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Unconventional Roundabouts: Third-Generation Insights from the United States and Europe

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Abstract

This paper presents a comparative analysis of unconventional roundabouts, commonly referred to as third-generation roundabouts, based on case studies from the United States and Europe, specifically Croatia and Italy. These intersection designs deviate from traditional circular geometries to overcome limitations in safety, capacity, and spatial integration, especially in constrained or high-demand environments. The study focuses on three major typologies: raindrop, turbo, and two-geometry roundabouts (TGRs), examining their geometric characteristics, operational principles, and context-specific implementations. Based on real-world examples and qualitative assessments, each national section investigates design rationale and performance considerations in relation to local traffic dynamics. The paper contributes to the understanding of adaptive and context-sensitive intersection design, offering a conceptual framework for comparing unconventional roundabout typologies across different regulatory environments. The comparative analysis reveals that each typology responds to specific operational and spatial constraints rather than representing a universally optimal solution. In particular, raindrop and dog-bone roundabouts are most effective in interchange contexts, turbo roundabouts enhance safety and capacity in regulated multilane environments, while TGRs provide greater adaptability in constrained and irregular urban settings. These findings highlight the importance of context-dependent design strategies and support the need for flexible and context-sensitive evaluation frameworks.

Keywords: roundabout evolution; raindrop roundabout; dog-bone roundabouts; turbo roundabout; two-geometry roundabout; adaptive intersection design; international case studies

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1. Introduction

Unconventional roundabouts are innovative intersection configurations that deviate from traditional circular designs to improve traffic flow, safety, and spatial efficiency.

These solutions are typically adopted in contexts where conventional one- or two-lane roundabouts are no longer adequate due to site-specific constraints, such as high traffic volumes, complex geometric layouts, or the presence of multimodal transportation. The main reasons for implementing unconventional roundabouts arise from the limitations of conventional designs when applied to such conditions. These disadvantages are often reflected in low levels of traffic safety and limited operational capacity, prompting the need for more adaptive and context-sensitive approaches [1–5]. Unconventional roundabouts belong to the so-called "alternative", or "third-generation" roundabouts. These terms are generally used to describe any deviation from the conventional circular design, whether through geometric innovation, traffic control enhancements, or multimodal integration [6,7]. The "first generation" refers to the old rotaries with large diameters, where yield is to the entries. The "second generation" refers to modern circular roundabouts with yield-to-circulating-traffic and compact geometries [6].

Several typologies of unconventional roundabouts have been introduced over the years to address specific functional and spatial challenges, such as dumbbell, raindrop, dog-bone, turbo, elliptical, and two-geometry roundabouts (TGRs). Dumbbell roundabouts consist of two conventional roundabouts connected by a short straight road section. Raindrop roundabouts feature an asymmetric raindrop-shaped central island [8–10], while dog-bone roundabouts consist of two raindrop-shaped channelized islands at either end of a connecting roadway segment [9]. Turbo roundabouts are multilane roundabouts that guide vehicles through entry and spiral lanes on the circulatory roadway separated by raised mountable lane dividers [11–15]. Elliptical roundabouts feature an elliptical central island and a uniform elliptical crown of constant width [16,17], while TGRs are characterized by an elliptical outer carriageway edge and a circular central island and provide variable lane widths [17–20]. Each of these innovative designs represents a distinct solution for balancing road safety requirements with operational efficiency and spatial constraints.

The research question that motivated this investigation was how national specificities and spatial contexts dictate the applicability, design, and effectiveness of third-generation roundabouts. To answer this question, the study systematizes the selection, design, and implementation criteria for third-generation roundabouts across diverse traffic environments, based on existing literature and documented applications. Through a comparative analysis of international experiences, this study seeks to identify the main advantages and specific limitations of these solutions in relation to specific traffic challenges, including high traffic volumes, unbalanced flow distributions, complex intersection geometries, and the presence of heavy vehicles or multimodal users. The working hypothesis was that third-generation roundabouts can enhance safety and traffic flow; however, their successful implementation relies heavily on adapting them to local spatial constraints, requiring a standardized yet flexible approach to evaluation methodologies. Unlike a purely descriptive review, this study adopts a structured comparative approach, in which real-world case studies are used as analytical units to identify recurring design principles, operational patterns, and context-dependent performance characteristics across different national frameworks. In this sense, the contribution of the paper lies not only in documenting existing applications, but in providing a cross-context interpretation of unconventional roundabout typologies, highlighting both common trends and systematic differences.

Despite these contributions, the growing body of literature on unconventional roundabouts still presents several limitations. First, most existing studies focus on individual typologies or specific national contexts, limiting the possibility of cross-national comparison and reducing the transferability of design insights. Second, the applicability of these configurations under different traffic and spatial conditions is not systematically addressed, as many contributions rely on isolated case studies or context-specific analyses. Third,

the long-term performance and broader operational implications of emerging designs remain only partially explored, mainly due to the limited availability of consistent empirical datasets. In this context, the present study aims to address these limitations by providing a structured comparative analysis of three representative unconventional roundabout typologies across different national frameworks. By explicitly linking geometric design features to operational and contextual conditions, the study supports a more systematic and context-sensitive understanding of their applicability.

In this regard, the study focuses on three countries, the United States, Croatia, and Italy, because each provides a consolidated and well-documented reference case for one of the main unconventional typologies examined. The United States offers mature applications of raindrop and dog-bone layouts, Croatia represents one of the most structured European contexts for turbo roundabouts thanks to dedicated national guidelines, and Italy provides several real-world implementations of TGRs, a configuration that has recently gained growing technical and academic interest. This selection enables a coherent examination of three distinct design approaches that are already established in practice and that reflect different cultural, regulatory, and geometric interpretations of unconventional roundabout design.

Following these considerations, the international comparison developed in this paper is structured around three specific typologies of unconventional roundabouts, raindrop/dog-bone, turbo, and TGR, examined respectively through case studies in the United States, Croatia, and Italy. This country–typology correspondence reflects the presence of well-established real-world implementations in each context, which ensures that the analysis is grounded in documented design practices and operational evidence.

The research methodology is based on the critical synthesis and induction of existing publicly available high-quality literature, design guidelines, orthophotography maps, satellite imagery, and official design documents. The qualitative assessment was conducted through a structured comparative analysis of selected case studies, in which each roundabout typology was examined according to a consistent set of geometric and operational criteria. These criteria include overall shape, central island configuration, circulatory lane geometry, U-turn capability, key geometric features, and typical application contexts. The visual documentation was systematically collected and organized to support the interpretation of geometric configurations and operational characteristics and to ensure coherence in the cross-case comparison. Through this approach, a conceptual framework for the design–operational nexus was established, enhancing the transparency and reproducibility of the analytical process.

The remainder of the paper is organized as follows. Following this introduction, Section 2 briefly outlines the historical evolution of unconventional roundabouts and performs a short literature review. Section 3 presents basic design criteria, capacity estimation procedures, and case examples for each of the three selected countries. Section 4 offers a comparative discussion, highlighting key findings from each experience, performance differences, design trade-offs, and the broader strengths and limitations of these unconventional roundabouts. Finally, Section 5 concludes with a synthesis of results and practical insights, outlining directions for future research and applications.

2. Evolution of Unconventional Roundabouts

Roundabout design has undergone a long evolutionary process, beginning with early circular intersections of the 20th century and gradually evolving into the modern roundabout, as defined by contemporary guidelines [6]. While conventional single-lane and two-lane roundabouts are now widely implemented worldwide, their limitations, especially in terms of safety and capacity, have prompted the development of alternative, or unconventional, designs [1–3].

Historically, the first significant shift occurred in the United Kingdom in the 1960s, with the introduction of modern roundabout principles emphasizing geometric deflection, yield-at-entry control, and compact layouts. Today, roundabouts are generally recognized for their ability to improve operational efficiency, often increasing capacity by 30–50% and reducing delays and queue lengths compared to conventional signalized or stop-controlled intersections [10]. Typical service volumes for single-lane roundabouts can be up to 20,000 Annual Average Daily Traffic (AADT), while two-lane roundabouts can handle 25,000 to 45,000 AADT [10].

However, over time, increasing traffic volumes and the growing complexity of urban environments revealed the operational weaknesses of conventional designs, particularly for multilane configurations. These shortcomings include high rates of merging and weaving conflicts, suboptimal lane discipline, and inadequate accommodation for vulnerable road users [2,21,22]. To address these issues, several new roundabout types have been proposed and tested, each characterized by modifications to entry geometry, lane arrangement, or internal circulation schemes [9,23,24]. Terminological clarity has become increasingly important, as terms such as "Turbo," "Flower," "Raindrop," or "Two-Geometry" roundabouts refer to specific layouts with distinct safety and operational characteristics [6,7].

National guidelines have played a crucial role in formalizing the development and application of unconventional roundabouts. Namely, raindrop and dog-bone configurations have been included in US national guidance documents and are frequently applied in suburban and arterial environments [25]. Primary US guidelines for raindrop and dog-bone roundabouts are NCHRP Report 1043 (general principles) [26], WSDOT Design Manual [27], and INDOT Guidelines [28], and for dog-bone roundabouts WSDOT Design Manual [27], INDOT Guidelines [28], and FHWA Guides [29].

The first guidelines for turbo roundabout application and design [30] were published by the Dutch Information and Technology Platform CROW in 2008. These guidelines were created based on the doctoral thesis of Dutch researcher Lambertus Fortuijn [31]. After their release, Dutch guidelines were used by road designers globally. Considering that local traffic conditions and driving behaviors differ from country to country, other countries soon began developing regulations and adjusting the turbo roundabout design to local driving standards, drivers' habits, and winter maintenance requirements [14]. The same month that the first turbo roundabout in Croatia was built, the Croatian guidelines for turbo roundabout design [32] were published.

In Italy, national regulations classify as unconventional all roundabouts with a non-circular shape or with an inscribed diameter greater than 50 m [33]. This definition creates a structural inconsistency for many modern unconventional layouts, such as elliptical roundabouts and TGRs, which typically have much smaller dimensions than those contemplated by the decree. Due to the absence of type-specific national guidelines, at the moment, Italian TGRs are designed through project-specific procedures that combine geometric checks, turning-path validation tools, and microsimulation-based performance assessments.

Another central driver behind the evolution of unconventional roundabouts has been the pursuit of improved safety performance in environments where conventional single-lane and multilane roundabouts were unable to mitigate conflict patterns or control operating speeds effectively. Across different unconventional layouts, their geometries have been adapted to reduce conflict points, modify crash types, and enhance speed control [1,6,9,15,34,35]. Collectively, the safety-oriented geometric innovations embedded in unconventional roundabouts represent a significant departure from conventional circular designs. Their evolution reflects attempts to adapt roundabout performance to complex operational environments, reduce severe crash types, and align geometric solutions with local traffic patterns and safety priorities.

Dog-bone and raindrop roundabouts, commonly applied at freeway ramp terminals in the United States, reduce the number of vehicle-to-vehicle conflict points to eight, compared to the 32 that are present at traditional four-leg signalized intersections. Their geometry enforces speed reduction through lateral deflection, and the elongated median connecting the two raindrops improves sight distance for approaching traffic. Empirical findings from US installations support these safety benefits: in Carmel (Indiana), dog-bone roundabouts reduced injury crashes by 84% and total crashes by 63% [36], with similar improvements observed or projected in Utah and Texas. However, the partial "non-yield" entry condition typical of some American dog-bone interchanges can shift conflict points to the ramp approaches, highlighting the importance of informed signing, markings, and speed management. A significant operational distinction arises in many dog-bone and raindrop interchange applications. For dog-bone roundabouts, while traffic entering from the freeway ramps typically yields to vehicles already circulating within the raindrop section, the through traffic on the crossroad that connects the two raindrops may be designed to proceed without yielding [9]. This configuration aims to reduce conflicts for vehicles entering from the ramps, thereby potentially increasing the capacity of the interchange compared to some other forms [9].

Similarly, for raindrop roundabouts, particularly as described in WSDOT guidance, traffic traveling on the main crossroad (the link between two ramp terminal intersections or nodes) often does not encounter a yield condition as it enters the raindrop sections [27]. This can facilitate higher throughput for the crossroad traffic but may result in limited gaps for vehicles attempting to enter from the off-ramp approaches, which must yield [27]. It has also been noted that this lack of a yielding requirement for one entry can sometimes lead to undesirable increases in speed on that approach if not otherwise managed by the overall geometric design [8].

Turbo roundabouts also demonstrate strong safety performance. Their raised lane dividers eliminate weaving and channel vehicles along predetermined paths, reducing sideswipe and high-angle collisions. Analytical evaluations have shown turbo roundabouts to exhibit significantly lower potential accident rates than conventional multilane roundabouts, largely due to the removal of weaving sections and the more controlled trajectories imposed by the spiral geometry [37]. International experience in Croatia, Slovenia, and the Netherlands consistently reports fewer severe conflicts and improved speed control compared to circular two-lane roundabouts and signalized junctions. Despite their safety advantages, some specific issues arise concerning drivers who are unfamiliar with the turbo roundabout design. Namely, infrequent users may experience confusion or make navigational errors if they are not paying attention to the signage. Nevertheless, the design of the turbo roundabout minimizes the risk of severe collisions by preventing dangerous maneuvers and keeping speeds low [11,37,38].

TGRs leverage an elliptical outer carriageway combined with a circular central island to induce speed control and improve deflection, particularly along the major axis. This geometric asymmetry produces variable-width circulatory paths that reduce entry speeds and lower the severity of conflicts within the circulatory roadway [17,20]. Their geometric flexibility also enhances maneuverability for heavy vehicles in constrained sites, contributing to safer operations in corridors with high volumes of freight traffic. A growing body of literature has supported the evolution of unconventional roundabouts through comparative capacity evaluations. However, the capacity assessment for unconventional roundabouts presents a specific challenge, as most classical capacity evaluation models were developed for conventional ones [19]. A mixed approach is commonly adopted, combining empirical references with simulation-based evaluations [39].

Analytical models derived from conventional roundabout theory often require calibration to account for the effects of geometric variation in unconventional roundabout layouts. Parameters such as entry width and angle, circulatory lane width, and approach curvature significantly influence both capacity and conflict dynamics in ways that differ from conventional layouts. The presence of variable-width segments introduces spatial heterogeneity, which affects gap acceptance, vehicle positioning, and lane selection behavior.

In this context, microsimulation tools have proven particularly effective in evaluating the performance of unconventional roundabouts [20,40]. These environments allow for detailed modeling of driver behavior, geometric constraints, and traffic dynamics across a variety of scenarios. Micro-simulation analyses have confirmed the adaptability of unconventional roundabouts under a range of demand scenarios, particularly in corridors with asymmetrical flows or frequent heavy vehicle traffic [8,39,40].

Beyond the regulatory frameworks, the practical adoption of unconventional roundabouts has followed distinct trajectories in each country. The following national experiences illustrate how these configurations have evolved in real-world applications, reflecting local traffic demands, design practices, and operational priorities.

In the US, INDOT guidance indicates that dog-bone roundabouts are suitable for locations where U-turns are not desired or frequent [28], suggesting these configurations are applicable only under specific traffic demand patterns [8]. It also implies a deliberate design choice tailored to the expected traffic patterns at an interchange; if U-turns from the ramps back onto the freeway or across the intersecting road are infrequent, the dog-bone configuration can streamline operations at the individual roundabout components. Unlike the circular roundabouts found in dumbbell interchanges, the fused teardrop islands in the dog-bone interchange create different circular radii at various locations of the interchange, thereby helping to reduce the circulation speeds. On the other hand, raindrop roundabouts are a widely used solution in T-intersection contexts where asymmetric traffic demands require directional prioritization. Compared to conventional roundabouts that permit continuous 360-degree circulation, raindrop/dog-bone roundabouts operationally restrict circulation patterns at each of the raindrop ends. Additionally, the geometry eliminates direct U-turn functionalities as both raindrop ends are integrated with the median of the connecting segment. This ensures vehicles traverse the width of the median to complete directional reversals. By eliminating the U-turns, operations at immediate ramp terminals get simplified, reducing conflict points and decision complexity for drivers.

In Croatia, the diffusion of turbo roundabouts has been driven by the inadequacy of two-lane roundabouts and the search for solutions that can be easily implemented within existing infrastructures while improving safety and capacity performance. Namely, turbo roundabouts have up to 1.5 times higher capacity when the volume on the main road is larger than the volume on the secondary road [41,42], and 10 conflict points fewer than two-lane roundabouts [43]. Their lane dividers eliminate weaving conflicts and prevent sideswipe collisions at roundabout entrances and exits [44,45], i.e., they lower the number of traffic accidents [11,37,38]. Compared to signalized intersections, turbo roundabouts require roughly the same area and provide equal or higher capacity, lower delays, and safety increased by 50% [41].

In Italy, unconventional roundabouts have progressively gained relevance, particularly in contexts characterized by spatial constraints, complex traffic dynamics, or a significant presence of heavy vehicles [18,46]. Among the emerging typologies, TGR represents a distinctive and adaptive design solution [18]. From a design perspective, the TGR is like an elliptical roundabout. While both typologies feature an elliptical outer carriageway edge, thus innovating over conventional layouts, TGR stands out for its combination of an elliptical outer carriageway edge with a circular central island, resulting in a variable

circulatory roadway width. This feature results in a dynamic profile that more effectively channels vehicle trajectories than standard circular roundabouts [17,18,20]. Geometric flexibility makes TGRs especially suitable for constrained urban or suburban environments, where traditional layouts may prove inefficient or impractical. The deliberate geometric asymmetry between the central island and the outer ring is a spatial adaptation and a deliberate traffic-calming strategy, as it promotes more effective deflection of vehicle paths, contributing to speed reduction and enhanced safety [19,20]. This feature is particularly beneficial in reducing the severity of conflicts at entries and within the circulatory roadway [17]. Another key advantage of the TGR layout lies in its ability to accommodate heavy vehicles: the wider sections along the major axis allow for smoother turning paths, improving navigability for large trucks and freight vehicles [16,46,47]. This is especially relevant in road corridors with high volumes of heavy traffic.

In summary, the evolution of unconventional roundabouts reflects a broader shift toward adaptive and context-sensitive intersection design. By systematically addressing the shortcomings of conventional roundabouts, these configurations have expanded the range of tools available to traffic engineers and urban planners, contributing to safer, more flexible, and more efficient road networks [4,24,48].

3. Case Studies

3.1. United States

3.1.1. Dog-Bone and Raindrop Roundabouts: Overview

A dog-bone roundabout is a specific configuration typically found at diamond interchanges, consisting of two raindrop-shaped channelized islands at either end of a connecting roadway segment. This design forms an elongated circulatory path where the central islands are integrated with the median of the connecting segment, creating a continuous, elongated overall island structure. From an aerial perspective, this configuration resembles a dog bone, hence its name [9].

The dog-bone fundamentally differs from a dumbbell interchange. While both feature roundabouts at the ramp terminals, the dog-bone's ends are not complete circles (as in the dumbbell case) but rather raindrop shapes. The Washington State Department of Transportation (WSDOT) defines the dog-bone as a variation of a twin roundabout interchange where the individual roundabouts feature a "double raindrop" shape [8].

This design is almost exclusively applied at grade-separated interchanges, where ramps are directly connected to a surface street. In this context, the dog-bone roundabout configuration is commonly adopted to manage traffic movements efficiently and safely. Figure 1 illustrates the typical geometric layout of a dog-bone roundabout.

The primary rationale for implementing these specialized dog-bone roundabouts in the US aligns with the general safety and operational benefits of roundabout designs. These include enhanced safety through reduced conflicting points and lower vehicle speeds, as well as improved operational efficiency with increased capacity and reduced delays compared to traditional signalized/stop-controlled intersections.

These benefits are particularly sought after at freeway interchanges, which often experience higher traffic volumes and congestion, as well as crash rates/risk at high-speed ramp terminals [49].

The application of dog-bone designs often addresses specific engineering constraints commonly observed in US transportation infrastructure projects.

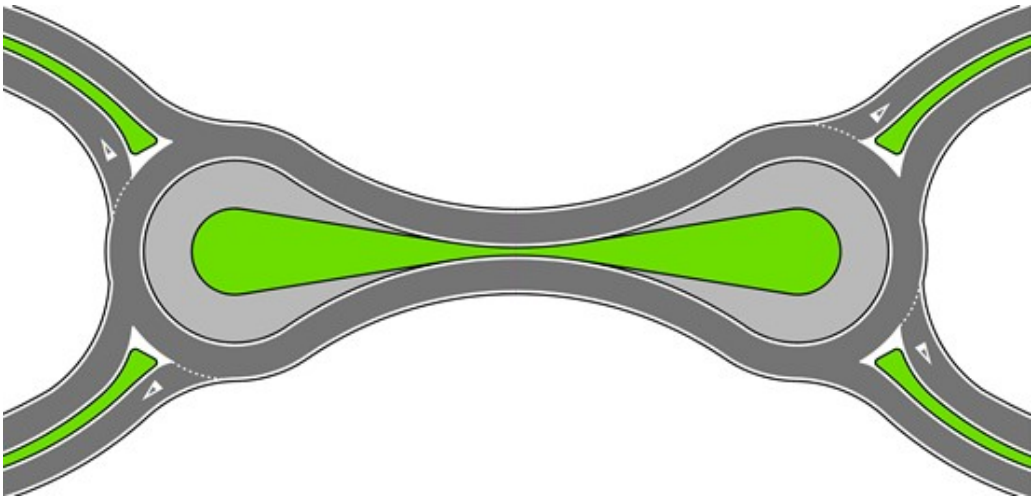


Figure 1. Typical dog-bone roundabout. (Source: created by authors).

These include:

1. Space-constrained locations: Locations where right-of-way (ROW) or adjacent land acquisition opportunities are limited or expensive to acquire;
2. Retrofitting constraints: Locations where existing infrastructure constrains other design options;
3. Bridge Optimization: Locations where there is a desire to minimize the footprint and/or cost of bridge structures;
4. Topographical constraints: Sites with steep terrains, waterways, or other existing infrastructure or natural constraints.

For example, the WSDOT Design Manual refers to raindrop roundabouts, allowing for a "wide node, narrow link" concept, which can be advantageous at ramp terminals [27]. Similarly, Indiana Department of Transportation (INDOT) guidance notes that raindrop designs can facilitate narrower or shorter bridges [28].

This adaptability makes them valuable tools for engineers facing complex site conditions common in US roadway networks, especially when upgrading existing interchanges.

3.1.2. Dog-Bone and Raindrop Roundabouts: Basic Design Criteria

Raindrop and dog-bone roundabouts are primarily defined by their raindrop-shaped central island [9]. A critical consequence of this island shape is that it does not permit continuous 360-degree circulation, a defining feature of conventional roundabouts [10]. These are often employed at interchange ramp terminals, particularly where U-turns are deemed unnecessary or are to be discouraged [8].

Geometry can also be advantageous where grade constraints or limited right-of-way make constructing a full circular roundabout challenging [8]. The shape of the island inherently guides traffic, especially for movements between ramps and a crossroad, and can simplify operations by reducing certain conflict points if U-turns are not a design consideration. While specific inscribed circle diameter (ICD) ranges for dog-bone and raindrop roundabouts are not as formally defined as for conventional types such as mini roundabouts (with ICD range 14–27 m or 45–90 ft), single-lane roundabouts (with ICD range 27–55 m or 90–180 ft), or multilane roundabouts (with ICD range 45–90 m or 150–300 ft) [50], their dimensions are heavily influenced by their application, typically at interchanges. For instance, a conceptual raindrop roundabout design in Hamilton County, Indiana, proposed an ICD of approximately 70 m (230 ft), with two circulating lanes [51].

Regardless of the overall shape, fundamental roundabout design principles such as appropriate approach geometry, carefully chosen entry and exit radii, and sufficient deflection remain critical for achieving speed control [27].

A notable variation in raindrop and dog-bone designs, particularly at interchanges, is that one entry (typically the through movement on the crossroad connecting two ramp terminals) may be designed to not require a yield to circulating traffic [8]. This is a significant departure from standard roundabout operation.

Dog-bone and raindrop roundabouts share with TGRs the general principle of non-circular geometry, which allows designers to tailor the alignment, circulatory width, and entry curvature to constrained sites or skewed intersections [8]. This geometric flexibility is particularly valuable in US retrofit projects, where right-of-way limitations, existing structures, or topographical constraints often preclude the use of standard circular roundabouts.

At freeway interchanges, the elongated shape also facilitates the accommodation of large design vehicles, although this typically requires more detailed turning-path and swept-path checks than in conventional roundabout layouts.

These design implications are summarized in Table 1, which outlines key considerations for dog-bone and raindrop roundabouts together with the relevant US guidance documents.

Table 1. Key considerations for design elements of dog-bone and raindrop roundabouts and examples of the relevant US Guidance Documents.

Design Element	Key Considerations for Dog-Bone/Raindrop	Relevant US Guidance Document(s) (Examples)
Central Island Shape	Raindrop shape restricts 360° flow; design of connecting segment in dog-bones is critical	WSDOT Design Manual [27], INDOT Guidelines [28], NCHRP 1043 (general principles) [26]
Entry/Exit Design	Manage speeds effectively; design for non-yielding through movements on cross-connector (if applicable); ensure adequate sight distance for yielding approaches (ramps)	NCHRP 1043 [26], FHWA Guides [52], WSDOT Design Manual [27]
Speed Control	Achieved via deflection, entry/exit radii; critical for approaches from high-speed facilities and for non-yielding movements	NCHRP 1043 [26], FHWA Guides [53], State DOT Manuals (e.g., KYTC [25])
Design Vehicle Accommodation	Ensure adequate path for large trucks (e.g., WB-67, OSOW) through non-standard geometry, including truck aprons	NCHRP 1043 [26], FHWA (OSOW guidance) [29], State DOT Manuals
U-Turn Provision	Typically restricted at individual raindrop ends; overall U-turns in dog-bones require navigating both ends; design based on U-turn demand	WSDOT Design Manual [27], INDOT Guidelines [28]
Ped/Bike Accommodation	Provide safe crossings, often set back with splitter island refuges; consider higher traffic volumes and complexity at interchanges; rectangular Rapid Flashing Beacons (RRFBs) may be warranted	NCHRP 1043 [26], FHWA Guides, MUTCD [54], PROWAG, State DOT Manuals (e.g., American Fork case [55])
Signage & Markings	Clear guidance for non-standard yielding rules, lane use on approaches and within elongated circulatory roadway	MUTCD Chapter 3C [54], NCHRP 1043 [26]

3.1.3. Dog-Bone and Raindrop Roundabouts: Notes on Capacity Estimation

Like all modern roundabouts, dog-bone and raindrop configurations generally operate under yield control at entry points, with vehicles circulating in a counter-clockwise direction around the central island(s). Geometric design is employed to encourage slow

and consistent speeds through the intersection [27]. This operational principle of allowing certain through-traffic movements (typically on the surface arterial crossing the freeway) to proceed without yielding is a deliberate design choice. It prioritizes these major flow movements to enhance the capacity and reduce queuing on the non-freeway arterial. However, this creates a non-standard roundabout entry condition for the yielding approaches (usually the freeway ramps). Clear and effective communication of these priority rules to drivers through signing and pavement markings is essential to ensure safe and predictable operations. There is an inherent trade-off that designers must manage: prioritizing arterial flow versus maintaining completely consistent roundabout operational principles (where all entries yield) and managing speeds effectively on all approaches. The capacity benefits of dog-bone and raindrop roundabouts at interchanges appear to be highly context-dependent, influenced by specific traffic volume distributions (e.g., the balance between ramp volumes and cross-street volumes) and the specifics of the geometric design. The findings from the FHWA study [10], which indicated higher overall delays for roundabout interchanges compared to Diverging Diamond Interchanges (DDIs) or Single Point Interchanges (SPIs) in many scenarios, suggest that the "uninterrupted flow" benefit for the cross-street in a dog-bone or paired teardrop design might not always translate to superior operational performance for the entire interchange system. This is particularly true if ramp volumes are heavy and experience significant delays while yielding to a prioritized, high-volume cross-street flow. A dog-bone configuration might perform very well if cross-street through traffic is dominant and ramp volumes are moderate, but it could struggle if ramp volumes are very high and face substantial difficulty finding gaps in the prioritized cross-street traffic. This underscores the importance of detailed, site-specific traffic analysis when selecting an interchange type.

3.1.4. Dog-Bone and Raindrop Roundabouts: Case Examples

The following examples highlight the practical advantages of dog-bone roundabouts implemented in the US. One relevant example is located along US 31 highway in Carmel, Indiana, where a previously signalized expressway intersection was redesigned with a grade separation and dog-bone layout. The new configuration introduced a series of roundabouts to connect to a medical center and unique roadway geometry, resulting in improved safety. Figure 2 illustrates the transformation of the intersection: the satellite image (a) displays the original expressway signal-controlled layout, while the final design solution is presented in the plan view (b), which highlights the dog-bone layout and integrated traffic-calming elements.

Another relevant example is located at Golden Hill and Union Roads in Paso Robles, California, where a previously problematic angled 4-way skewed (at an awkward 65-degree angle) stop intersection was redesigned with a dog-bone roundabout configuration, as shown in Figure 3. The council chose the dog-bone roundabout because it offered a better solution in terms of safely accommodating the movement of semi-trucks without the need for installation of traffic signals, which would have required costly land acquisition. The $5.96 million project, funded through Development Impact Fees and a county grant, opened in June 2023, creating a safer and more efficient transportation network. Construction began in August 2022 with a complete intersection closure, resulting in approximately $1 million in savings compared to phased construction approaches.

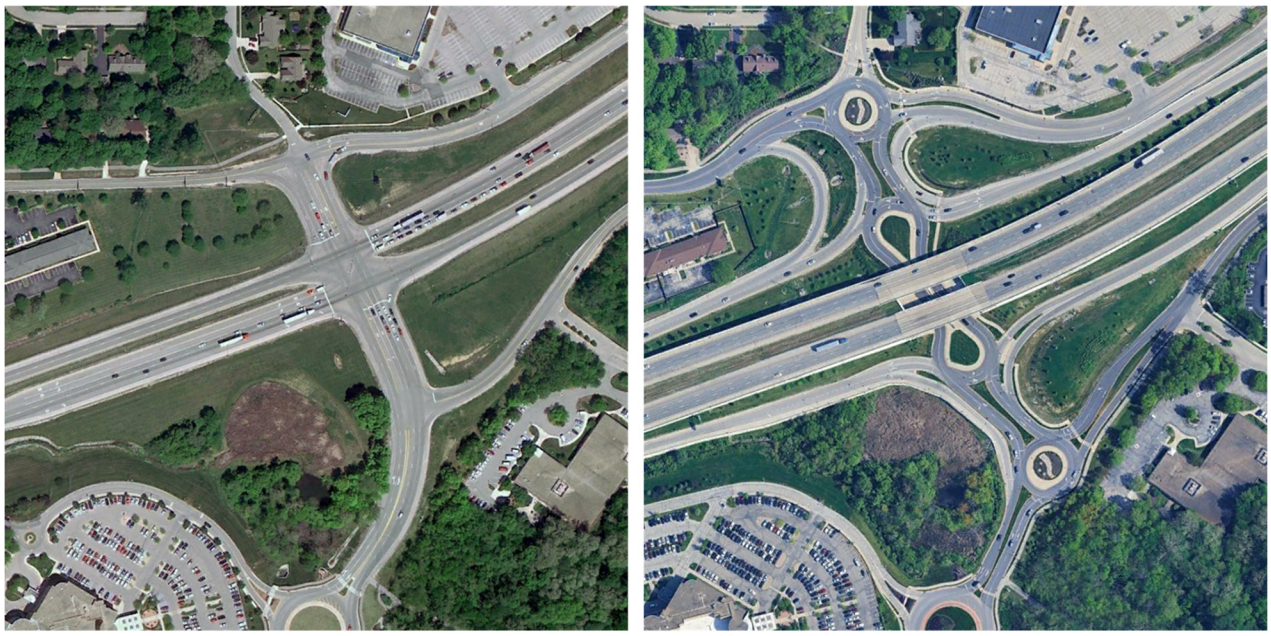


Figure 2. Conversion of an expressway signalized intersection along US 31 (Carmel, IN) into a dog-bone Roundabout: (**a**) Original layout; (**b**) Final design. (Source: Google Earth Pro. Available online: https://www.google.com/earth/ (accessed on 28 November 2025)).



Figure 3. Conversion of a skewed signalized intersection at Golden Hill and Union Roads in Paso Robles, CA, into a dog-bone roundabout: (**a**) Original layout; (**b**) Final design. (Source: [50,56]).

3.2. Croatia

3.2.1. Turbo Roundabouts: Overview

The application of turbo roundabouts in Croatia began in 2014, and out of 561 modern roundabouts in Croatia today, ten are turbo roundabouts. According to the Croatian guidelines for turbo roundabout design [32], turbo roundabouts should be applied when existing two-lane roundabouts exhibit poor traffic safety and low capacity. Their layouts, shown in Figure 4, are divided into two groups: (1) layouts recommended when there is no dominant traffic flow (Basic); (2) layouts recommended in the case of one dominant traffic flow (Egg, Knee, and Stretched-Knee).

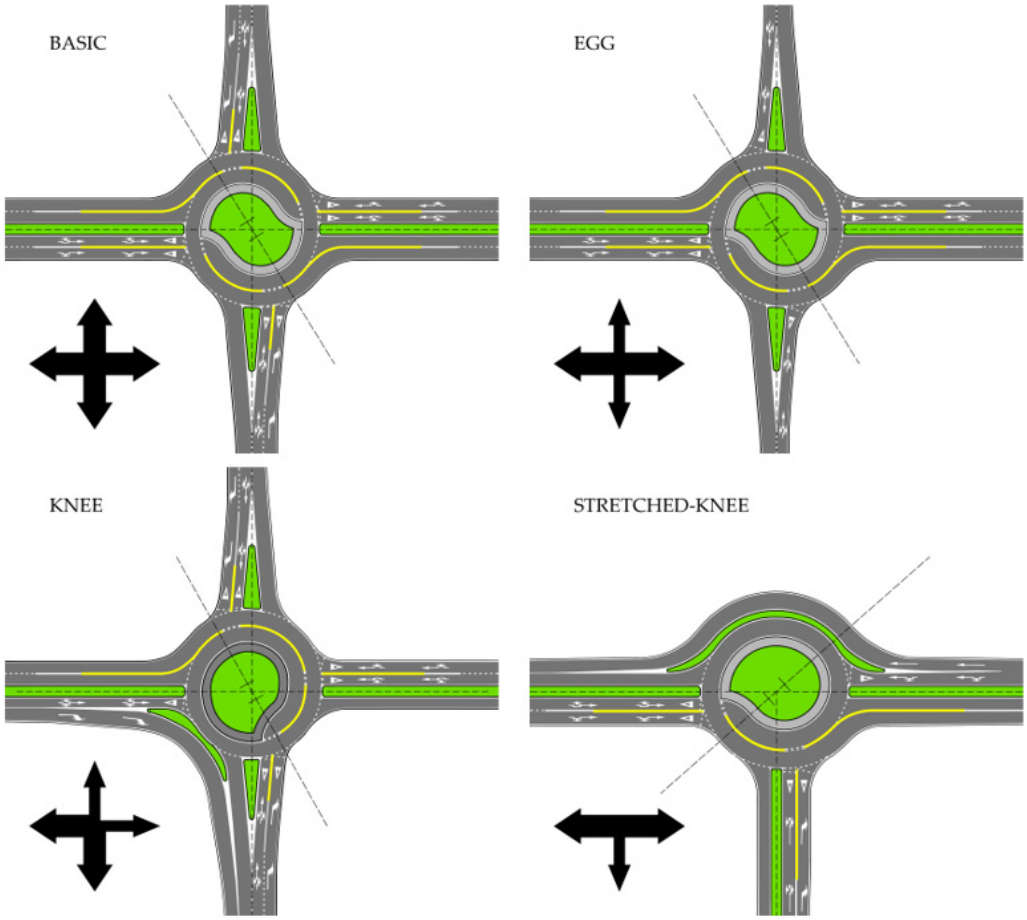


Figure 4. Geometric layout of turbo roundabouts. (Source: created by authors according to [32]).

3.2.2. Turbo Roundabouts: Basic Design Criteria

According to the guidelines [32], turbo roundabout design is an iterative procedure consisting of three main steps:

Selection of one of the available roundabout forms depending on the traffic conditions;

1. Design of elements depending on the circulatory roadway radius;
2. Analyses of the design vehicle's horizontal swept path and the fastest path vehicle speed.

If the analyses show that applied roundabout elements fulfil swept and fastest path vehicle speed requirements, the design solution can be adopted. If not, the redefinition of applied elements should be performed.

The design is based on the selection of a turbo roundabout template (also known as a turbo block—an auxiliary construction used in turbo roundabout design) with radial approach legs, depending on the size of the roundabout's circulatory roadway. After creating a turbo block, the remaining turbo roundabout elements can be designed: central island, approaches, and raised mountable lane dividers.

The turbo block consists of four pairs of circular arcs with consecutive larger radii (R1, R2, R3, R4), with centers on the line called a translation axis, shown in Figure 5. Circular arcs R1 and R2 represent the inner and outer edge of the inner circulatory lane Bu, while circular arcs R3 and R4 represent the inner and outer edge of the outer circulatory lane Bv. At the beginning of the inner circulatory lane L1, widening which gradually decreases towards the lane end is performed.

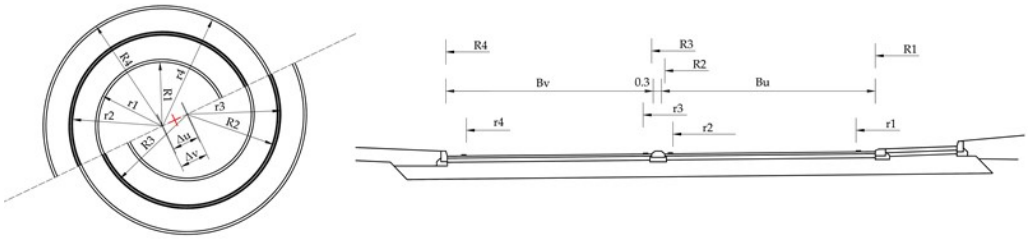


Figure 5. Geometric layout of a standard turbo block. (Source: created by authors according to [32]).

This widening is achieved by designing four centers of circular arcs on the translation axis: two centers on the left side of the roundabout geometric center CG, and two centers at the same distance on the right side of the roundabout geometric center. Distance between the outer centers is labeled with Δv, and the distance between the inner centers with Δu.

Outer centers represent the centers of the smallest circular arcs R1, while the inner centers represent the centers of larger circular arcs R2, R3, and R4. Physical separation of the traffic lanes is achieved by 30 cm wide raised mountable lane dividers, made of special concrete elements or stone granite cubes.

Croatian guidelines define four different turbo block templates with predetermined geometric dimensions. These templates are selected according to the size of the roundabout circulatory roadway and are intended to standardize the design of turbo roundabouts.

The corresponding dimensional characteristics of each template are summarized in Table 2.

Table 2. Turbo block template. (Source: [32]).

Element	Mini	Regular	Medium	Large
R1 [m]	10.45	12.00	14.95	19.95
R2 [m]	15.5	17.15	20.00	24.90
R3 [m]	16.15	17.45	20.30	25.20
R4 [m]	21.20	22.45	25.25	29.95
Bu [m]	5.40	5.15	5.05	4.95
Bv [m]	5.05	5.00	4.95	4.75
Δv [m]	5.75	5.30	5.15	5.15
Δu [m]	5.05	5.00	4.95	4.75

The turbo block should be designed in a way that circular arcs at one side of the translation axis overlap with circular arcs at the other side of the translation axis, i.e., that the inner circular lane at one side of the translation axis continues the outer circular lane at the other side of the translation axis [57]. Turbo block templates given in the Croatian guidelines fulfil that condition completely. The recommended position of the translation axis is clockwise "five minutes until five" for four-leg intersections and "ten past eight" for three-leg intersections. The recommended maximum width of the circulatory lane is 5.25 m.

The central island consists of a traversable apron and a non-traversable central part. The traversable apron is defined as a surface where special emergency vehicles and regular vehicles, in case of emergency, can stop. The width of the traversable apron recommended by this group of regulations ranges from 2.0 m to 2.5 m. The non-traversable part of the central island is a roundabout element considered "irrelevant in terms of traffic operations" and represents the "redundant roundabout space". The beginning of the traversable apron, i.e., inner circulatory lane, should be designed as a spiral, but additional instructions on its design are not provided.

Approaches are defined with the following parameters: width of entry and exit lanes, width of splitter islands, and entry and exit radii, i.e., radii of curvature of roadway edges between the roundabout approaches and the circulatory roadway. All these parameters should be chosen based on the roundabout size, the relevant design vehicle swept path, and the required driving speed through a roundabout. The minimum width of the splitter island is 2.0 m, the minimum radius of entry curves is 12 m, and the minimum radius of exit curves is 15 m.

Raised mountable lane dividers 30 cm wide and 7 cm high are recommended, as well as specially designed traversable elements beginning on a mountable lane divider for suburban turbo roundabouts. This element prevents the impermissible traffic flow weaving on the circulatory roadway and facilitates the passage of long vehicles through a roundabout. The curvature of these dividers depends on the applied entry curve radii Re and outer circulatory lane inner radii R3. This design approach allows the designer to choose an arbitrary length that will precisely accommodate the design vehicle's swept path and prevent weaving on the circulatory roadway.

3.2.3. Turbo Roundabouts: Notes on Capacity Estimation

Given that turbo roundabouts are a relatively recent development in traffic engineering, there are currently no implemented examples that allow for a comprehensive analysis of their long-term performance at the end of a planning period. As a result, empirical (experience-based) models are not typically applied to turbo roundabouts. Instead, capacity evaluation is conducted using either analytical or simulation-based models.

According to [32], the most widely adopted analytical models for estimating the capacity of turbo roundabouts based on traffic flow theory are those developed by Bovy and Brilon. In contrast, gap acceptance-based models frequently employ the formulations proposed by Hagring, Fisk, Tanner, and Troutbeck. Analytical models tailored to turbo roundabouts are typically derived from modified versions of Bovy's and Hagring's equations. These modifications are based on empirical findings from Dutch experiments conducted under real-world traffic conditions.

3.2.4. Turbo Roundabouts: Case Examples

Out of the ten turbo roundabouts currently operating in Croatia, 60% adopt an Egg layout, while 30% follow a Standard layout and 10% a Knee layout. In terms of size, the majority are regular (60%), followed by medium-sized (30%) and large configurations (10%). Most installations are situated in suburban areas and are primarily implemented along state roads, typically accommodating one dominant traffic flow. Physical separation of the traffic lanes is achieved by 30 cm wide raised mountable concrete lane dividers, designed according to the recommendations given in Croatian guidelines [32].

The first turbo roundabout constructed in Croatia was built in 2014 on the edge of the City of Osijek's suburb Višnjevac, as shown in Figure 6, to replace a signalized four-legged intersection. It is situated along the European Route E73 (state road DC2), which overpasses this intersection. It is medium in size and has an alternative Egg layout with a triangular splitter island along its dominant flow and median splitter island along the E73. Its turbo block consists of four pairs of circular arcs with radii of 15.0, 20.0, 20.4, and 25.2 m. The distance between their centers on the translation axis is 5.05 m both for outer and inner radii. The inner circulatory roadway width is 5.0 m, the outer circulatory roadway width is 4.8 m, and the traversable apron is 2 m wide. The 0.4 mil. EUR project opened in September 2014 after a two-month construction, creating a new tram link between this suburb with the center of Osijek.



(a) (b)

Figure 6. First turbo roundabout in Croatia (Višnjevac, Osijek): (**a**) Original layout; (**b**) Final design. (Source: Google Earth Pro. Available online: https://www.google.com/earth/ (accessed on 28 November 2025)).

The latest turbo roundabout constructed in Croatia, shown in Figure 7, is a regular-sized, Standard-layout turbo roundabout located near the City of Varaždin. This roundabout was built to replace a signalized four-legged intersection on state roads DC2 and DC35. The 1.56 mil. EUR project opened in September 2024 after five months of construction, creating a safer and more efficient transportation network.



(a) (b)

Figure 7. Newest turbo roundabout in Croatia (Gojanec): (**a**) Original layout; (**b**) Roundabout in construction. (Source: Google Earth Pro. Available online: https://www.google.com/earth/ (accessed on 28 November 2025)).

3.3. Italy

3.3.1. Two-Geometry Roundabouts: Overview

Several implementations of two-geometry roundabouts (TGRs) have already been realized in Italy, particularly in the Tuscany region, where they have been integrated into newly designed junctions, as well as into the upgrading of existing intersections. The growing adoption of this layout reflects its ability to reconcile safety-oriented design principles with the geometric and spatial constraints often encountered in suburban and peri-urban contexts. Thanks to the combination of geometric flexibility, operational safety, and suitability for constrained environments, the TGR has progressively established itself as a significant innovation in the Italian approach to modern intersection design [18,19].

From a geometric standpoint, the defining characteristic of the TGR is the differentiation between the shape of the outer circulatory edge and that of the central island, which remains circular. The resulting non-circular outer geometry allows the alignment of approach legs to be optimized even in cases where the intersection arms are not symmetrically arranged. Compared to conventional circular roundabouts, this configuration enables a more effective adaptation to irregular or space-limited road networks, while preserving

adequate trajectory deflection at entries. The variable width of the circulatory roadway further contributes to controlling vehicle speeds, discouraging abrupt lane changes, and facilitating the maneuvers of heavy and long vehicles, which are often critical design constraints in the Italian context [18].

3.3.2. Two-Geometry Roundabouts: Basic Design Criteria

From a regulatory standpoint, Italian design standards classify roundabouts with non-circular geometry or large inscribed diameters as unconventional. This classification typically implies the need for context-specific geometric design, simulation-based validation, and, in certain cases, project-specific approval. As a result, adaptive design approaches that prioritize functionality over geometric regularity have become increasingly common in contemporary Italian traffic engineering practice [18,19]. The main parameters that define TGRs' geometry include the major and minor axes of the ellipse (a and b), the radius of the central island (R), and the variable width of the circulatory lane (x and y). These elements are schematically illustrated in Figure 8.

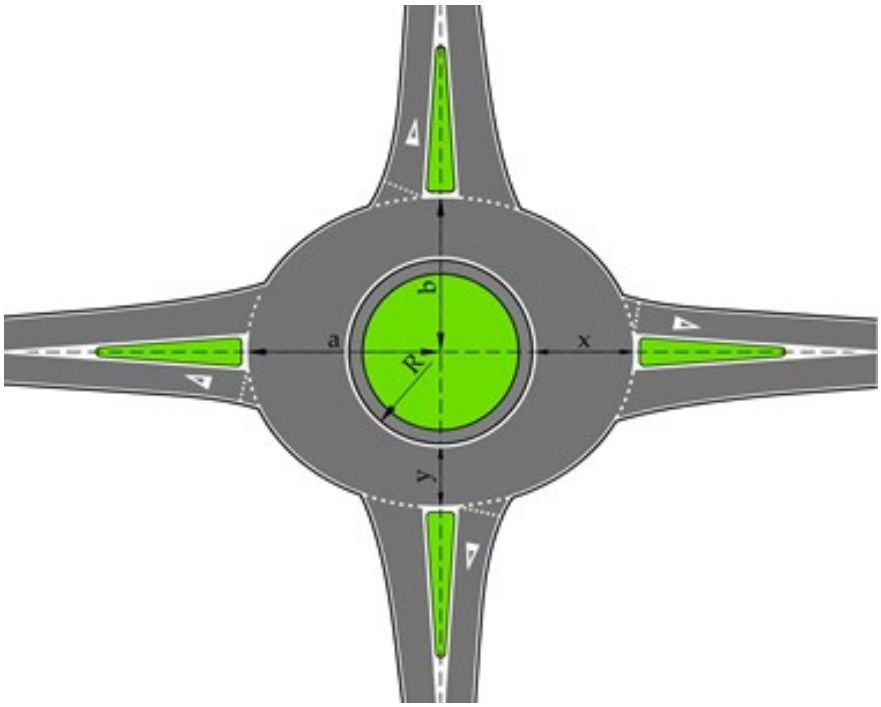


Figure 8. Geometric layout of TGR, showing major axis (a), minor axis (b), central island radius (R), and variable ring widths (x, y). (Source: created by authors according to [18]).

Geometric relationships generally satisfy the following conditions: $0.75 < b/a < 0.90$; $b = R + x$; $a = R + y$; and $4.00\ m < x < 6.00\ m$.

In typical configurations, the width of the circulatory carriageway is intentionally varied to meet different operational needs: narrower segments are used to enforce entry deflection and reduce speed, while wider segments, particularly along the major axis, facilitate turning maneuvers for large vehicles [46]. This geometric adaptability makes TGRs especially suitable for environments with limited space or diverse access geometries.

Additional elements such as surmountable bands (e.g., truck aprons) are often included to accommodate occasional incursion by heavy vehicles without compromising overall lane discipline [16]. Moreover, the use of variable widths enhances visibility at entries and improves drivers' perception of the roundabout's geometry, thereby promoting safer and more predictable behavior [46].

3.3.3. Two-Geometry Roundabouts: Notes on Capacity Estimation

TGR designs cannot be evaluated through the procedures prescribed for large-diameter roundabouts, leading to difficulties in applying the standard national calculation framework. This regulatory gap has encouraged the development of several studies aimed at identifying suitable approaches for assessing their performance and estimating their capacity [18,19]. Studies based on real-world implementations in Italy have shown that TGRs can offer improved capacity and reduced delays compared to equivalent circular configurations, especially under moderate-to-high demand [19].

Their asymmetric shape promotes a more balanced distribution of flow across the circulating lane and reduces speed variability, which in turn mitigates turbulence and enhances lane utilization. Ultimately, the estimation of capacity and performance in TGRs requires a case-specific analysis that integrates geometric design, expected traffic volumes, and local driving behaviors [40]. While the inherent adaptability of the configuration makes it suitable for a wide range of applications, it also necessitates careful methodological choices during the planning and assessment phases.

3.3.4. Two-Geometry Roundabouts: Case Examples

Several case studies highlight the practical advantages of TGRs implemented in Italy, particularly in the Tuscany region, a key economic and cultural area in central Italy.

The two representative examples, shown in Figures 9 and 10, present distinctive implementations of the TGR concept, featuring a circular green central island and an elliptical surmountable apron. These configurations represent advanced applications of the TGR model, combining spatial adaptability with clear vehicle deflection and improved heavy vehicle accommodation within constrained urban environments.



Figure 9. Conversion of a four-leg intersection on Via Aurelia Nord (Pisa) into a two-geometry roundabout: (**a**) Existing layout; (**b**) Final TGR solution. (Source: Google Earth Pro. Available online: https://www.google.com/earth/ (accessed on 28 November 2025)).

The first case is situated in the northern section of Via Aurelia in Pisa, where a conventional four-leg intersection was transformed into a TGR. Figure 9 shows the original layout with traffic lights and direct crossing flows (a) and displays the final TGR solution (b).

The new roundabout features an elliptical outer shape with a major axis of 44.0 m and a minor axis of 36.0 m (axis ratio: 0.82). The central island is circular with a diameter of 11.8 m, and the circulating lane varies between 8.5 m and 10.0 m in width. The roundabout proved particularly well-suited to the site, largely thanks to a prior design decision to

convert the original four-leg configuration into a three-leg intersection, thereby simplifying geometry and improving overall functionality.

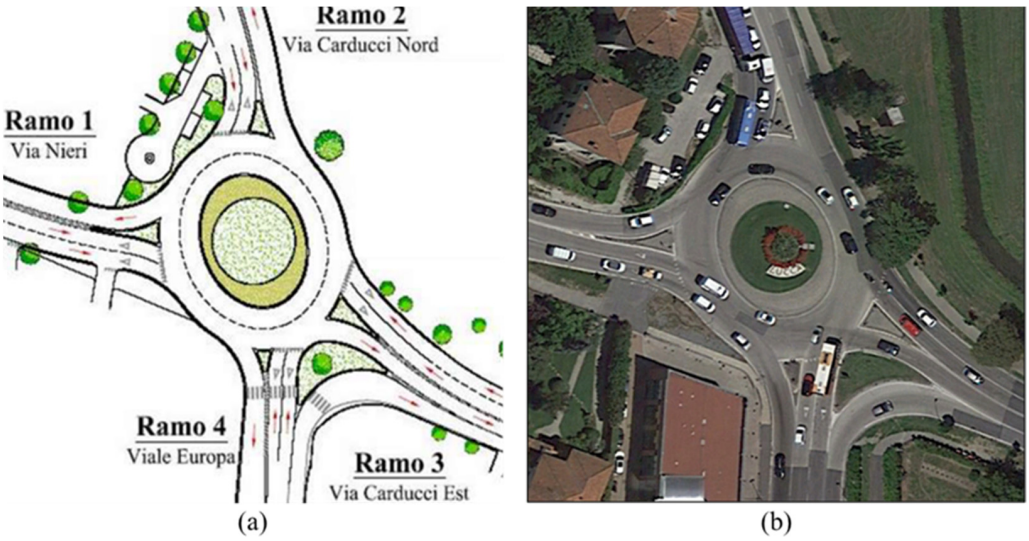


Figure 10. Comparison between planned and built layout of a two-geometry roundabout: (**a**) Design layout; (**b**) Real-world implementation. (Source: Google Earth Pro. Available online: https://www.google.com/earth/ (accessed on 28 November 2025)).

The design significantly enhanced maneuverability and operational safety, especially for heavy vehicles, while preserving the surrounding urban fabric and optimizing land use.

The second case involves a project in the city of Lucca, where a high-volume intersection was redesigned to improve traffic flow and safety. Figure 10 presents the design layout (a) and shows the built roundabout in operation (b).

The TGR geometry consists of a major axis of 46.0 m and a minor axis of 40.0 m (axis ratio: 0.87), with a constant ring width of 8.4 m. The configuration includes asymmetric surmountable aprons (5.0 m along the major axis and 2.0 m along the minor axis) supporting smooth turning paths for large vehicles.

The implementation has proven successful in maintaining functional consistency with the planned design while accommodating the operational demands of both passenger and freight traffic.

These case studies confirm the adaptability of TGRs to diverse operational and spatial contexts, especially where conventional circular designs often face critical limitations.

4. Comparative Discussion

The unconventional roundabout typologies examined in this study, raindrop, dog-bone, turbo, elliptical and TGR, exhibit distinct geometric and operational characteristics that reflect their functional objectives and the national contexts in which they were developed. Accordingly, a feature-based comparison is given, highlighting the most relevant differences and clarifying the conditions under which each configuration is most effective. The key features considered are:

- Overall Shape: Conventional roundabouts are circular, whereas raindrop and dog-bone layouts adopt elongated forms defined by one or two teardrop islands. Dumbbell roundabouts consist of two separated circular roundabouts connected by a tangent segment. Turbo roundabouts maintain a circular or slightly oval footprint shaped by spiral lane separators. TGRs feature an elliptical outer carriageway combined with a circular central island, producing an elongated but continuous ring with variable

width. Elliptical roundabouts, by contrast, adopt a fully elliptical geometry with a uniform-width crown.

- Central Island Shape: Conventional roundabouts have circular or oval islands. Raindrop and dog-bone roundabouts employ teardrop-shaped islands. Dumbbell roundabouts use conventional circular islands. Turbo roundabouts have circular or near-circular islands, guiding spiral movements—arcs of circumferences with different centers and radii or Archimedean spiral [7]. TGRs combine a circular central island with an elliptical outer boundary, while elliptical roundabouts feature an elliptical central island and a ring of constant width.
- Circulatory lane: Conventional roundabouts support continuous 360° circulation around central island, while raindrop and dog-bone designs allow only partial circulation around each teardrop [10]. Dog-bone layouts permit full circulation only for movements that traverse both ends, such as indirect U-turns [9]. Turbo roundabouts restrict lane changes through raised separators, eliminating weaving within the circulatory roadway. In TGRs, circulation is continuous but influenced by variable-width segments along the major axis, which introduce controlled deflection. Elliptical roundabouts also enable full circulation but with uniform lane width and smoother curvature.
- U-Turn Capability: Conventional, dumbbell, turbo, TGR and elliptical roundabouts generally allow U-turns within the circulatory roadway. Raindrop designs do not support direct U-turns within the teardrop island, while dog-bone configurations restrict U-turns at each end; full reversal requires navigating both teardrops.
- Key Geometric Features: Raindrop roundabouts employ a single non-circular island that restricts full circulation and prioritizes dominant flows. Dog-bone designs merge two teardrop islands into an elongated structure that simplifies interchange footprints. Dumbbell layouts retain two independent circular roundabouts. Turbo roundabouts rely on raised spiral lane dividers that impose predetermined paths and eliminate weaving. TGRs combine a circular central island with an elliptical outer boundary, generating variable-width circulatory segments that improve deflection, speed control and heavy-vehicle accommodation. Elliptical roundabouts apply a uniformly elliptical geometry that enhances alignment and deflection while maintaining a constant ring width.
- Typical Application: Raindrop roundabouts are common at ramp terminals or constrained locations where U-turns are unnecessary. Dog-bone layouts are primarily used at diamond interchanges, offering a compact alternative to dual roundabouts. Dumbbell configurations are also applied at interchanges but retain a fully circular geometry. Turbo roundabouts are implemented at at-grade intersections with multilane flows requiring strict lane discipline. TGRs are suited for constrained urban or suburban contexts, particularly corridors with a high presence of heavy vehicles or asymmetric flows. Elliptical layouts are chosen when deflection or spatial alignment benefits from a non-circular footprint without the variable width typical of TGRs. In addition to vehicular performance, the suitability of each configuration is also influenced by its interaction with multimodal users. Pedestrian crossing conditions, cyclist safety, and the integration of dedicated infrastructure may vary depending on the geometric layout and traffic control strategy. Therefore, multimodal considerations represent an important factor in the practical application of unconventional roundabouts.

Table 3 compares the main geometric and operational characteristics of conventional and unconventional roundabout typologies, based on the features discussed above.

Table 3. Comparative characteristics of conventional and unconventional roundabout types.

Feature	Conventional	Dumbbell	Raindrop	Dog-bone	Turbo	Elliptical	TGR
Overall Shape	Circular	Circular elongated	Elongated	Elongated	Circular or Oval	Elliptical	Elliptical
Central Island Shape	Circular or Oval	Circular or Oval	Raindrop	Raindrop	Circular or Spiral	Elliptical	Circular
Circulatory lane	Continuous	Continuous (within each roundabout)	Partial	Partial	Continuous (spiral, lane-separated)	Continuous (uniform curvature)	Continuous (variable width)
U-Turn Capability	Yes	Yes	No direct	No direct	Yes	Yes	Yes
Key Geometric Feature	Single circular island	Two separate circular roundabouts connected	Single non-circular island	Two non-circular islands fused	Spiral circulatory roadway with raised mountable	Elliptical, constant-width circulatory roadway	Elliptical, variable-width circulatory roadway
Typical Application	At-grade intersections (various contexts)	Diamond interchanges	Ramp terminals, constrained locations	Diamond interchanges, replacing two roundabouts	At-grade intersections (multilane)	At-grade intersections, constrained locations	At-grade intersections, constrained locations

Although several configurations are classified as supporting continuous circulation, their operational mechanisms differ significantly. Turbo roundabouts impose predefined vehicle paths through spiral lane separation with physical dividers, effectively eliminating lane-changing within the circulatory roadway. In contrast, TGRs rely on variable-width geometry to influence vehicle trajectories and speed profiles without physical constraints. Elliptical roundabouts, instead, maintain continuous circulation through uniform curvature, without introducing internal control mechanisms.

A schematic representation of the analyzed roundabout types is provided in Figure 11 to support the interpretation of the main geometric differences.

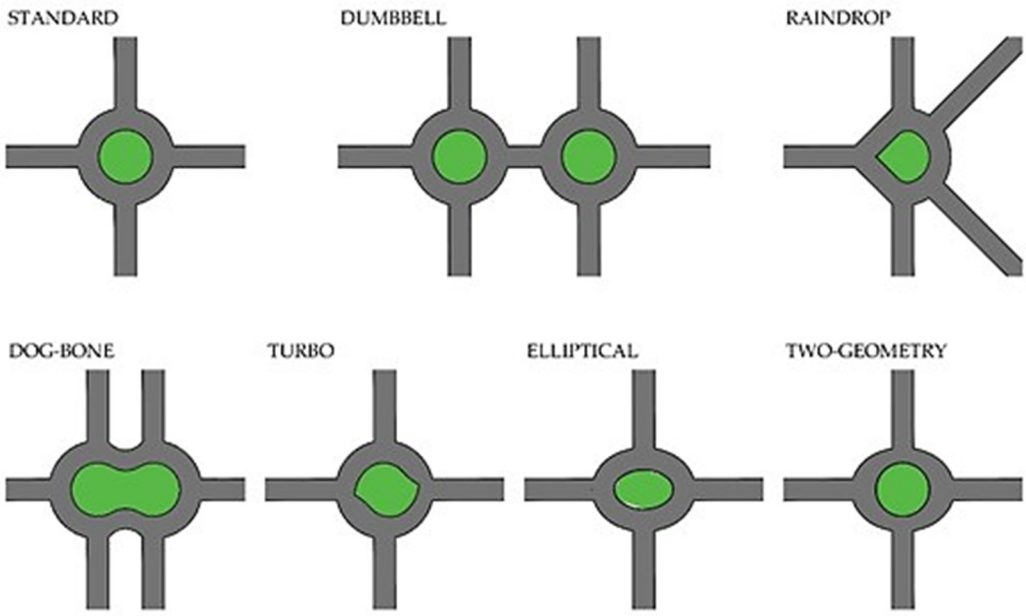


Figure 11. Schematic representation of conventional and unconventional roundabout types considered in the study (standard, dumbbell, raindrop, dog-bone, turbo, elliptical, and two-geometry roundabouts). (Source: created by authors).

From a cross-national comparative perspective, the three national contexts reveal both convergences and structural differences in the implementation of unconventional roundabouts. In the United States, their development is strongly associated with interchange design and the need to manage high traffic volumes with directional flows, supported by relatively flexible design practices and context-driven implementation strategies. In Croatia, the implementation of turbo roundabouts is guided by well-defined national standards, reflecting a more regulated and standardized approach to multilane roundabout design. In Italy, the application of two-geometry roundabouts is largely influenced by spatial constraints and urban context complexity, often requiring adaptive and site-specific design solutions.

Despite these differences, several common challenges emerge across all contexts, including the need to balance safety and capacity, the management of complex traffic patterns and traffic composition (e.g., heavy vehicles and multimodal users), and the integration of unconventional geometries within existing road networks. These aspects highlight the importance of context-sensitive design approaches and confirm that the effectiveness of unconventional roundabouts is closely linked to their adaptation to local operational and spatial conditions.

5. Conclusions and Further Insights

This paper presented a comparative examination of three major families of unconventional roundabouts, raindrop and dog-bone designs in the United States, turbo roundabouts in Croatia, and Two-Geometry Roundabouts (TGRs) in Italy. The study aimed to clarify how these configurations emerged, why they are adopted in their respective national contexts, and what geometric and operational principles define their performance. By analyzing real-world applications, this work highlighted the ways in which unconventional roundabouts respond to limitations of conventional circular layouts, especially in environments characterized by spatial constraints, unbalanced traffic flows, high-speed approaches, or the presence of heavy vehicles. The comparative discussion demonstrates that these designs should not be considered alternatives to one another, but rather context-specific solutions optimized for different operational challenges. Their distinct geometries reflect divergent priorities but a common goal: enhancing safety, improving operational efficiency, and achieving geometric adaptability where modern single- or multilane roundabouts may fall short.

Dog-bone and raindrop roundabouts represent specialized and innovative intersection solutions that are finding increasing application within the United States, primarily at freeway interchanges and other constrained locations. Their unique geometric characteristics, featuring teardrop-shaped islands and often non-standard yielding protocols, offer distinct advantages in terms of managing specific traffic movements, potentially reducing construction footprints, and enhancing safety by lowering speeds and minimizing severe conflict types compared to traditional interchange designs. US case studies demonstrate their successful implementation and highlight benefits in safety, operational efficiency under certain conditions, environmental impact, and even community aesthetics. However, their application is not without challenges. Operational performance, particularly concerning overall delay and queuing, can be outperformed by other innovative interchange designs such as DDIs or SPIs under heavy traffic conditions. The non-standard yielding rules require careful design and clear communication to drivers to ensure safety and avoid confusion, and the accommodation of pedestrians and bicyclists at these often large and complex interchange locations demands meticulous attention. Key US design guidance is provided by NCHRP reports (notably Report 1043), FHWA publications, and increasingly by state-specific DOT manuals that offer tailored advice for these unconventional forms.

Turbo roundabouts have established themselves in Croatia as a reliable and safety-oriented solution, supported by one of the most complete and prescriptive national guideline frameworks currently available in Europe. Their distinctive geometry, characterized by spiral lane organization, raised mountable dividers, and enforced lane discipline, offers significant advantages when compared to conventional two-lane roundabouts, particularly in environments with dominant traffic flows or safety issues related to weaving and lane-changing behavior. Despite these strengths, challenges remain. Firstly, real-world intersections with skewed approach legs require modifications of layouts provided by the guidelines. Secondly, the turbo roundabout behavior is strongly influenced by driver compliance with lane-keeping prescriptions, making clear signage and markings essential. Thirdly, the absence of long-term empirical datasets limits the ability to quantify performance at the end of the planning period, reinforcing the reliance on analytical models and microsimulation. Nevertheless, the Croatian experience underscores the importance of consistent national standards: dedicated guidelines [32] have ensured a rather high degree of uniformity, facilitated construction, and enabled coherent design practice of turbo roundabouts across the country. Future work should focus on investigating if and how modified turbo roundabout layouts influence their safety and capacity, expanding empirical databases, refining gap-acceptance models for spiral geometries, and integrating multimodal considerations, particularly for pedestrian and cyclist safety.

The Italian implementation of TGRs highlights how non-circular roundabout geometries can be used to achieve operational flexibility in constrained urban and peri-urban environments. Their combined elliptical outer boundary and circular central island create variable-width circulatory lanes, enhancing deflection, improving speed control, and providing superior maneuverability for heavy vehicles. Case studies from Tuscany and central Italy show that TGRs are particularly effective in irregular or spatially limited sites, where conventional circular roundabouts either underperform or cannot be accommodated. Nonetheless, TGRs face specific challenges. The absence of national design guidelines means that each project requires a bespoke approach, often relying on microsimulation, turning-path analysis, and context-specific geometric validation. This increases design time and can lead to variability across implementations. Moreover, long-term performance assessments are still limited, particularly regarding capacity estimation, which must often rely on hybrid approaches combining adapted analytical models and simulation results. Despite these limitations, TGRs represent a promising design direction for Italy: their adaptability aligns with the geometric complexity typical of Italian road networks, and their safety benefits, derived from controlled deflection and variable lane widths, are increasingly recognized. Continued development of methodological frameworks and the eventual introduction of dedicated guidelines would further strengthen their role in national practice. From a practical perspective, the absence of national design guidelines for TGRs highlights the need for a progressive and structured standardization process. This could include the development of context-specific design frameworks based on accumulated case studies, the definition of reference geometric ranges, and the integration of microsimulation as a supporting tool within a more structured design procedure. Transitional strategies may involve the validation of pilot applications and the gradual consolidation of best practices. In this regard, experiences from countries with established guidelines, such as the Croatian framework for turbo roundabouts, demonstrate the importance of iterative development supported by both empirical observations and design practice.

Taken together, these findings provide a coherent cross-national perspective on the role of unconventional roundabouts as context-specific solutions rather than universally applicable designs. The performed systematic synthesis of geometric and operational characteristics presented in Table 3 establishes a conceptual framework for the design–

operational nexus. This framework is not limited to a descriptive classification, but reflects a set of underlying design principles that govern the selection and performance of unconventional roundabouts. These principles include the balance between geometric flexibility and traffic control, the management of conflict points through layout configuration, and the adaptation of circulation patterns to specific traffic demands. In this context, the classification logic adopted in Table 3 highlights how different roundabout typologies respond to distinct operational needs. Configurations characterized by forced trajectory control, such as turbo roundabouts, are designed to minimize conflicts and regulate vehicle interactions in high-demand multilane environments. In contrast, geometrically adaptive solutions, such as TGRs and elliptical roundabouts, rely on shape modulation and variable widths to influence driver behavior and improve performance in constrained or irregular contexts. From a practical perspective, the framework summarized in Table 3 supports context-sensitive design selection by linking geometric features to operational outcomes. It provides a structured reference for supporting design decision-making and identifying the most suitable roundabout configuration based on factors such as traffic composition, directional imbalance, spatial constraints, and the presence of heavy vehicles.

The limitations discussed across the analyzed case studies highlight that each unconventional roundabout typology presents context-specific constraints that must be carefully considered during the design process. Rather than being universal solutions, these configurations require adaptation to local traffic conditions, geometric constraints, and regulatory frameworks. This reinforces the need for integrated and context-sensitive evaluation approaches, capable of capturing both the benefits and the operational limitations associated with each design.

Beyond these typology-specific limitations, a broader research gap emerges. The primary research gap identified in this study is the absence of standardized performance evaluation frameworks for non-traditional roundabout designs. While numerous configurations have been developed and implemented in practice, their assessment is often based on heterogeneous criteria, making cross-context comparison difficult and limiting the transferability of design practices. Consequently, future research on third-generation roundabouts should adopt a multidisciplinary approach and concentrate on the following key areas:

- Long-term empirical data collection on safety, capacity, and multimodal performance;
- Refinement of analytical and simulation-based capacity models;
- Behavioral studies to evaluate driver compliance, lane discipline, and speed adaptation;
- Integration of multimodal safety considerations for pedestrians and cyclists;
- International harmonization of terminology and classification.

Across all three contexts, unconventional roundabouts are progressively shaping a new generation of intersection design. By consolidating real-world evidence and expanding methodological tools, transportation engineers and planners will be better equipped to deploy unconventional roundabouts where they can deliver meaningful improvements in safety, efficiency, and spatial integration. These innovative configurations represent an essential evolution of roundabout design, reflecting a broader shift toward context-sensitive and performance-driven infrastructure planning.

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