ntl.bts.gov/view/dot/66498
[10] "Roundabouts: An Informational Guide" Retrieved from: https://www.fhwa.dot.gov/publications/research/safety/00067/00067.pdf

experienced at 2x2 roundabouts. **Figure 2** below indicates key turbo roundabout features, which include the following:

1. **One or more approach lanes.**
2. A **radial entry** alignment that proceeds into a spiral path along the circulatory roadway to encourage smooth flow.
3. **Robust and enhanced channelization** between lanes to reinforce lane discipline, discourage lane changing, and require drivers to select the proper lane prior to entering the roundabout. This channelization is always provided between the lanes in the circulatory roadway and is sometimes provided between the lanes on the entry approach. The channelization may be flush, such as widened pavement markings, or raised and mountable.
4. **Mountable aprons** in the central island or along the outside corner radius between adjacent intersection legs to offer needed maneuvering space for large vehicles such as buses and tractor-trailer trucks.

Turbo Roundabouts

The term "turbo" refers to the turbine-style geometric shape of the roundabout and **not** the speed of vehicles traveling through the roundabout. Their design has been developed to mitigate conflict points within the roundabout as a means toward improved safety performance relative to conventional multilane roundabouts. Turbo roundabouts operate similarly to modern multilane roundabouts, but they have several distinct geometric characteristics that provide safety enhancements to address conventional roundabout conflicts. Typical speeds are between 10-15 mph.

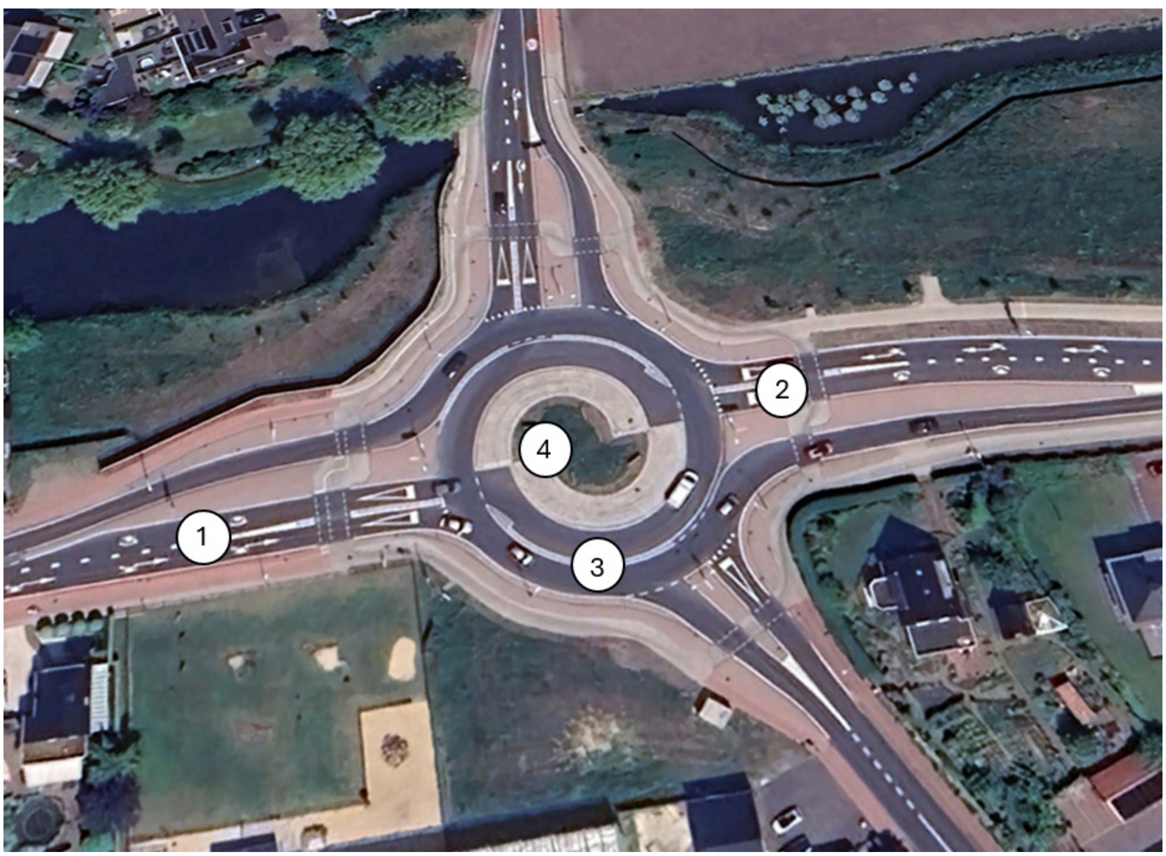


Figure 2: *Turbo roundabout features (Source: Google Earth; Annotations by FHWA)*

Over time, turbo roundabouts have continued to be adopted internationally to reduce entry, exit, and circulatory roadway lane-changing conflicts and associated PDO crashes; and, in some cases, to achieve better capacity due to improved lane utilization. The major differences between conventional roundabouts in the U.S. and turbo roundabouts are (1) the use of lane separation and channelization and (2) a radial approach alignment that results in a more compact entry conflict zone to improve safety for all road users while accommodating a range of traffic volumes and vehicle sizes. International adopters have noted a reduction in all types of crashes (fatal, injury, property damage), as well as increased capacity compared to conventional multi-lane roundabouts. With the proper application of turbo roundabouts in the U.S., the potential exists for capacity and safety improvements.

Those interested in learning more about the history and geometric design details of turbo roundabouts are encouraged to refer to FHWA's Advancing Turbo Roundabouts in the United States: Synthesis Report[11] and FHWA's Informational Primer on Turbo Roundabouts.[12]

[11] "Advancing Turbo Roundabouts in the United States: Synthesis Report." September 2019. Retrieved from: https://safety.fhwa.dot.gov/intersection/roundabouts/fhwasa19027.pdf
[12] "Turbo Roundabouts Informational Primer." Retrieved from: https://safety.fhwa.dot.gov/intersection/roundabouts/fhwasa20019.pdf

Preliminary Research and Field Study Preparation

Desk Review

The study team conducted a desk review to assess the current state of turbo roundabouts internationally and domestically. The desk review focused on design and implementation considerations among nine countries that have constructed turbo roundabouts on a significant scale or that have unique implementation circumstances of interest to the U.S.

The desk review gathered information from academic literature and government guidance documents, as well as interviews conducted with international transportation researchers and practitioners. This information was synthesized to:

- Document international literature and publications on turbo roundabouts.
- Identify locations where turbo roundabouts are being implemented.
- Compare turbo roundabout design and implementation among selected peer countries.
- Address topical knowledge gaps from a previously conducted turbo roundabout synthesis.
- Prioritize areas of interest and implementation challenges as focus areas for the in-person phase of the study.

To complete the desk review, the study team reviewed the development of guidance for turbo roundabouts in the countries of interest. The first design guidelines for turbo roundabouts were developed by the Dutch organization CROW in 2008. These guidelines have been used as the starting point for many other countries interested in implementing turbo roundabouts. Several countries have since developed their own guidance documents, including the Czech Republic, Poland, Slovenia, Germany, Serbia, and Croatia. In other countries, it is less clear if formal guidance has been published.

In Germany, a non-profit association known as the Road and Transportation Research Association (Forschungsgesellschaft für Straßen- und Verkehrswesen e. V., or FGSV) formed a working group in 2010 to develop national turbo roundabout guidelines. Since then, FGSV published draft guidelines in 2013 and an official working document on turbo roundabout use and design in 2015. Slovenia developed a draft version of technical specifications for turbo roundabouts in 2011, three years after the Dutch guidelines were published. At the time, the country had two turbo roundabouts in place. In the Czech Republic, the Brno University of Technology published design guidelines in 2015, and the Krakow University of Technology followed suit in Poland in 2022. Meanwhile, other European countries have designed their turbo roundabouts in accordance with Dutch or Slovenian guidelines.

A list of design guidelines and manuals by country can be found in **Appendix D**: Design Guidelines and Manuals.

Informational Meeting and Interviews

Virtual Meeting

In January 2023, the study team convened a meeting with international practitioners to provide an overview of the study effort and better understand turbo roundabout development in each country. This meeting was informed by individual interviews that occurred with international representatives during 2022.

During the meeting, researchers and practitioners from Germany, the Czech Republic, Poland, and the Netherlands met with the study team to discuss a series of questions related to the development and implementation of turbo roundabouts in their respective countries. The information provided during the virtual meeting included a broad range of implementation considerations, with a focus on road classification, speed limits, safety, and design considerations. Key points included:

- **Safety of Turbo Roundabouts**: Turbo roundabouts address specific conflict scenarios and crash types associated with conventional multi-lane roundabouts.
- **Turbo Roundabout Capacity**: The capacity of turbo roundabouts appears to be comparable to conventional multi-lane roundabouts but with advantages in optimizing lane utilization and reducing unnecessary lane changing that leads to operational turbulence.
- **Raised Lane Dividers**: The use of raised lane dividers as a means of channelization in turbo roundabouts varies among countries. For example, the Netherlands requires raised dividers, Germany uses only painted (flush) lane dividers, and Poland initially used only painted lane dividers before transitioning to both painted and raised dividers. Poland has since updated their design guidance to recommend raised lane dividers on new turbo roundabouts.
- **Bicyclist and Pedestrian Considerations**: Countries have varying approaches to designing for bicyclists and pedestrians in and around roundabouts. For example, the Netherlands gives vehicles priority outside of built-up areas, while bicyclists are given priority in built-up areas or are diverted to bicycle networks not tied to the roadway alignments. Germany prefers to physically separate modes at turbo roundabouts. Overall, European roadways are designed for all modes and reflect a culture of respecting and prioritizing bicyclists and pedestrians.
- **Speed Limits**: In the Netherlands, speed limits are typically 80 kilometers per hour (kph) (50 miles per hour (mph)) on non-motorways outside of built-up areas and reduced to 70 or 50 kph (45 or 30 mph, respectively) on approaches to junctions. Inside built-up areas, the speed limit is usually 50 km/hour (30 mph) with no reduced speed limit on approaches.
- **Traffic Control Devices**: The countries have specific signing and pavement markings at turbo roundabouts, with mostly standardized signing in the Netherlands and new guidelines defining markings in Poland.
- **Roundabout Evaluation**: In the Netherlands, a spreadsheet tool has been developed to assist in selecting the appropriate type of roundabout based on traffic volume.

Subject Matter Expert Interviews

Prior to the in-person study visits, the study team conducted a series of interviews with subject matter experts. A summary of those interviews is included below.

Germany

Turbo roundabouts were introduced in Germany in 2002. There are now approximately 34 that meet the country's turbo roundabout criteria (i.e., at least one inner lane addition at an entry, no spiral marking), although it can be difficult to properly classify roundabouts due to differences in individual designs. Common deviations from standard design recommendations include:

- zebra crossings present (not permitted at roundabouts with multi-lane entries and exits)
- lane changes allowed
- direction arrows on lanes
- diameter greater than 70 meters (m) (230 feet (ft)) or smaller than 45 m (148 ft)
- one entry or exit with an unusual design
- road islands for pedestrians between lanes of the same exit or entry

Some of Germany's turbo roundabouts are completely new, while others were converted from signalized intersections. Most of the turbo roundabouts are in suburban areas, connecting commercial/industrial areas with supra-regional roads; or urban areas, connecting regional or supra-regional roads with each other. Only a few are in rural locations where they connect a highway with supra-regional roads. Only two roundabouts include raised features due to concerns about weather, maintenance, and motorcycle safety. Germany does not have turbo roundabouts with more than two entry lanes. Other countries, such as the Netherlands, allow up to three lanes, but this design would likely require the use of raised lane dividers.

The interviewees reported that it is generally recommended that a turbo roundabout should only be planned if pedestrian and bicycle traffic in the two-lane entrances can take place in another level or route or at a (possibly signalized) crossing point away from the junction. For traffic safety reasons, bicycle traffic on the roadway is not recommended.

In Europe, trucks are frequently smaller than those in the U.S. and can travel through turbo roundabouts without moving into another lane.

During the interviews, it was noted that it can be difficult to measure the safety benefits of turbo roundabouts due to limited data and that the number of crashes varies significantly between different roundabouts. It was also mentioned that there is not readily available information about driver education for turbo roundabouts, and overall, public reaction has been neutral.

Netherlands

In the Netherlands, the primary motivations for implementing turbo roundabouts are safety, capacity, space, and cost. Many of the country's existing turbo roundabouts were retrofitted from conventional roundabouts, and almost all use raised lane dividers.

The maximum approach speed is 80 or 100 kph (50 or 62 mph) in rural areas and 100 kph (62 mph) on connecting roads, where the roundabout shields (signs) cover the horizon from afar to reduce speed to about 36 kph (22 mph) near the entry. For urban areas, the maximum approach speed is 50 kph (31 mph). Speeds at a conventional two-lane roundabout would be above 30 or 40 kph (19 or 25 mph).

Snowplows are fitted with rubber flaps to prevent damage to the road surface. They are not often used, but when they are, they are small enough to navigate turbo roundabout lanes. The same is true for street sweepers.

Selection of Focus Countries and Organizations

Based on the initial research findings, the study team selected Poland, the Czech Republic, and the Netherlands for the in-person study. These countries offered a diverse set of turbo roundabout experiences within the team's areas of interest, including design guidance, diverse user needs, weather-related concerns and maintenance, performance evaluation, and conversions from other roundabouts. Key factors for the selection of each country, as well as the host organizations of interest within each country, are summarized below:

Poland

Poland began implementing turbo roundabouts in 2006 and now has nearly 200 in operation. Turbo roundabouts are currently considered the standard design choice for two-lane roundabouts. Poland's early turbo roundabouts did not incorporate raised lane dividers; however, they are now recommended for new roundabouts. The country's approach to retrofitting conventional multi-lane roundabouts and addressing weather-related operations and maintenance concerns were also of interest to the study team.

Host Agencies:

- The General Directorate for National Roads and Motorways (Generalna Dyrekcja Dróg Krajowych i Autostrad, or GDDKiA): GDDKiA is an agency subordinate to the Ministry of Transportation and is responsible for construction, maintenance, road safety, and traffic management on national roads in Poland. It is also responsible for Poland's national road system and influences national road transportation policy, including recommendations, requirements, and maintenance for turbo roundabouts.
- Krakow University of Technology: Researchers at the Krakow University of Technology have conducted extensive research on turbo roundabout safety, operations, and design and developed Poland's turbo roundabout design guidelines.

Czech Republic

As of 2023, there were 29 turbo roundabouts in the Czech Republic. The Czech turbo roundabout guidelines are based on those of the Netherlands and recommend raised lane dividers. However, the Czech Republic utilizes wider lane widths than are typical in other European countries, which is relevant to the U.S. context and the need to accommodate large freight vehicles. The Czech Republic also has experience addressing weather-related concerns such as snow removal.

Host Agencies:

- Transport Research Center (Centrum Dopravního Výzkumu, or CDV): CDV is a public research institution that has conducted extensive safety reviews of turbo roundabouts in the Czech Republic.
- Brno University of Technology: The Faculty of Civil Engineering at the Brno University of Technology developed the Czech Republic's turbo roundabout design guidelines.

- Road and Motorway Directorate (Ředitelství Silnic a Dálnic, or RSD): The RSD is a state-owned enterprise that manages motorways in the Czech Republic.

Netherlands

The turbo roundabout originated in the Netherlands in 1999, and the country currently has the largest number of turbo roundabouts in the world (approximately 396). Dutch standards are well-developed and are frequently used by other European countries in their design and construction guidelines. Furthermore, the Netherlands is experienced in developing pedestrian and bicyclist infrastructure, including roundabouts with at-grade pedestrian and bicyclist crossings, a key area of interest for the study team.

Host Agencies:

- Rijkswaterstaat: Rijkswaterstaat is responsible for public works and water management in the Netherlands, including the design, construction, management, and maintenance of infrastructure projects.
- Delft University of Technology (TU Delft): TU Delft is a public technical university. Their researchers have conducted several studies on the design and operations of turbo roundabouts.
- CROW: CROW is a non-profit agency with extensive transportation planning and engineering expertise. They are responsible for the development of turbo roundabout guidelines in the Netherlands.
- Office of the Province of South Holland: This office is responsible for the operation and maintenance of turbo roundabouts within its jurisdiction.
- Rotterdam University of Applied Sciences: The Rotterdam University of Applied Sciences is a vocational university. Their staff have expertise in civil and traffic engineering and have experience working on turbo roundabouts at the municipal level.

Germany

While not selected for an in-person visit due to logistical considerations, the study team also conducted additional virtual engagement with Germany. Due to weather-related concerns, maintenance considerations, and motorcycle safety concerns, Germany generally does not use raised channelization features. Out of at least 19 turbo roundabouts, Germany has just two turbo roundabouts with raised features. Additionally, due to bicyclist and pedestrian safety concerns, Germany currently only recommends using turbo roundabouts for junctions outside of built-up (i.e., urban) areas or in areas that are transitioning to a built-up area. Like the Netherlands, Germany recommends that, if possible, pedestrian and bicyclist facilities should be separate from the roadway or at signalized crossings. Germany does not recommend the turbo roundabout as a pedestrian safety countermeasure.

Study Findings

This section summarizes the information gathered during the in-person meetings and site visits in Poland, the Czech Republic, and the Netherlands.

Safety Performance

Previous research findings indicate that turbo roundabouts have the potential to offer several safety improvements compared to conventional multi-lane roundabouts.[13] These may include reduced vehicular speeds through the intersection, reduced or modified conflict points, a more compact conflict zone at the entry to the roundabout, improved lane discipline where raised lane dividers are used, and higher driver yielding rates to pedestrians and bicyclists. The study team noted the following observations with respect to turbo roundabout safety performance:

- **Crash Reporting**: When reviewing safety data, it is important to note that many countries do not collect data on PDO crashes, making comparisons to the U.S. context challenging. This underreporting is largely due to cost constraints associated with reporting crashes that do not result in injuries or fatalities. However, it was consistently explained that safety assessments of turbo roundabouts versus conventional multi-lane roundabouts in the countries visited showed decreases in fatal and severe injury crashes.

- **Crash Type**: The more compact conflict zones and presence of lane dividers at turbo roundabouts can lead to fewer crashes involving entering, circulating, and exiting maneuvers.

- **Modal Representation in Crashes**: In the Netherlands, bicyclists and moped riders tend to use the same facilities and are often reported together in crash statistics. At turbo roundabouts where bicyclists and moped riders have priority (i.e., inside built-up areas), they account for more than 50% of the crashes that also involve cars. At locations where they do not have priority, the same crash reduction occurs as for other traffic.

  When the turbo roundabout was introduced, there was concern that raised channelization could cause safety concerns for motorcyclists. To mitigate these risks, warning signs were used to alert drivers to the presence of raised dividers. After implementation of the turbo roundabouts, it was observed that the risk of crashes was considerably lower for motorcyclists, which was a significant benefit. A known risk to motorcyclists has been the potential for skidding on pavement markings, so the Dutch guidelines do not recommend pavement markings for compact turbo roundabouts.

[13] "Turborotonde en turboplein: Ontwerp, capaciteit en veiligheid (Turbo Roundabout and Turbo Circle: Design, Capacity, and Safety)." 2012. Retrieved from: https://doi.org/10.4233/uuid:e01364ce-78de-465b-a8c8-39e28a4585dd

Operational Performance

All three study countries acknowledged that it is difficult to collect the necessary data to assess changes in operational performance resulting from implementing turbo roundabout design features. However, existing observational and qualitative data do provide some understanding of the potential improvements. The study team observed the following themes regarding the operational performance of turbo roundabouts:

- **Improved Operational Capacity:** Based on the site visit observations and discussions with international transportation officials and subject matter experts, the team found that movement through and around turbo roundabout intersections is greatly improved compared to conventional roundabouts. Turbo roundabout design features can address many issues stemming from saturated flows, queueing lengths, and critical gaps. Overall, turbo roundabouts may improve the operational capacity of a conventional multi-lane roundabout with positive impacts to movements through and around the intersection.

  For example, in Wroclaw, Poland, the team observed a turbo roundabout near an airport that had been retrofitted from a poorly operating standard multi-lane roundabout. The roundabout had a history of congestion challenges and unbalanced lane utilization that caused queues of up to more than 2 kilometers (1.2 miles) long. Following the conversion to a turbo roundabout and the addition of right-turn bypass lanes, queue lengths were greatly reduced, and drivers made improved lane selection choices due to advance signing.

- **Fewer Legs, Better Efficiency:** Officials in Poland determined that too many legs on a turbo roundabout greatly reduces the efficiency of the intersection. This is because drivers must process more information to navigate the intersection to their desired destination with several more vehicles entering and exiting simultaneously. Due to this impact, Polish road authorities noted that, when possible, they will avoid building more than four legs on a turbo roundabout.

- **Improved Freight Efficiency:** The team observed that turbo roundabouts facilitated efficient movement of freight through the intersections, using both outside and inside lanes and mountable truck aprons. The team visited turbo roundabouts located near major intermodal logistics facilities with sustained high volumes of trucks and observed no evidence of related problems. However, large trucks have different dimensions, particularly the cab and location of the kingpin, that make them more maneuverable than large trucks in the U.S.

- **Environmental Benefits**: The Netherlands has demonstrated the public health benefits of all types of roundabouts, including reduced emissions and air pollution. When comparing signalization to roundabouts, the latter produce 29% less CO_2 and 21% less NO_x due to reduction of idling and trip times of vehicles. [14]

[14] "SWOV Fact Sheet: Roundabouts and other intersections." June 2022. Retrieved from: https://swov.nl/en/fact-sheet/roundabouts-and-other-intersections

Methods and Effectiveness of Lane Separation

Enhanced lane separation, also referred to as lane dividers or channelization, on the approaches and in the circulatory roadway is a critical component of turbo roundabout design and perhaps one of the most obvious distinctive characteristics. This separation may be created through enhanced (wide or buffered) pavement markings or slightly raised, curb-like mountable treatments.

During the site visits, various methods of lane separation were observed by the study team. The effectiveness of lane separation on lane discipline was as expected: the more substantial the separation design, the slower the overall speeds and the better drivers would conform to the proper lane use on the approach and within the intersection. Based on this behavior, the countries visited generally expressed a preference for raised lane dividers over painted lane dividers. Since speed control, and potentially more PDO crashes, occur when drivers do not demonstrate lane discipline, this could be a key safety consideration when retrofitting existing conventional multi-lane roundabouts or developing plans for new turbo roundabouts. The team also observed the benefits of incorporating raised lane dividers on the approach to the roundabout to emphasize lane separation prior to entry. However, a lane divider should not be so high that damage to a vehicle would occur if it were run over. In the Netherlands, a height of 7 centimeters is standard.

Basic Lane Markings

In general, the locations observed by the study team used more lane-use arrow markings in a series than is typical in the U.S. This is discussed further later in this section in combination with signing. Regarding longitudinal markings, the study team visited several sites that had been retrofitted to varying degrees, including some sites that made small changes to the approach and interior geometry but otherwise retained basic lane separation markings as seen in **Figure 3**. Consistent with expectations, these more modest and limited retrofit changes produced less robust effects on driver behavior, with numerous observed instances of poor lane discipline and path overlap.

Figure 3: *Example of approach lane markings in Poland (Source: FHWA)*

Flush or Painted Lane Separation Markings

The study team visited several locations with painted lane dividers, which often took the form of widened markings (Poland: red or white paint; Netherlands: white paint) as shown in **Figure 4**. The team noted that drivers' compliance with painted lane separation varied depending on certain contextual factors, including vehicle volumes, signing and markings, speed control, and overall size of the roundabout. Painted lane dividers were more successful at smaller turbo roundabouts that operated at or near capacity. Higher traffic volumes made it more difficult for drivers to change lanes. Speed control and lane discipline can be expected to diminish with the use of painted lane dividers rather than raised separation.

Figure 4*: Examples of painted lane separation markings in the circulatory roadway in Poland (Source: FHWA)*

Raised Separation

In all three countries, raised lane dividers were used to reduce vehicle speed and achieve lane discipline more effectively. Agencies generally found that these features improved the likelihood of a driver staying within the chosen lane to their desired destination while posing low risk to two-wheeled motorized vehicles. When Poland began retrofitting multi-lane roundabouts into turbo roundabouts, road authorities, researchers, and practitioners found that painted lane dividers were not as effective at reducing crashes and consequently established policies that all newly retrofitted or constructed turbo roundabouts require raised dividers. Polish representatives noted their success with mountable raised forms of separation, with a preference for those constructed with precast concrete or granite versus rubberized or plastic material alternatives. Those alternatives proved to be less durable and required more intensive maintenance and replacement. **Figure 5** shows an example of a plastic divider that failed and resulted in maintenance challenges, while **Figure 6**, **Figure 7**, **Figure 8**, and **Figure 9** depict more durable dividers in varying locations.

Figure 5*: Example of a plastic raised divider that failed in Poland (Source: FHWA)*

Figure 6: *Raised channelization in the circulatory roadway at a rounded inner lane center island in the Netherlands (Source: FHWA)*

***Figure 7**: Raised channelization in the circulatory roadway at a rounded inner lane island in Poland (Source: FHWA)*

***Figure 8**: Raised channelization at the exit of a turbo roundabout in the Czech Republic (Source: FHWA)*

Figure 9: *Raised channelization on the exit (forefront), entrance (near truck), and circulatory roadway with a right-angle inner lane in the center island in the Netherlands (Source: FHWA)*

Some sites also incorporated raised lane dividers within approaches to separate inner and outer entries into the circulatory roadway (see **Figure 10**). The study team noted that, given that radial entries are the most common type of entry to a turbo roundabout, this practice is easier to implement as drivers are not approaching turbo roundabouts on a curve. Emphasizing correct lane assignments prior to entry also helps drivers make decisions further from the entry to the roundabout.

Figure 10*: Example of basic pavement markings and a raised lane divider within the approach in the Netherlands (Source: FHWA)*

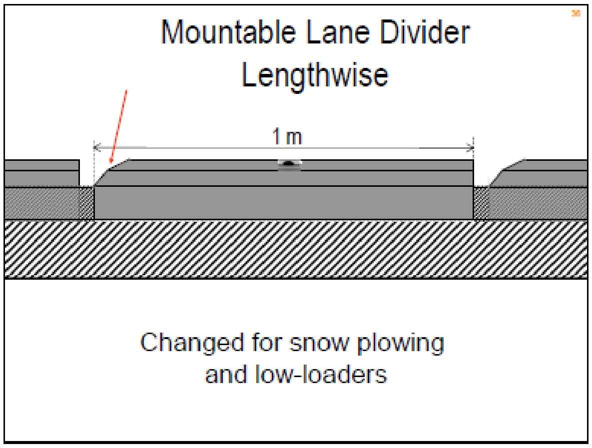


***Figure 11:** A diagram of a mountable lane divider (Source: Bertus Fortuijn)*

Polish road authorities have studied and refined maintenance operations to accommodate plowing operations in turbo roundabouts with raised lane dividers. The likely amount of snow and duration of snow events needs to be considered. In areas where there is no frost in the ground, snow events typically result in only minimal or modest accumulation, and temperature fluctuations result in snow melting within hours or a few days. In these cases, raised lane dividers remain the preferred method of lane separation. Ideally, the cross-sectional design and material composition of the dividers should mimic a truck apron, as shown **Figure 11**, which can withstand snowplow activity. In areas where snow events occur more frequently and the roads may be snow covered for weeks or months, raised lane dividers may not always be practical due to the impact on winter maintenance activities, unless the design is fully plowable and maintenance staff have been consulted during design.

In addition to snow removal, other maintenance concerns with raised lane dividers include drainage and litter/debris removal. Each of the countries visited used different longitudinal and cross-sectional designs to allow water and debris to drain to the outside of the roundabout. Most designs provided segmental raised lane dividers to allow water to pass and did not require additional drainage structures. Designers should factor in the design of raised lane dividers into their overall drainage design of the roundabout. Consideration should also be given to drainage concerns in the circulatory roadway to minimize ponding of slow-moving water and the shoulder seasons' cycle of daytime thaw and nighttime re-freeze of runoff.

Signing and Pavement Marking Practices

As with all road design, the signing and pavement markings need to complement and reinforce the design to effectively communicate to drivers. At the turbo roundabouts visited by the study team, the importance of advanced messaging was apparent for considering human factors and helping drivers make decisions early and more confidently while approaching and navigating the roundabout. All three countries had slightly different recommendations for general turbo roundabout signing and pavement marking design criteria; however, this was mostly due to the built environment and what communication was determined to be effective to drivers in each location. Despite the differences, there was consensus that:

- A series of pavement marking arrows based on lane assignment, corridor speeds, and expected queue lengths should be used in advance on approaches.
- Signing and pavement markings should be complementary. Enhanced signing, such as both left- and right-side installations, or overhead lane assignment signing, can provide additional benefits to the driver.
- Markings and signing should be consistent across locations. Based on the sites visited by the study team, it was evident that treatments typically evolve over time with growing turbo roundabout experience.

Advance Signing and Marking Techniques

Discussions with country representatives found that there is a strong emphasis on advance signing and pavement markings at all intersections. All three countries emphasized that the use of multiple sets of lane-use arrows on approaches, as well as a confirmation set within the circulatory path, is crucial for lane compliance. Each country had slightly different recommendations for the number of sets of lane arrow pairings in each approach lane, but the decision is generally guided by the normal queue length for each lane. Overall, the team observed the use of a significantly higher number of lane-use arrow pavement markings (in some cases eight or more sets) on the approaches to turbo roundabouts, conventional roundabouts, and non-roundabout intersections than would be customary in the U.S.

The team also noted that lane-use arrow pavement markings were not consistent from one location to the next: some locations had standard arrows, others had fish-hook arrows, and some used both. The study team noted that this is also an issue in the U.S., and that for turbo roundabouts, it will be important to understand whether different types of arrows influence drivers' lane selection decisions. Areas with lower demand require fewer markings and less signing, while higher demand areas need more of both, especially if queueing occurs. With very high demands, overhead lane assignment signing on approaches provides additional benefits. Additionally, redundancy in marking signing is generally important in rural and isolated areas as posted speeds are typically higher.

Signing and Pavement Markings at Entries, Exits, and in the Center Island

Clear navigation information at entries and exits is needed to ensure that drivers reach their chosen exit without changing lanes after entering the turbo roundabout.

Figure 12: *Large center island signing (outlying area) in the Netherlands (Source: FHWA)*

In the Netherlands, the team observed the use of the "shield" sign assembly, which consists of a circulation sign bordered by chevron arrows on both sides placed in the central island across from the entry lanes and directly in the line of sight to approaching drivers (**Figure 12**, **Figure 13**). While all sites visited used red-on-white chevrons (**Figure 14**, **Figure 15, Figure 16**), there was some variation in the number and arrangement. Additionally, the team learned that research into crashes on curves of 80 kph roads has shown that blocking visibility by shielding the horizon is a very effective means of preventing serious crashes. Therefore, roundabout shields in the central island should screen the horizon from afar as seen from the motorist's perspective.

Figure 13: *Large center island signing (urban context) in the Netherlands (Source: FHWA)*

Figure 14*: A series of large chevrons in the center island at a roundabout in Poland (Source: FHWA)*

Figure 15*: Large directional arrows in the center island of a retrofit turbo roundabout in a freight corridor in Poland (Source: FHWA)*

Figure 16*: Example of entry signing and markings at a turbo roundabout in Poland (Source: FHWA)*

Figure 17: Series of approach pavement markings (distance based on expected queue length) in Poland (Source: FHWA)

User Considerations and Experience

Pedestrian and Bicyclist Facilities and Crossings

A key study focus area was strategies for pedestrian and bicyclist facilities at turbo roundabouts. In the U.S., pedestrian safety and the expanding network of bicycle facilities necessitate that turbo roundabouts, just like all other intersection designs, must be introduced with such vulnerable road users in mind.

Figure 18: *Example of pedestrian and bicyclist road marking in Poland (Source: FHWA)*

Cultural Influences and Non-Motorized Users

An important consideration for road safety are the cultural expectations of how drivers, pedestrians, and bicyclists should interact. Poland, the Czech Republic, and the Netherlands all noted that policy changes and culture shifts played a role in improving safety for pedestrians and bicyclists. For example, Poland has implemented sizable financial penalties for drivers who do not yield to pedestrians in marked crosswalks. In the Netherlands, it was explained that there is a general assumption that in the case of a vehicle-bicyclist crash, the responsibility lies almost entirely with the driver. These policies, laws, and cultural norms inform the population that pedestrians and bicyclists are vulnerable road users and should be prioritized and respected. The team noted that, almost uniformly in the locations visited, drivers showed considerable deference to them while walking through sites and when bicycling.

Research conducted by the Netherlands Organisation for Applied Scientific Research has shown that road users respond primarily to the 'shark's teeth' on the road surface that indicate the need to yield the right of way. The safety issues in providing bicyclists with priority is not that motorized traffic is unaware that bicyclists have priority, but that the steering task distracts drivers from noticing cyclists from different directions.

Types and Locations of Observed Crossings

The study team observed many locations that had pedestrian crosswalks in contexts similar to U.S. conditions, although the driver yielding rates were higher in the visited countries. In the Netherlands, the extensive separated bicycle networks often crossed turbo roundabouts and had two different priority rule scenarios – one where bicycles yield to vehicles, and one where vehicles yield to bicycles – depending on the context. While the use of two priority scenarios at crossings makes sense from a traffic engineering perspective based on modal demands, the team perceived that it was challenging for drivers to process the specific scenario and act accordingly in real time.

In cases where facilities were separated, the bicycle lanes were often colored red, as shown in the figures below. In all cases, the country representatives stressed the importance of crosswalk visibility, sight distance, speed control, and compliance with traffic laws, while also acknowledging the cultural differences between Europe and the U.S. The Netherlands has found raised crosswalks, as shown in **Figure 20**, to be a sufficient traffic calming device for both pedestrian and driver safety due to speed control before entering the circulatory road.

Figure 19: *Typical separated pedestrian and bicycle facilities on the approaches to roundabouts in the Netherlands (Source: FHWA)*

Figure 20: *Rural turbo roundabout with a rounded inner lane center island in Poland (Source: FHWA)*

Figure 21*: Raised pedestrian and bicycle crossing in the Netherlands (Source: FWHA)*

Figure 22: *Pedestrian crossing near a large transit transfer center in the Czech Republic (Source: FHWA)*

Figure 23*: Separated pedestrian and bicycle pathway crossings in Poland (Source: FHWA)*

Figure 24: *Separated pedestrian and bicycle pathway crossings in Poland (Source: FHWA)*

Figure 25: *Pedestrian and bicyclist crossings (from bicyclist perspective) in the Netherlands (Source: FHWA)*

Transit Accommodations

In the Czech Republic, the study team observed two turbo roundabouts with electrified "trolley-style" buses, including one at a transit hub (**Figure 25**). Both turbo roundabouts were high-volume.

Figure 26: *A transit vehicle navigating a turbo roundabout in the Czech Republic (Source: FHWA)*

Freight and Large Vehicles

The study found that turbo roundabout designs can effectively accommodate larger trucks as well as buses and large agricultural equipment. In each of the three countries, larger commercial vehicles were observed successfully navigating turbo designs, including traveling side-by-side. The Netherlands provided specific design vehicles to use for different elements of turbo roundabout designs (retrofitting, reconstructing, or new installations), including buses up to 45 ft and large trucks up to 62 ft.

Figure 27: *Exit ramp from a major motorway in Poland (Source: FHWA)*

***Figure 28**: Vehicles traveling side-by-side with raised channelization in the Netherlands (Source: FHWA)*

***Figure 29:** A truck traveling through a turbo roundabout interchange with raised channelization in the circulatory roadway in Poland*

The study team also observed how trucks, buses, and larger commercial vehicles complied with lane separations when navigating around the circulatory roadway. Most drivers had good lane discipline and did not have side-by-side navigation issues (e.g., braking or letting others move forward before they did), which shows that drivers were confident in making their movements. Many locations also accommodated larger commercial vehicles with inner or outer truck aprons using granite blocks, cobblestones, concrete, or channelization, which allow fewer opportunities for lane encroachment.

Despite these promising results, it is important to consider differences in vehicle size between the U.S. and Europe as shown in **Figure 29** below. The study team found that while the overall dimensions of European trucks were similar to U.S. trucks, the tractor style (cab-over vs. cab-behind), and the location of the kingpin and the EU tractors' ability to move the kingpin toward the cab or back toward the trailer based on the configuration of the trailer greatly decreased off-tracking and external apron needs. The location of the rear tandem axles on the trailers were also flexible based on likely destinations and roadway configurations. The flexibility in tractor and trailer configurations made it easier for the drivers to negotiate more compact circulatory paths.

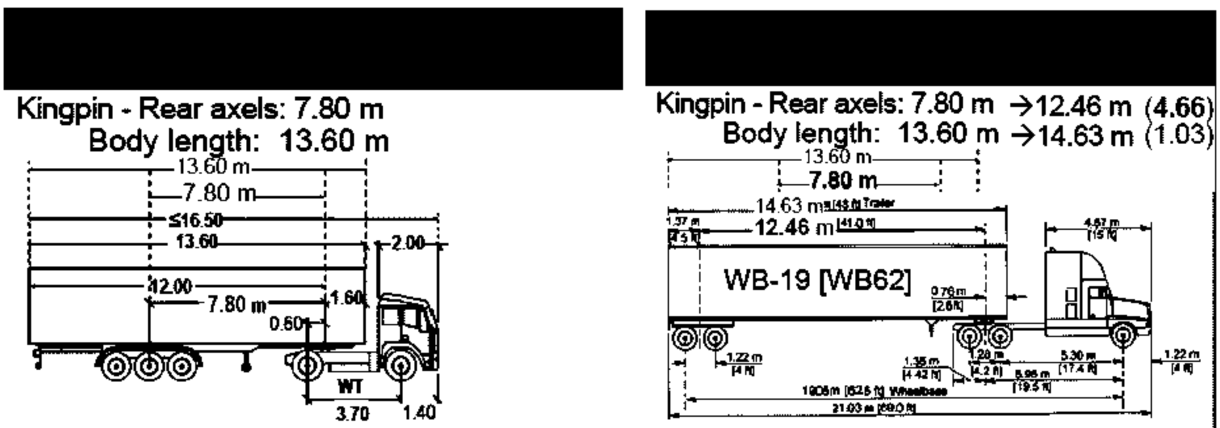


Figure 30*: Comparison of standard truck dimensions in Europe and the U.S. (Source: Dr L.G.H. Fortuijn compiled on the basis of European legislation regarding vehicle dimensions and dimensions for the maximum swept path (left); NCHRP Program Report 505 Figure 10 (right))*

Design Guidance

Entry and Circulation Geometrics

Radial versus tangential entries and effects on safety and operations

The turbo roundabouts visited by the study team were mostly radial entry designs, as opposed to the tangential style common in the U.S. It was evident that utilizing radial entry designs for turbo and non-turbo single lane roundabouts helps reduce the overall footprint of the approach and the roundabout and results in more speed control on entry, which is also beneficial overall for pedestrian and bicyclist crossings.

Shape of interior lane (right angled, rounded) and effect on driver/user behavior

The study team observed that the shape of the inner circulatory lane affected driver behavior. When meeting with representatives from the Netherlands, the consensus was that a right-angled design had become preferable to a rounded design (**Figure 30**). The sites visited in all countries included both types. The study team observed that the right-angled design helped make it clear at the entry point which lane to proceed to from the yield line.

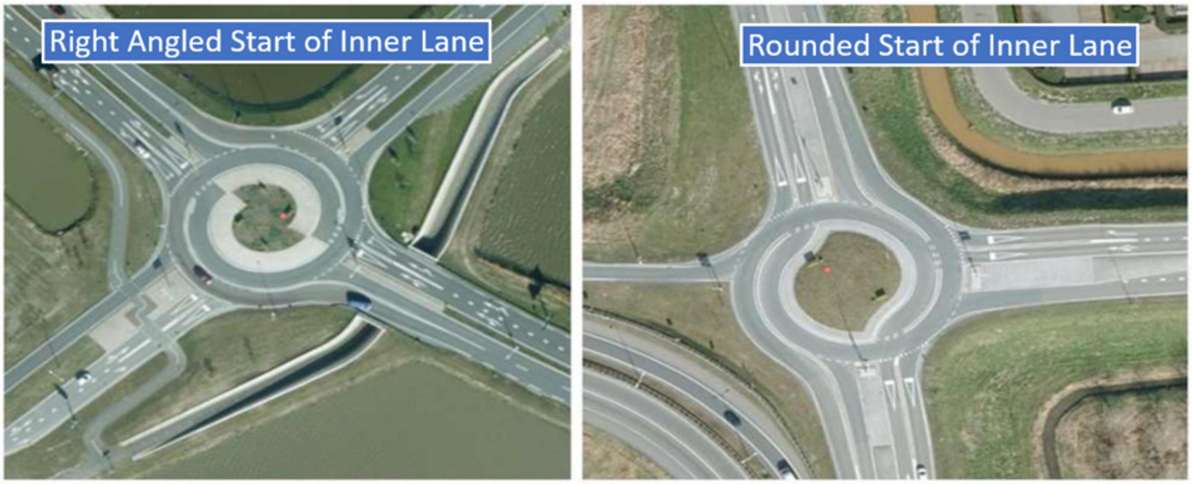


Figure 31*: An aerial comparison of right-angled and rounded inner lane designs (Source: Google Earth)*

The shape of the inner lane can also influence driver sight lines and intuitive path as shown in **Figure 31** below.

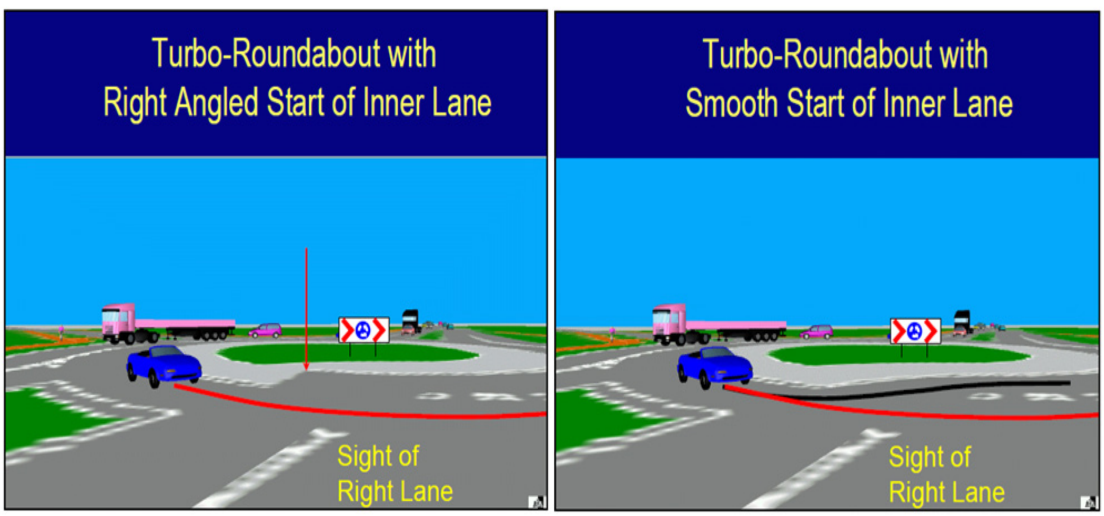


Figure 32: *Comparison of driver sight lines based on angle of inner lane (Source: Bertus Fortuijn)*

Width of splitter island and effects on driver/user behaviors

Wider splitter islands with either hardened pavement markings or concrete and curb were installed at locations where pedestrian and bicyclist crossings were present. If neither mode were crossing, splitter islands were significantly reduced with radial entries ultimately reducing the amount of space required for the roundabout. Reducing the splitter island widths, however, did appear to have a negative impact on gap acceptance and capacity of the roundabout. In locations where splitter island widths were narrow, it was difficult for an entering vehicle to distinguish between a vehicle exiting downstream or a vehicle continuing to circulate.

When retrofitting from a conventional multi-lane roundabout, splitter islands should be reconfigured so the approaches lead to a more direct, radial entry (or more closely aligned as such). The Netherlands shared that retrofitting to this type of radial entry approach with splitter islands resulted in a reduced crash rate as drivers have more visibility and can more easily move forward into the inner lane instead of changing to the inner lane of the circulatory path.

Retrofitting Modern Conventional Roundabouts to Turbo Roundabouts

The study team visited several turbo roundabouts which had been retrofitted from conventional multi-lane roundabouts that were experiencing PDO crashes.

Observed Projects

The team observed retrofits in all three countries. Many conventional roundabouts have been retrofitted to reduce the number of circulating lanes and conflicts as well as to add channelization. This was typically achieved by reducing the minor street approach to one entering lane; the second lane was either eliminated completely or converted to a right turn only lane.

In one notable location at an interchange near the airport in Wroclaw, Poland, the conventional roundabout had a recurring, extended queue (>2km) that would regularly back up onto the high-speed motorway. This 3-legged intersection was retrofitted from a conventional 2X2 multi-lane roundabout to a 2X1[15] turbo roundabout, along with the addition of right-turn bypass lane from the motorway. The retrofit changes resolved the recurring queue concern.

Figure 33: *A retrofitted turbo roundabout near Wroclaw, Poland (Source: FHWA)*

[15] A 2x2 roundabout has two entering lanes and two circulating lanes, while a 2x1 roundabout has two entering lanes and one circulating lane.

The study team also visited another roundabout outside of Wroclaw in an industrial area with significant development and freight movements. The original design was a full 2X2 with a 76 m (250 ft) inscribed circle diameter. This design resembled some of the early multi-lane roundabouts built in the United States. The retrofit is a 2X1 that operates more safely and efficiently due to reduced lane changing and weaving, and better overall lane utilization.

Figure 34*: Ground level and aerial views of a retrofitted turbo roundabout near Wroclaw, Poland (Source: FHWA and Google Maps)*

Varying Extent of Retrofits

The study countries demonstrated different approaches to retrofitting, ranging from adding or modifying pavement markings to installing permanent changes such as aprons, vertical tube delineators, and curbing. There were often differences between sites in the use of signing and pavement markings, especially on the approaches, to encourage proper lane selection based on the downstream destination and to optimize lane utilization for operational efficiency. In most cases, lanes and capacity were reduced in retrofits, but with the result of improved operations.

Temporary materials were sometimes used to study functional operation and design capacity of retrofitted turbo designs in multi-lane roundabouts to inform final design decisions or future changes. It was a great benefit to the study team to witness this interim decision-making in person. The Polish retrofit turbo roundabouts featured temporary materials like paint, raised vertical delineators and preformed curbs, and temporary portable barriers.

Permanent implementation costs for retrofitting multi-lane roundabouts to turbo designs can be considered, but often low-cost treatments can be deployed quickly. Representatives from road authorities in Poland noted that they cannot always afford to rebuild or reconstruct multi-lane roundabouts, so the organization focuses on repainting to accommodate turbo design modifications. These road authorities also utilize partnerships with private developers and other stakeholders on road design projects. This process allows the road authorities to have authority to choose a turbo roundabout option over other intersection control strategies since they will ultimately own and maintain the site.

As demonstrated by several designs the team visited, the associated costs of retrofitting may be less of a burden if existing curb lines and drainage can be maintained. In Poland, there were turbo roundabout designs that were able to leverage maintenance funds because the proposal was relatively inexpensive and only required new pavement markings. The study team was able to verify that such modifications are feasible and allow for designers and stakeholders to understand the safety and operational implications of such a modification.

Figure 35: *Examples of temporary lane delineators used to retrofit roundabouts in Poland (Source: FHWA)*

Overall Observations and Findings for the U.S. Context

Turbo roundabouts have been an established roundabout alternative in the Netherlands for nearly two decades. Poland, Germany, and other European countries followed the Netherland's lead with implementation of this modified roundabout design that featured raised and widened channelization on the approaches and in the circulatory roadway as well as a modified center island design. The turbo roundabouts were observed to have reduced PDO crashes while maintaining the safety benefits of significant reductions in fatal and injury crashes compared to conventional intersection designs.

The FHWA GBP study on turbo roundabouts resulted in many valuable observations and findings. Lessons learned from early turbo roundabout adopters in the Netherlands, Poland, and Czech Republic provided data and information on key safety, design, and operational elements that increased confidence about the transferability of turbo roundabouts to the domestic context, while acknowledging that certain factors will require further investigation and deliberation among the U.S. practitioner community.

Key observations from the study countries and the associated considerations for the U.S. include the following:

- **Safety Performance:** Turbo roundabouts were developed and adopted within the Netherlands, Poland, and the Czech Republic due to their ability to preserve the reduction of fatal and injury crashes associated with roundabouts generally while also reducing PDO crashes associated with multi-lane roundabouts, to keep people in the correct lanes on the approach and within circulatory roadway, and to reduce conflict points. At the observed locations, pedestrians, bicyclists, freight vehicles, transit vehicles, and motor vehicles navigated turbo roundabouts slowly, efficiently, and safely. The safety performance of turbo roundabouts is consistent with what agencies are seeking in the U.S.

- **Operational Performance:** The study team observed that the turbo roundabouts were efficient during peak and off-peak periods for all users. U.S. agencies will need local data on gap acceptance and follow-up times to be able to accurately model the performance of proposed turbo roundabouts. Modeling tools currently used in the study countries could help the U.S. evaluate turbo roundabouts more accurately in the future.

- **Methods and Effectiveness of Lane Separation:** In the study countries, turbo roundabouts with raised and painted (flush) were observed. Raised lane dividers resulted in consistent speed control and lane discipline. Painted (flush) lane dividers were used at some locations where raised features could not reasonably be implemented, at retrofitted roundabouts, or at roundabouts installed prior to the use of raised dividers being standard practice. The team observed trade-offs in speed control and lane discipline at those locations, especially during non-peak periods. For U.S. implementation, the design and specifications for raised or painted lane divider features on the approach or in the circulatory roadway should be examined with respect to motorcyclist safety.

Routine (daily and seasonal) and long-term maintenance practices for turbo roundabouts were widely accepted throughout the visited countries. Specification and design of the channelization materials and layout was done with maintenance consultation. Findings from the study suggest that raised lane dividers should be made of durable materials to reduce maintenance, and longitudinal breaks in the raised channelization are needed to allow for the water runoff. Further study on cross-sectional and longitudinal design of raised features would be beneficial to account for needs related to drainage, snow, ice, and plowing in the U.S.

- **Signing and Pavement Marking Practices:** Pavement marking on the approaches included a series of lane use arrows that began at a distance representative of the typical queue length. This appeared to aid in the early selection of the drivers desired lane and destination. Proper lane selection on the approach prior to the entry is more critical for turbo roundabouts due to the channelization that discourages lane changing.

  Robust center island signing provided conspicuity of the intersection and was consistent in the study countries. Although the types and number of signs were different from one country to the next, they were all visible from the approaches. Additionally, high visibility crosswalk and bike lane markings across the approaches (entry and exit) were robust.

- **User Considerations and Experience:**
  - Pedestrian and Bicyclist Facilities and Crossings: Existing policies and pedestrian- and bicyclist-friendly cultures in the study countries clearly resulted in intersection and roadway environments where all users could navigate safely and efficiently. The U.S. continues to improve conditions for pedestrians and bicycles, but continued education, outreach, and policies around yielding behaviors are needed.

    The observed pedestrian and bicyclist crossings had high visibility markings on the approaches with generous crossing widths to accommodate pedestrian and bicyclist volumes. In all intersection designs, regardless of traffic control, the pedestrian and bicyclist movements were separated at the crossings on the approaches. In many cases, the countries provided parallel bike pathways that allowed bicyclists to not queue or mix with vehicles and pedestrians, especially for right turn movements. Recent research and publications in the U.S. document pedestrian and bicyclist crossing infrastructure as noteworthy practices, and these features have begun to be implemented by some agencies.

    Raised crosswalks were observed at numerous turbo and conventional roundabouts. The Netherlands has found raised crosswalks to be a sufficient traffic calming device for both pedestrian and driver safety due to speed control before entering the circulatory road. Additional consideration for raised crosswalks at any multi-lane entry to slow vehicle speeds and to address accessibility requirements in the U.S. is encouraged.

- Freight and Large Vehicles: Differences in design vehicles, particularly large vehicles and trucks (e.g., cab, length, axle arrangement, and kingpin distance) will affect the design and performance of turbo roundabouts in the U.S. as compared to other countries.

- **Design Guidance:** All three study countries have design guidance that prioritizes single lane roundabouts; if a multi-lane roundabout is needed based on traffic volumes, a turbo roundabout will be designed and built. This practice excludes the implementation of conventional multi-lane roundabouts.

  The study team observed several design features that influence the performance of turbo roundabouts. Key geometric elements, such as splitter island width and the shape of the inner lane, influenced the human factors associated with gap acceptance, yielding, capacity, and proper navigation of the turbo roundabout.

  Throughout the study countries, radial approaches were used to create a significantly smaller conflict zone for a vehicle to maneuver when entering the roundabout, which influenced overall roundabout capacity due to the change in the gap needed to enter. The use of a radial approach, as opposed to the tangential approach (with deflection) that is common in the U.S, would require a shift in thinking in terms of impacts on speed control, capacity, and concerns about drivers incorrectly turning left.

  At the observed locations, the right-angle and rounded inner lanes both commanded lower speeds (10-15 mph) on entry as compared to tangential multi-lane designs (15-25 mph). Speed reduction on the approaches was similar to that of stop and signal control intersections.

- **Retrofitting Conventional Roundabouts to Turbo Roundabouts:** Retrofitting conventional roundabouts to turbo roundabouts was common in the study countries. The retrofits consisted of a reduction in lanes through pavement markings and curbing and additional channelization on the approaches and in the circulatory roadway. Most of the retrofits were done with low-cost modifications and resulted in more efficient roundabouts, reduction in PDO crashes, and reduced conflict points. Retrofitting existing multi-lane roundabouts in the U.S. could be a feasible option to reduce PDO crashes.

In summary, the study resulted in numerous findings of successful implementation of turbo roundabouts that are relevant and transferable to the practice in the U.S. The study team will continue to evaluate the study findings and their applicability to the U.S over the coming years.

Appendix A: U.S. Study Team Members

Jeffrey Shaw, PE, serves as the Intersection Safety Program Manager for the Federal Highway Administration, Office of Safety. In this role, he manages programs, projects and products of national interest that are intended to enhance intersection safety. He is a registered professional engineer in Illinois and a board-certified Professional Traffic Operations Engineer and Road Safety Professional. He serves as co-Chair of the TRB Performance Effects of Geometric Design Committee and represents FHWA on the PIARC World Road Association Road Safety Technical Committee.

Hillary Isebrands, PE, PhD, has thrived in the engineering profession for over 27 years. Hillary has expertise as a leader, teacher, roadway design and safety engineer, and transportation researcher. She is currently a Team Leader and Senior Roadway Safety Engineer with the FHWA Resource Center - Safety and Design Team. She specializes in technical assistance and instruction of roadway design and safety courses, including modern roundabouts, and local and rural roads., Hillary also oversees the cooperative agreement for the National Center for Excellence for Rural Road Safety. Prior to FHWA, Hillary worked as a researcher at the Iowa State University, Center for Transportation Research and Education and was a highway designer and project manager at an engineering consulting firm in WI. Hillary is a Professional Engineer, a National Highway Institute (NHI) Certified Instructor, the 2019 FHWA Engineer of the Year, and the 2020 Top 10 Federal Engineer of the Year. She is the Chair of the Transportation Research Board (TRB) Standing Committee on Roundabouts and Other Intersections, and a Member of the TRB Rural Transportation Issues Coordinating Council.

Letty Schamp, PE, is the Director of Transportation & Mobility for the City of Hilliard, Ohio. She oversees transportation planning; budgeting and implementation of the city's transportation capital improvement program, including all pedestrian and bicycle infrastructure; traffic engineering and safety programs; and asset management of the local transportation system. Letty holds a Bachelor's Degree in Civil Engineering from The Ohio State University and is a registered Professional Engineer in the State of Ohio.

Douglas Carter, PE, LEED, AP, is the State Geometric Engineer, has 25 years of experience in road design, and has worked for the State of Minnesota for 13 years. His private sector experience and technical background include geotechnical and dam engineering, Superfund site assessment, and LEED-accredited water resource design. Doug graduated from Seattle University with a Bachelor's Degree in Civil Engineering and a minor in Chemistry. Doug races Cyclecross with his two children in his spare time.

Joseph E. Hummer, PhD, PE, is the State Traffic Management Engineer with the North Carolina Department of Transportation in the Mobility and Safety Division. He specializes in alternative intersection and interchange designs and recently developed an interest in automated vehicles. He began researching alternative designs in 1990, has published numerous articles about them, and has invented several new designs. On automated vehicles, he is the author of the 2020 book "Driverless America" that forecasts life after widespread deployment. Joe spent most of his career as a Professor at North Carolina State University before serving as Chair of Civil Engineering at Wayne State University. He returned to North Carolina and joined the NCDOT in 2016 to work on the implementation of new ideas.

Renée Blackburn, PhD, is a Policy Analyst at the U.S. DOT Volpe Center, supporting projects related to Vision Zero, the Safe System approach, and the National Park Service. Prior to joining the Volpe Center, she worked at the NHTSA as a Regional Program Manager (RPM), providing technical assistance and grants management and oversight to State Highway Safety Offices. In her work, she supported Federal, State, and local partners with assistance in areas such as pedestrian and bicycle safety, occupant protection and child passenger safety, and public health-based approaches to traffic safety. She also oversaw the Federal-level management and oversight of a State Highway Safety Plan.

She is a graduate of MIT with a PhD in the Program in History, Anthropology, and Science, Technology, and Society, where she completed a dissertation on the intersections and effects of community-based activism in public policy decision-making and technology development in the United States. She also holds an MS from Michigan Technological University and a BA from Oakland University.

Appendix B: Focus Questions

The following questions were developed to clarify the study team's main areas of interest. These questions were provided to host agencies to make them aware of the topics, issues, and subject areas the study team was most interested in and to serve as a framework for discussion.

- **Design Guidance**
    - Does design guidance for turbo roundabouts differ for different contexts, i.e., rural/suburban/urban intersections or freeway interchanges? Do most of your country's turbo roundabouts fall on only certain road classification types or are they found throughout the road network hierarchy and land use contexts?
    - Does design guidance for turbo roundabouts in your country address trade-offs between vulnerable road users and large vehicles? How do you balance the competing needs of these road users in your turbo roundabout designs?
    - Are there still cases where a conventional (non-Turbo) roundabout design would be chosen as an alternative instead of a Turbo Roundabout design, or have Turbo Roundabouts become the sole option where multiple lanes are needed?
    - Can you help us identify any available published design criteria, guidelines, standards, or specifications on Turbo Roundabouts used in your country at any level – national, regional, provincial, or local?
    - Can you provide any recent examples of project-level final plans, specifications, and special provisions for one or more Turbo Roundabout projects?

- **Diverse User Needs**
    - What Turbo Roundabout design elements are most often the source of controversy or dispute between different types of users, e.g., vehicles vs. ped-bike, or large trucks (similar to U.S. WB-67 class) vs. motorcycles?
    - In the U.S., there are groups that advocate specifically for the interests of pedestrians, bicyclists, and motorcyclists. Do such groups exist in your country, and if so, have they ever provided feedback (positive or negative) about their experiences with Turbo Roundabouts?
    - In the U.S., there are civil rights laws that govern accessibility requirements for users of all abilities, such as wheelchair users or individuals with limited or no vision. Does your country have similar accessibility requirements, and if so, what requirements are there for Turbo Roundabouts?
    - Do you know of any examples where a Turbo Roundabout was designed (or retrofitted later) specifically to accommodate very large trucks (similar to the U.S. WB-67 class) and oversized freight (such as special loads like wind turbine blades)?
    - Do the raised lane dividers typically used with turbo roundabouts present any observed or perceived safety concerns for motorcyclists?

- **Driver Education**

- In the U.S., for traffic control devices such as signs and pavement markings, there is the Manual on Uniform Traffic Control Devices, which stipulates the minimum requirements and also provides for optional treatments. For the customary traffic signs and pavement markings at Turbo Roundabouts in your country, which are "mandatory" minimums that are always required and which are "optional" enhancements?
- When a Turbo Roundabout is constructed in a community for the first time, is there any special public education or awareness campaign that is done prior to opening?
- Do you have print or video materials for community education?
- Have you found that drivers in your country find turbo roundabouts to be "intuitive" and easier to navigate than conventional multi-lane roundabouts?
- Are there published laws or rules regarding Turbo Roundabouts that are different from other roundabouts and intersections?

- **Weather-Related Concerns and Maintenance**

  - Do turbo roundabouts create any unique drainage concerns, and if so, how were those concerns mitigated?
  - Clearing debris and garbage from the raised features?
  - Do the additional features needed for channelization and raised dividers require more frequent maintenance or repair?

- **Evaluation (Safety)**

  - Are there published studies available from your country that provide a basis for a safety comparison involving Turbo Roundabouts, such as a crash modification factor (or crash reduction factor)? Do these studies differentiate between property damage only crashes and injury or fatal crashes?
  - The primary basis of speed control for conventional roundabouts in the U.S. is approach and entry geometry (curvature and deflection on entry). Do you have any studies of speeds with the radial entries used with Turbo Roundabouts compared to similarly sized conventional roundabouts with curved entries?
  - Was property damage only (PDO) crash history at conventional multi-lane roundabouts the primary reason that turbo roundabouts were implemented in your country or were there other factors?
  - In locations where a turbo roundabout replaced a conventional roundabout, did PDO crash frequency and/or crash rate go down? Do you have any before-after data?
  - If you have turbo roundabouts without raised lane dividers, does weaving or lane changing still occur? Does a lack of raised channelization/dividers contribute to higher occurrences of entry-circulating crashes?
  - Do you have any turbo and conventional roundabout intersections that have similar traffic volumes and contextual setting? If yes, what is the comparative crash history between the two types of roundabouts (PDO and F/SI)?
  - Are there published case studies or presentations available about Turbo Roundabout projects in your country?

- **Evaluation (Operations)**
    - Are there published studies available from your country that provide a basis for operational comparison involving Turbo Roundabouts, such as for capacity, delay, and queuing?
    - What capacity analysis software do you use?
- **Conversions from Other Roundabouts and Traffic Circles**
    - Do you have an inventory, or select examples, where turbo roundabouts were constructed to replace an existing conventional roundabout or other type of intersection?
- **Cost and Right-of-Way Impacts**
    - Do you have capital construction cost information from recent turbo roundabout projects? Do you have any general information about how their costs compare to other intersection types?
    - With respect to overall footprint and necessary right-of-way, in your experience how do turbo roundabouts compare to equivalent conventional multi-lane roundabouts? If more is required for Turbo Roundabouts, does this affect the decision about whether or not to install?
    - How does the land acquisition process work in your country? Are eminent domain and condemnation used to acquire land for transportation purposes? Is the process time-consuming and if so, are there ways to reduce that time (in the U.S., some agencies can use a "quick take" process for certain projects)?
    - Is there a higher emphasis on private property owner rights/impacts or public good in your country?

Appendix C: Reference Materials

Anagnostopoulos, A., & Kehagia, F. (2018). Turbo-Roundabouts as an Alternative to Roundabouts in terms of Traffic Safety, Capacity, and Pollutant Emissions. *7th Pan-hellenic Road Safety Conference*. Larissa, Greece. Retrieved from https://www.researchgate.net/publication/332529517_Turbo-Roundabouts_as_an_Alternative_to_Roundabouts_in_terms_of_Traffic_Safety_Capacity_and_Pollutant_Emissions

Brilon, W. (2011). *Studies on roundabouts in Germany: lessons learned*. Carmel, Indiana.: 3rd International TRB Conference on Roundabouts. Retrieved from http://www.teachamerica.com/RAB11/RAB11Papers/RAB1122Brilon-0097.pdf

Caltrans. (2022). *Highway Design Manual*. Retrieved from https://dot.ca.gov/-/media/dot-media/programs/design/documents/chp0400-a11y.pdf

de Baan, D. (2021, December 27). *Number of 'spotted' turbo roundabouts*. Retrieved from https://www.dirkdebaan.nl/locaties.html

Džambas, T., Ahac, S., & Dragčević, V. (2017, February). Geometric Design of Turbo Roundabouts. *Tehnicki Vjesnik, 24*(1), 309-318. doi:10.17559/TV-20151012162141

eKapija. (2022, April 7). This is What Novi Sad Waterfront Might Look Like in Rough Outlines – Turbo Roundabouts to Be Implemented. Belgrade, Serbia. Retrieved from https://www.ekapija.com/en/news/3651974/this-is-what-novi-sad-waterfront-might-look-like-in-rough-outlines

Elhassy, Z., Abou-Senna, H., & Radwan, E. (2021). Performance Evaluation of Basic Turbo Roundabouts as an Alternative to Conventional Double-Lane Roundabouts. *Transportation Research Record, 2675*(7), 180–193. doi:https://doi.org/10.1177/0361198121994838

Engelsman, J. C., & Uken, M. (2007). Turbo Roundabouts as an Alternative to Two Lane Roundabouts. *Proceedings of the 26th Southern African Transport Conference*, (pp. 581-589). Pretoria, South Africa. Retrieved from http://www.lags.corep.it/doc/turbo-roundabout.pdf

Federal Highway Administration. (2019). *Turbo Roundabouts: Informational Primer*. Federal Highway Administration, Safety Program. Retrieved from https://safety.fhwa.dot.gov/intersection/roundabouts/fhwasa20019.pdf

Fortuijn, L. G. (2009). Turbo roundabouts: Design principles and safety performance. *Transportation Research Record: Journal of the Transportation Research Board, 2096*(1), 16-24.

Fortuijn, L. G. (2011). Roundabouts in the Netherlands, Development and experiences. TU Delft. Retrieved from https://nmfv.dk/wp-content/uploads/2012/06/RDC_Netherlands_2.pdf

GDOT, G. (2021). *Roundabout Design Guide*. Retrieved from http://www.dot.ga.gov/PartnerSmart/DesignManuals/Alternative%20Intersections/GDOTRoundaboutDesignGuide.pdf

Krivda, V., Petru, J., Macha, D., Plocova, K., & Fibich, D. (2020). An Analysis of Traffic Conflicts as a Tool for Sustainable Road Transport. *Sustainability, 12*(17), 7198. doi:https://doi.org/10.3390/su12177198

Lingwood, P. (n.d.). Union Street roundabout: Turbo-style roundabouts - the future? Bedford Borough Council. Retrieved from University College London: https://www.ucl.ac.uk/transport/sites/transport/files/patrick_lingwood.pdf

Macioszek, E. (2013). Turbo roundabouts signing and marking - current situation in Poland. *Archives of Transport System Telematics, 6*(1), 27-31. Retrieved from https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.884.5234&rep=rep1&type=pdf

Metcalfe, J. (2016, March 10). Why Does America Hate Roundabouts? *CityLab*. Bloomberg. Retrieved from https://www.bloomberg.com/news/articles/2016-03-10/mapping-america-s-resistance-to-traffic-roundabouts

National Academies of Sciences, Engineering, and Medicine. (2010). *Roundabouts: An Informational Guide*. Washington, D.C.: The National Academies. doi:10.17226/22914

Overkamp, D. P., & van der Wijk, W. (2009). *Roundabouts-Application and design, A practical manual*. Royal Haskoning DHV. Ministry of Transport. Public Works and Water management, Partners for Roads. Retrieved from https://puc.overheid.nl/rijkswaterstaat/doc/PUC_138926_31/

Petru, J., & Krivda, V. (2021). An Analysis of Turbo Roundabouts from the Perspective of Sustainability of Road Transportation. *Sustainability, 13*(4). doi:https://doi.org/10.3390/su13042119

Porter, R., Gooch, J., Peach, K., Chestnutt, C., Moore, B., Broeren, P., & Tigelaar, J. (2019). *Advancing Turbo Roundabouts in the United States: Synthesis Report*. Federal Highway Administration. Retrieved from https://safety.fhwa.dot.gov/intersection/roundabouts/fhwasa19027.pdf

Schmitt, D. (2022, September 29). (R. Blackburn, Interviewer)

Silva, A., Santos, S., & Gaspar, M. (2013). Turbo-roundabout use and design. *CITTA 6th Annual Conference on Planning Research, Responsive Transports for Smart Mobility*. Retrieved from https://www.dec.uc.pt/~abastos/Outputs/congressos%20nacional/Citta2013_turbo.pdf

Skvain, V., Petru, J., & Krivda, V. (2017). Turbo-Roundabouts and their Basic Evaluation at Realized Constructions in Czech Republic. *190*, pp. 283-290. Procedia Engineering. Retrieved from https://doi.org/10.1016/j.proeng.2017.05.339

Smělý, M., Patočka, M., Radimský, M., & Apeltauer, J. (2015). *The Methodology for designing of turbo-roundabouts*. VUT Brno.

Stephenson, E. (2020, May 29). *UK-first changes to Ashford's busiest roundabout*. Retrieved from KCC Media Hub: https://kccmediahub.net/uk-first-changes-to-ashfords-busiest-roundabout745

Tollazzi, T. (2014). *Alternative Types of Roundabouts: An Informational Guide*. London: Springer.

Tollazzi, T., Mauro, R., Guerrieri, M., & and Rencelj, M. (2015). Comparative Analysis of Four New Alternative Types of Roundabouts: "Turbo," Flower," Target" and "Four-Flyover" Roundabout. *Periodica Polytechnica Civil Engineering, 60*(1), 1-10.

Tollazzi, T., Turnšek, S., & Renčelj, M. (2012). Slovenian Experience with Turbo-Roundabouts. *e-ZBORNIK*(3). Retrieved from https://e-zbornik.gf.sum.ba/images/radovi/e_zbornik_03_01.pdf

Tollazzi, T., Zgrablić, T., Bergoč, J., & Renčelj, M. (2020). Comparative Analysis of "Turbo", "Reduced-Turbo", "Flower" and "Semi-Turbo" Roundabout. *Tehnički vjesnik, 27*(5), 1410-1417. doi:https://doi.org/10.17559/TV-20190131115411

Troncoso, R. (2022, February 10). *They call it a 'turbo roundabout'; drivers may call it confusing*. Retrieved from WJCT News: https://news.wjct.org/first-coast/2022-02-10/they-call-it-a-turbo-roundabout-drivers-may-call-it-confusing

Vos, C. (2016, January 31). *Analyse verkeersveiligheid turborotondes*. Retrieved from https://www.dirkdebaan.nl/blog/effecten-realisatie-turborotonde-onderzocht

Wankogere, E. J., Kwigizile, V., Oh, J.-S., & Ikonomov, P. (2017). Comparison of Driver Navigation at Turbo Roundabouts and Modern Two-Lane Roundabouts: Simulation Study. *Transportation Research Record: Journal of the Transportation Research Board*, 89-98. doi:https://doi.org/10.3141%2F2637-11

WVU Today. (2022, February 7). *WVU engineer exploring American implementation of newer, safer 'turbo roundabout'*. Retrieved from WVU Today: https://wvutoday.wvu.edu/stories/2022/02/07/wvu-engineer-exploring-american-implementation-of-newer-safer-turbo-roundabout

Appendix D: Design Guidelines and Manuals

Croatia

- *Smjernice za projektiranje kružnih raskrižja sa spiralnim tokom kružnog kolnika na državnim cestama* (Guidelines for Design of Roundabouts with Spiral Circulatory Roadway on State Roads). 2014. https://hrvatske-ceste.hr/hr/stranice/tehnicka-dokumentacija/dokumenti/45-smjernice-za-projektiranje-kruznih-raskrizja

Czech Republic

- The Methodology for Designing of Turbo-roundabouts. VUT Brno. 2015.

Germany

- Arbeitspapier Turbokreisverkehre (Working Document on Turbo Roundabouts). FGSV, 2015
  - Turbo Roundabouts: https://www.fgsv-verlag.de/ap-turbokreisverkehre
  - Construction of Roundabouts: https://www.fgsv-verlag.de/anlage-von-kreisverkehren
  - Guidelines for the Construction of City Streets: https://www.fgsv-verlag.de/rast

Finland

- Turbo-Kiertoliittymän Suunnittelu (Turbo-roundabout Design): https://julkaisut.vayla.fi/thohje/ttiens/tts_89.pdf

The Netherlands

- Roundabouts – Application and Design (English language). 2009 https://www.debaanverkeersadvies.nl/uploads/1/0/0/5/10059444/manual_roundabouts_final.pdf

Poland

- Polish guidelines on intersections Wytyczne Projektowania Skrzyżowań Drogowych. Część II. GDDP, Warszawa (2001).

Serbia

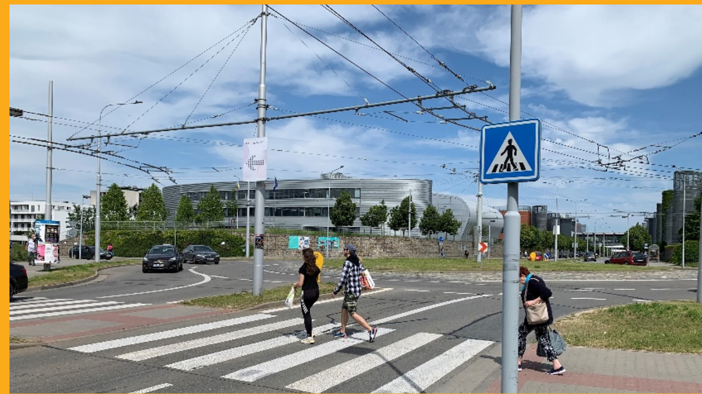
- Priručnik za projektovanje puteva u Republici Srbiji, Dio 5.3 Kružne raskrisnice (Manual for Road Design in Republic of Serbia, Part 5.3 Roundabouts). 2012 https://www.putevi-srbije.rs/images/pdf/harmonizacija/prirucnik_za_projektovanje_puteva/SRDM5-3-kruzne-raskrnice(120427-srb-konacni).pdf

Slovakia

- Technické Podmienky Projektovanie Turbo-Okružných Križovatiek (Technical Conditions Design of Turbo Roundabouts), 2018. https://www.ssc.sk/files/documents/technicke-predpisy/tp/tp_100.pdf
- Dodatok c. 1 Projektovanie turbo-okruznych krizovatiek (Appendix 1 Design of Turbo Roundabouts), 2018. https://www.ssc.sk/files/documents/technicke-predpisy/tp/tp_100_dodatok_1_2018.pdf

Slovenia

- Krožna križišča s spiralnim potekom krožnega vozišča (Roundabouts with a Spiral Course of the Circulatory Roadway). Ministry of Transport Republic of Slovenia, TSC 03.XXX, draft version, 2011. https://www.gov.si/assets/organi-v-sestavi/DRSI/Dokumenti-DRSI/Tehnicne-specifikacije/TSC_03_341_2011_Krozna_krizisca.pdf



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