vehicles

Review

An Overview of the Efficiency of Roundabouts: Design Aspects and Contribution toward Safer Vehicle Movement

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Abstract: Transforming intersections into roundabouts has shown that a sufficient degree of road safety and traffic capacity can be achieved. Because of the lower speeds at the area of a roundabout, drivers tend to become more easily adaptive to any kind of conflict with the surrounding environment. Despite the contribution to safety, the design elements of roundabouts are not uniformly fixed on a worldwide scale because of different traffic volumes, vehicle dimensions, drivers' attitude, etc. The present study provides a brief overview of the contribution of roundabouts to road safety and the interactions between safety and the design elements of roundabouts. In addition, discussion points about current challenges and prospects are elaborated, including findings from the environmental assessment of roundabouts; their use and performance on the era of autonomous vehicles that will dominate in the near future; as well as the role and importance of simulation studies towards the improvement of the design and operation of roundabouts in favor of safer vehicle movement. The criticality of roundabouts, in terms of their geometric design as well as the provided road safety, lies upon the fact that roundabouts are currently used for the conventional vehicle fleet, which will be gradually replaced by new vehicle technologies. Such an action will directly impact the criteria for road network design and/or redesign, thereby continuously fostering new research initiatives.

Keywords: roundabouts; road design impact; traffic safety; capacity; pavement condition; environmental aspects; autonomous vehicles; simulation

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1. Introduction

Road crashes are considered to be amongst the eight top leading causes of deaths globally according to the World Health Organization [1]. The most critical locations and conflict points that are vulnerable to incidents and/or fatal accidents are at or near intersections. According to [2,3], almost one in every four fatal crashes occur at or near intersections.

Transforming intersections into roundabouts has shown that a sufficient degree of road safety and traffic capacity can be achieved without the need for traffic signals that induce traffic delays [4]. During the approach of a roundabout, drivers must reduce their speed, something that helps them move smoothly into, around, and out of a roundabout. Typical maximum, minimum, and mean speed profiles are shown in Figure 1. Lower speeds allow drivers to become adaptive to any kind of conflict with surrounding vehicles already in the circular pathway, such as pedestrians and bicyclists. Thus, converting junctions to roundabouts appears to be a commonly applied road safety measure in many countries [2,5–7].

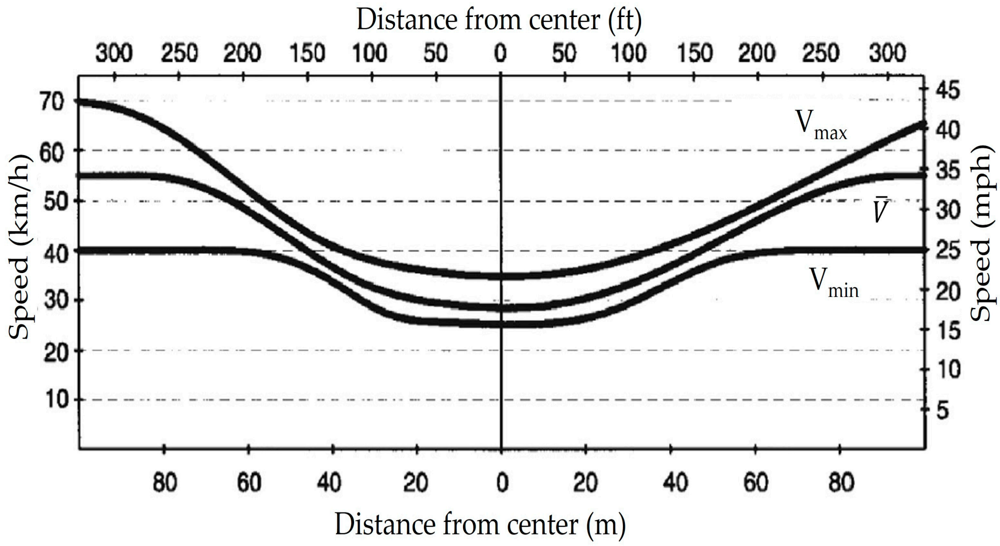

Figure 1. Typical speed profiles for vehicles travelling near a roundabout (adapted from [8]).

Despite these positive remarks, the design elements of roundabouts are not uniformly fixed on a worldwide scale because of the variety in the traffic volumes on the axes/legs of a roundabout, the available space at the area of a roundabout that could affect the number of the selected lanes, and the local traffic regulations or policies [5,9,10]. Most importantly, the trade-off of fulfilling safety and capacity criteria controls the design type and the efficiency of a roundabout [9]. The general rule is that the higher the number of lanes enabling parallel vehicle movement, the less safety levels of roundabouts because of the high-speed values that can be achieved [11]. On the contrary, single-lane roundabouts that force vehicles to drastically reduce their speeds can improve the level of the provided road safety. Moreover, due to lower speeds and fewer conflict points, roundabouts are considered to be a sustainable intersection type because of the safer travelling modes and the reduced vehicle emissions that limit the impact on air pollution [11,12].

Building upon these preliminary remarks, the aim of the present paper is to briefly overview the main design features of roundabouts, the contribution of roundabouts to road safety, and provide a collection of discussion points and thoughts on current challenges and future perspectives for that type of road element. First, the terminology related to roundabouts is recalled together with the types of roundabouts, their advantages, and disadvantages. Thereafter, aspects about the contribution of roundabouts to road safety and the interaction with the design elements are discussed, followed by current research findings on the use of roundabouts by autonomous vehicles (AVs) and challenges related to simulation analyses. Finally, the concluding remarks of this review are summarized. As such, the main contribution of this paper lies upon revealing that roundabouts are major contributors to a safer vehicle movement, provided that the importance of geometric design elements is well-understood for both the era of the current vehicle fleet, as well as for more modern vehicle technologies. The research's flowchart is given in Figure 2.

In respect to the survey methods, since more articles are covered in the Scopus database compared to other ones (e.g., Web of Science), it was decided to employ an advanced search in Scopus. Relevant articles mainly falling within the last decade (i.e., 2013 and thereafter) were selected to capture the most recent trends on roundabout design and safety interactions. Key indicators including road design impact, traffic safety and capacity, pavement condition, and environmental aspects were studied for both conventional and autonomous driving patterns. Both research and review papers were evaluated from multiple publishers, including Elsevier, MDPI, Springer, Taylor and Francis, etc. To a lesser extent, some conference papers were also overviewed.

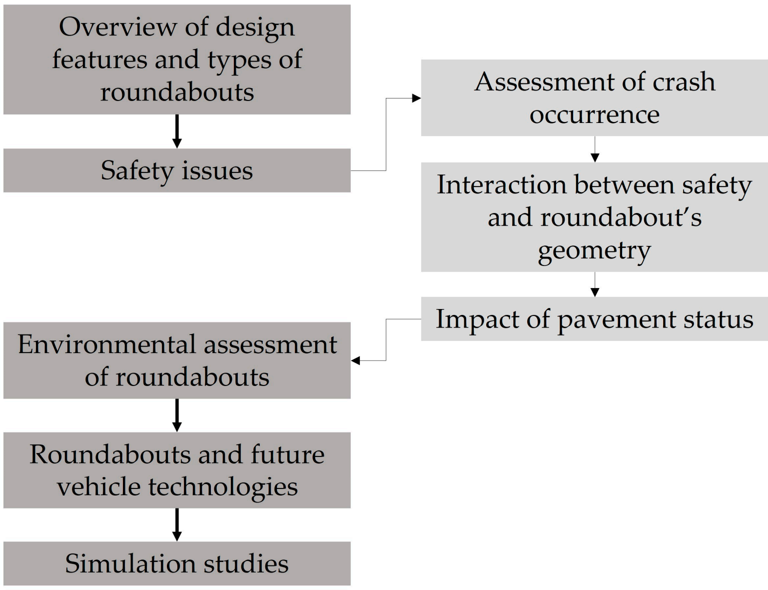

Figure 2. Research framework of this paper.

2. Characteristics of Roundabouts

2.1. Overview

Modern roundabouts were formally recognized in 1929 in the UK. Close cooperation between the Ministry of Transport and the Town Planning Institute led to the development of draft guidelines, according to which crossings of one or more major roads at the same conflict point required enough space, so that vehicle flow could be performed through a circulated traffic mode, or else a "roundabout" system [13].

It should be clarified that roundabouts differentiate from the conventional circular intersections. Vehicles moving in the circle yield to those entering the cyclic path. In these cases, drivers not experienced with circular intersections can indeed be confused by a poorly designed system and can eventually feel trapped when confronted by other vehicles in the circle. This behavioral pattern can result in travel delays, backed-up traffic. collisions, injuries, and even fatalities. On the contrary, a modern roundabout generally features a smaller footprint than a traditional traffic circle [14]. An important distinction between a modern roundabout and a traditional traffic circle is that the roundabout requires drivers who want to enter the circular intersection to yield to the vehicles already circling the roundabout, rather than completely stopping [15].

The level of maturity within the design and implementation processes for roundabouts is not unique. Several countries on a worldwide scale have adopted, to a variable extent, this type of road element for both urban and rural roads. The general trend is that roundabouts are mainly observed in Europe and Australia compared to America, where the term "rotary" is most commonly used in situations consisting of high radii [16]. Factors including variabilities in the traffic composition, the dimensions of design vehicles, driving habits, and culture explain the reason why little consensus exists about the optimal design of an "ideal" roundabout.

This fact justifies why research on roundabout features about optimal design, safety issues, crash patterns, traffic flow behavior, contribution to a sustainable traffic management, etc., continuously revive, so that design optimization and efficiency can be reached [14,17,18]. In addition, the transition era to the new types of AVs will definitively reveal new research capabilities for roundabouts [11].

2.2. Typical Structure

According to Figure 3, typical design elements in a roundabout include:

- The radii for the entry and exit curves; selecting small values for those radii ensure that drivers are easily guided into a transition area before and after the roundabout. As such, this component is most related to the aspect of safety.
- The flare length, which is the area of the approach that is widened. Usually, an additional lane is added at this length so that more vehicles can be accommodated. As such, traffic queues are reduced and better traffic flow is allowed [19]. This component is most related to the aspect of a roundabout's capacity.
- The central and splitter islands (if applicable) are usually concrete islands that are elevated compared to the pavement surface. They can improve both the deflection of vehicles, acting as a guide, and the pedestrian flow through the cross areas.

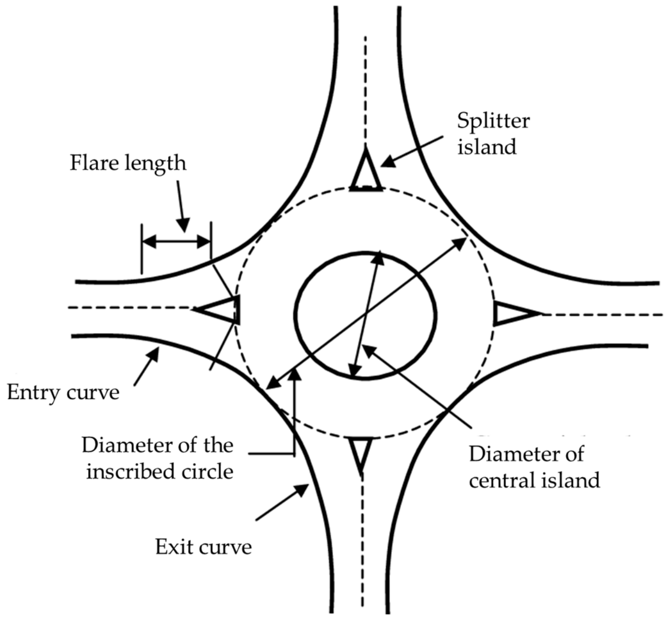

Figure 3. Core elements of a typical roundabout.

It is noted that both the diameter of the central island and the theoretical diameter of the inscribed circle have to also be defined. The latter is the largest circle that can be fitted into the junction outline.

2.3. Types of Roundabouts

Depending on their size and the number of lanes, roundabouts are divided into three categories (Figure 4): (a) mini roundabouts, (b) single-lane roundabouts, and (c) multi-lane roundabouts. The first type is suitable for urban areas and low-volume roads, where lower speeds are generally observed. The central island is of a relatively small diameter. A mini roundabout corresponds to a single-lane circulatory road path with a fully traversable central island, so that potential heavy vehicles can make use of the whole area available.

Single-lane roundabouts consist of a single lane for both entrance and exit at all legs and one circulatory lane. In those cases, higher diameters can be found for the central island, enabling higher operating speeds to be reached. In addition, the central island is non-traversable and it includes an apron.

Finally, multi-lane roundabouts are mainly applied in rural areas, or even suburban areas, where a higher number of vehicles is to be accommodated. In the circulatory path, vehicles travel side by side, and at least one entry has two or more lanes.

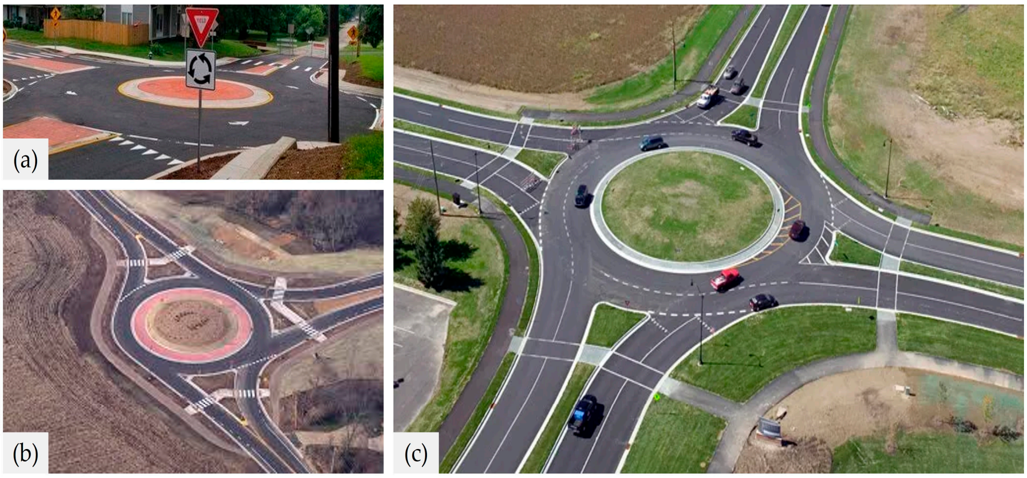

Figure 4. Basic types of roundabouts: (**a**) mini roundabout, (**b**) single-lane roundabout, and (**c**) multi-lane roundabout (with two lanes).

All of the aforementioned types belong to the category of modern roundabouts. Another classification for roundabouts takes into account the shape of the central island [20]. From this view, the following categories can be found (Figure 5): (a) modern (cyclic) roundabouts, (b) elliptical, and (c) turbo roundabouts. In the elliptical roundabout, the diameter ratio for the major and minor approaches is usually set to 2:1, which is consistent with most common design methodologies [21]. Comparative multi-parametric analysis has shown that elliptical roundabouts are more efficient for those cases where traffic congestions are expected [20]. Once avoided, higher speeds can be reached, thereby leading to increased crash severity at elliptical roundabouts, even though crash frequency is kept at low levels [20,22].

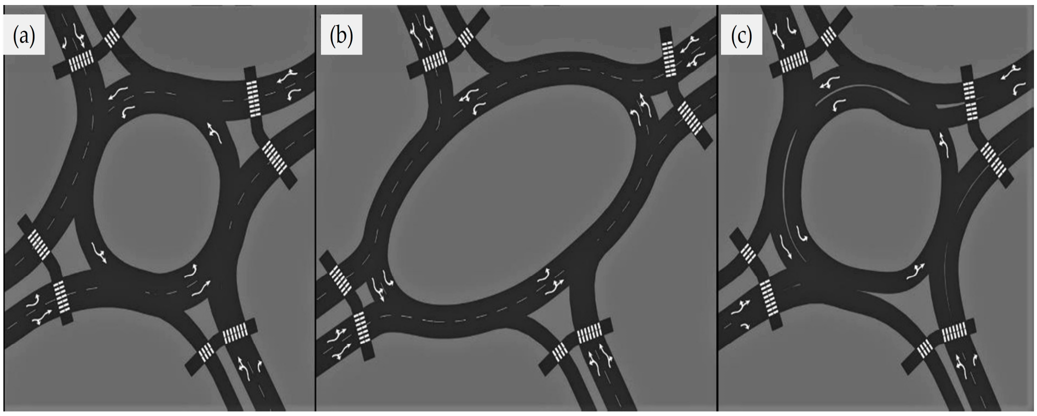

Figure 5. (**a**) Typical modern roundabout, (**b**) elliptical roundabout, and (**c**) turbo roundabout (adapted from [20]).

Before introducing the concept of a turbo roundabout, it is useful to clarify that a single-lane roundabout outperforms multi-lane ones in terms of safety because of the lower speeds. However, they fail to sustain higher traffic volumes (i.e., saturation). On the contrary, a multi-lane roundabout has a better traffic capacity, but may lack in traffic safety. Based on this contradiction, a turbo roundabout is a relatively new type, which provides a spiraling flow of traffic that forces drivers to choose their direction before entering the roundabout, thereby enhancing the levels of both safety and capacity [23,24].

The first attempt to construct a turbo roundabout was observed in the Netherlands in 2000, and it soon became so popular among other countries as well that it was followed by the development of design guidelines and recommendations during the early 2000s too [25,26]. Based on their concept, the deployment of turbo roundabouts has attracted increased research interests about the interaction between geometric design features and traffic aspects. For example, research by Dabiri et al. [23] based on microsimulation scenarios with three-legged and four-legged roundabouts, found that increasing the diameter of the central island can cause traffic congestions and delays, thereby reducing the provided level of service. On the contrary, the diameter increase was found to positively affect the performance of a turbo roundabout in terms of capacity. Table 1 provides characteristic values for typical configurations of four-legged circular roundabouts applied in the US according to [27].

Table 1. Characteristics of four-legged roundabouts (adapted from [27]).

Configuration Parameters	Mini Roundabout	Urban Single-Lane	Urban Double-Lane	Rural Single-Lane	Rural Double-Lane
Typical daily service volume (veh/day)	10,000	20,000	>100,000	20,000	>80,000
Typical inscribed circle diameter (m)	13–25	30–40	45–55	35–40	55–60
Recommended maximum entry design speed (km/h)	25	35	40	40	50
Maximum number of entering lanes	1	1	2	1	2
Splitter island configuration	Raised if possible, crosswalk cut if raised	Raised with crosswalk cut	Raised with crosswalk cut	Raised and extended with crosswalk cut	Raised and extended with crosswalk cut

Other researchers have investigated different design vehicles so that their swept paths are taken into consideration during the design of roundabouts [24]. Because of the different dimensions of vehicles that may use the roundabout and the necessity to select direction before entering the circulatory paths, the individual vehicle paths will be considered. Compared to the more conventional types of roundabouts, there is sufficient evidence on the necessity to (i) increase the width of the circulatory lanes in modern types, (ii) increase the radii of the entry and exit paths, and (iii) alter the positioning of the separator island [28,29]. Research on their design principles is still ongoing.

3. Road Safety at Roundabouts

Once properly designed and placed within a road network, roundabouts enclose many contributions compared to signalized intersections. The most critical component of a road network is to be able to sustain a certain amount of vehicle flows (i.e., capacity) and ensure safe travelling of all driving vehicles (i.e., safety). There is a general agreement on the international literature that roundabouts aim at enhancing both of the aforementioned parameters [5,12,19,30]. The reason is simple: conflict points are eliminated or at least altered, compared to conventional intersections, and drivers are forced to slow down, so it becomes much easier to control their potential to engage in an incident [19]. Of course, selecting a specific type of roundabout with proper values for its geometric elements aims at achieving a balance between capacity and safety. The latter is definitely affected by the geometric design elements, the drivers' perception of danger (related to their experience and driving performance), and the condition of pavement surface to some extent [31].

3.1. Overview of Crash Occurence at Roundabouts

At a roundabout's entry locations, cars should yield to the oncoming traffic rather than completely halt [15]. As a result, there may be fewer traffic waits and a smoother transition pattern at this kind of intersection. In fact, it has been documented that turning a signalized crossroad into a roundabout, results in an 89% decrease in traffic delays and a 56% decrease in vehicle stops [32]. With respect to the safety pillar of roundabouts, Burdett et al. [33] reported a 38% reduction in fatal injury and severe crashes because of the lower vehicle speeds. In the same context, De Brabander et al. [34] reported an average rate of reduction of 34%, 30%, and 38% for the total number of injury accidents, light injury accidents, and serious injury accidents, respectively. Reduction rates of 65% for the number of fatalities and 40% for injuries have also been mentioned elsewhere [5,35].

However, the effect of roundabouts on the number of non-injury crashes is yet to be clarified [35]. The international literature agrees on an increase in the total number of low-severity crashes. Polders et al. [36] confirm that despite the contribution of roundabouts to road safety, crashes still occur. Indeed, an even conservative increase of 12% has been reported [33], but the increase rate exhibits some variability. Zubaidi et al. [2] jointly studied the impact of roundabouts on the road safety level and reported that despite the advantages of roundabouts, road crashes still occur. Noticeably, crash frequency at roundabouts is higher in the US compared to Europe and Australia.

On the one hand, severe fatalities and injuries appear to be limited, probably because of the reduced speeds of vehicles at roundabouts, but the evolutionary trend of injury crashes or damage-related (with no injury) crashes is unambiguous. The number of available lanes is critical. Mamlouk and Souliman [37] indicated that single-lane roundabouts decreased the overall rate of accidents by 18%, while double-lane roundabouts increased the accident rate by 62%. The damage rate increased by 2% and 60% for single-lane and double-lane roundabouts, respectively. Most recently, Johnson [38] also observed a significant increase in property-damage-only (PDO) crashes for multi-lane roundabouts. Therefore, the higher the number of lanes, the higher potential for light non-injury crashes.

Moving forward, studies focusing on the crash patterns at roundabouts have been performed over the past decades. In particular, Daniels et al. [39] looked at the severity of crashes at roundabouts to see what elements were most important. Data from 1491 crashes at 148 roundabouts in Flanders, Belgium, were gathered by the researchers. To evaluate the data, they employed hierarchical binomial logistic regression and logistic regression approaches. The findings indicated that a higher frequency and severity of accidents were caused by the presence of vulnerable users. Furthermore, this effect was exacerbated throughout the night by inadequate street illumination [39,40]. Polders et al. [36] investigated four dominant crash types with data from urban roundabouts in Belgium too. These include rear-end crashes, collisions with vulnerable road users, entering–circulating crashes, and single-vehicle collisions with the central island. It was found that about 80% of the crashes occurred on the entry lanes (i.e., roundabout approach area). Road users who were found to be susceptible to the risk of being involved in a serious injury crash were the cyclists and moped riders.

No matter the cause of crashes, the increase in those less serious incidents can lead to a negative public perception about roundabout benefits [33]. This is expected to affect (i) younger drivers because of lack of driving experience and reactions in a complex environment, (ii) older drivers, and (iii) pedestrians in the case of urban areas. As per the older drivers, their vulnerability lies upon the fact that an increasingly complex road network raises the demand for their adaptability. In other words, older drivers experience difficulties in regulating their operational level of driving behavior [41].

With regards to pedestrians, a random crossing at the roundabout definitively limits its capability in terms of both vehicle capacity management as well as pedestrian safety [42]. Vignali et al. [43] recognized that research about roundabout safety usually focuses on drivers and vehicle movement and, unfortunately, overlooks the importance of safety for the vulnerable users including pedestrians and bicyclists. A solution to this issue could be the improvement of infrastructure conditions, like proper pavement marking (Figure 6). Indeed, in a recent study, the potential of moving the pedestrian crossings before the entrance to the roundabout has been commented as a contributor to road safety in the case of urban roundabouts [43].

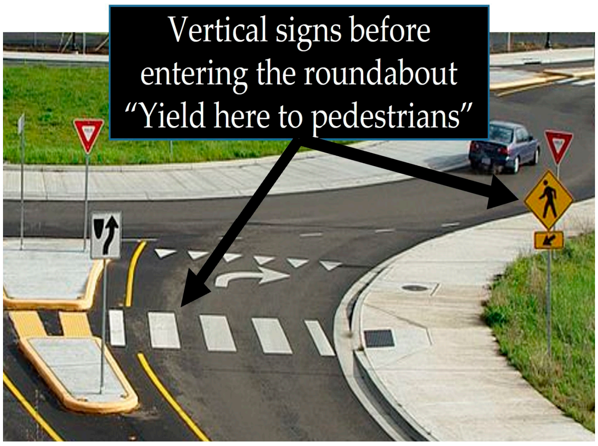

Figure 6. Entrance to a roundabout and markings for pedestrians.

The importance of proper pavement markings and improved guide signs (Figure 7) at a roundabout are also critical for better directional management of the vehicle position within the circulatory path, especially for younger and older drivers [33]. This aspect becomes even more pronounced for cases of larger roundabouts that could mimic the concept of traffic circles. Herein, the problem of limited directional information for drivers can occur. Wan et al. [44] claim that in those cases, drivers take more time to identify the exit they want to follow, thereby influencing the intersection capacity and safety.

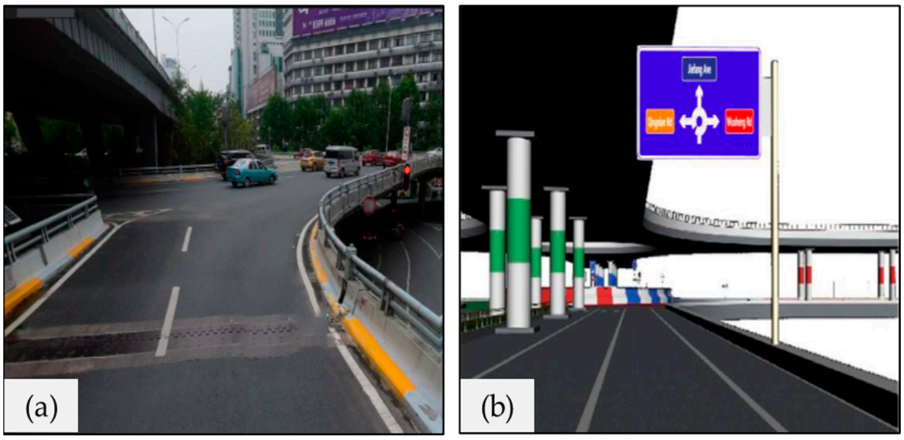

Figure 7. (**a**) View of the approach area of a roundabout, and (**b**) theoretical location for guide sign positioning in favor of improving road safety.

Following the example of Figure 7, it can be expected that properly selected positions for pedestrian crossings, together with improved guide signs, can help drivers in urban areas to accurately identify the exit they want to follow, thereby reducing the travel time needed to drive in a roundabout [44].

3.2. Interaction with Geometric Design Elements

So far, many studies on roundabouts have shown that, despite the high level of safety recognized for this type of intersection, there are several factors influencing the drivers' behavior [31]. The geometry of the roundabout is the major contributor to drivers' behavior. Design elements including entry and exit width, circulatory roadway width, entry radius, deflection angle, etc., can definitively have an impact on the way a driver adjusts its speed and driving performance during three critical types of maneuvers: (i) at the entry, (ii) at the circulatory path, and (iii) at the exit. This implies that the path of the turning vehicles is a matter in need of research in order to continuously improve the design of roundabouts. Table 2 provides a collection of roundabout geometry elements related to traffic conflict events.

Table 2. Dependency of traffic incidents on geometric design elements (adapted from [45]).

Characteristic	Type of Conflict	Contributing Factor
Radius of entry and exit approach	Run-off-road/entering–circulating/exiting–circulating	Vehicle speed or deflection angle
Inscribed circle diameter	Entering–circulating/exiting–circulating/rear-end/sideswipe	Length of weaving section/interactions between circulating and entering vehicles
Number of legs	Rear-end/entering–circulating	Increase in conflict points
Number of lanes and lane width of an approach	Exiting–circulating/rear-end/sideswipe	Increase in conflict points/distance between parallel vehicles

Furthermore, a methodology to assess and generate the variations in the vehicle paths as a result of geometric elements at circle intersections was developed in [46]. It was experimentally observed that the paths of right-turning vehicles are more sensitive to the vehicle speed and turning angle, whereas those of left-turning vehicles are additionally sensitive to the intersection corner radius.

As already known, the most frequent case of using roundabouts is within urban roads [43,47]. Anjana and Anjaneyulu [48] identified the crash causes and assessed safety performance measures for Indian urban roundabouts with the consideration of geometric design elements. They found that increasing the circulatory roadway width, exit angle, angle to the next leg, and splitter island width is associated with reduced crash rates at the roundabout approaches. Kim and Choi [49] coordinated field surveys in order to investigate the real movement of vehicles at several urban roundabouts. Their aim was to correlate the speed of vehicles for a given geometric design of a roundabout and the crash likelihood.

In another study, the importance of geometric design was also emphasized as being a crash contributing factor at urban roundabouts [50]. Factors related to the improper design of roundabouts, thus not related to the drivers' attitude and vehicle condition, were identified. The radius of deflection and the deviation angle were considered to be the most critical ones. Low entry angles force drivers into merging positions, where they must either look over their shoulder to their left or attempt a true merge using their mirrors. In the latter case, sight issues appear, as the drivers could disregard the give-way line and reach high entry speeds that contradict the road safety benefits of roundabouts. On the other hand, low values of the deflection angle contribute to failures to give way, increased pass-through speeds, and underestimations of these speeds by other vehicles being positioned in conflict points, like the subsequent approach on the right [50].

Based on an in-depth statistical analysis about the users' perception of road geometric elements, it seems that drivers prefer simple roundabout configurations, and in particular, single-lane circulatory pathways [31]. Furthermore, because of the interaction between markings, signs, and geometric design, it can be confidently stated that improving markings, i.e., complete vertical and horizontal signs, can significantly improve the road safety levels at sites where geometric design deficiencies are indeed contributors of crashes and incidents [44,50]. In other words, clear guidance can alert the drivers of the potential black spots of roundabout geometry.

Thereafter, for a given geometry of roundabout and a given set of available markings, vehicles tend to reach certain speeds. Relevant studies have demonstrated a strong relationship between the number of lanes, entry width, and exit leg speed [51,52]. Larger entry width and multi-lane roundabouts make the drivers increase their average vehicle speed at the entry legs [52]. In addition, a positive correlation has also been reported between the speed and the diameters of both the inscribed circle and the central island (recall Figure 3). Davidovic et al. [52] developed a regression model for the prediction of vehicle speed based on the radius of the circulatory lane. Of course, the speed of a vehicle may come as an additional result of the driver's perception, experience, and age, as well as the vehicle's status, like its age, the service performance, brake condition, etc. However, the purpose of the paper was mainly to investigate the interaction between speed and geometric design features.

Estimating speed as precisely as possible is an iterative process of roundabout design [51]. Once the characteristic speeds at a roundabout are known, either through measurements or model-based estimations, an improvement on the design or redesign of a roundabout can be made, as well as more accurate simulation models can be used to assess how these roundabouts affect traffic conditions and road safety levels in a road network. This guarantees that the street network can be managed more sustainably, making it possible to evaluate how each component affects travel times and traffic conditions. This is very important for a trustworthy determination of design parameters during the road planning phase and when choosing a long-term strategy for improving road safety and traffic flow management [52].

3.3. Pavement Condition

In terms of the pavement surface, the most impactful parameter is the skid resistance, or the frictional force that develops in the tire–pavement area. Provided that adequate construction quality has been achieved for pavement layers and materials [53,54], the focus is usually being put on the functionality of the pavement [55]. Less vehicle stops correspond to non-zero speeds, thereby rutting, shoving, or other severe distresses, typically observed at simple intersections, tend to be absent provided that shear-resistant asphalt mixtures are properly designed.

On the other hand, there is sufficient literature evidence that surface texture and skid resistance are considered contributing factors to traffic incidents, as they can interact with the skidding event of vehicles that affects road users' safety [56,57]. The peculiarity of roundabouts is that because of the circulatory paths, increased demand for lateral friction is required to ensure vehicle stability. However, this can be counterbalanced by low vehicle speeds occurring, especially at single-lane roundabouts. The impact of weather conditions has to also be highlighted; rainy or icy surfaces tend to reduce the provided skid resistance levels. Moreover, adverse weather conditions are known to be highly interrelated to increased accident rates that can hinder road safety.

In addition, even for a dry surface, the presence of oils or other contaminants on the pavement has been reported to cause traffic crashes at roundabouts [50]. Therefore, frequent visual inspections and/or friction measures could help preserve the condition status of the roundabout's pavement at acceptable levels. Other types of pavement-related contributing factors include the presence of surface defects, like potholes [50], that may limit the operational capabilities of the travelling vehicles.

4. Current Challenges and Prospects for Roundabouts

4.1. Environmental Implications

The environmental impact of traffic is well-known and has been growing during the recent decades, posing challenges for both the vehicle industry as well as traffic and road engineers too. Vehicular emissions are dependent on the total amount of traffic, intersection control type (e.g., signalized, roundabout, etc.), driving patterns, vehicle age, and vehicle condition [58].

The design of modern roundabouts has become dominant across many European countries in the 1980s [59]. Frequent construction activities have been observed in Europe over the last 30 years. Based on the "yield-to-entry" rule, complete vehicle stops that corresponds to abrupt decelerations and re-accelerations are limited. The longer the time of the stop, the more fuel is consumed. Thus, the required fuel is reduced during the entry to a roundabout with additional improvement in the air quality, apart from the contribution to road safety.

From this perspective, roundabouts help achieve the goals of sustainable transportation modes, according to which the environment is protected and resources are conserved by considering societal needs, benefits, and costs [60]. Ahac et al. [61] explain that the fulfillment of sustainability goals in road network planning, design, and management can be ensured through the incorporation of roundabouts in the road design network. Modern roundabouts have been commented to outperform traditional signalized intersections in terms of environmental sustainability, since a reduction is observed in the idling time as well as the rates of acceleration and deceleration that definitively contribute to a positive trend in the level of pollutant emissions and fuel consumption rates [62,63]. The level of noise pollution is also known to be reduced at the vicinity of roundabouts [61]. Reported average reduction rates of approximately 16–60% for the emissions of carbon monoxide and dioxide and a reduction of 1–4 dB in noise emission argue in favor of the sustainable potential of roundabouts [61,63,64].

However, careful environmental considerations have to be made before the decision on the type of new roundabout during the feasibility study of a new project. For example, detailed field investigations from pollutant emission measures at urban turbo roundabouts have yielded no considerable environmental improvement compared to the conventional ones [12]. Therefore, a balance between all of the individual aspects could lead to an optimized design and functionality of roundabouts. Considering environmental implications of roundabouts is definitely an open issue subject to additional research.

Finally, the aesthetic contribution of roundabouts should not be overlooked. Roundabouts, among others, are located in critical city places (i.e., with or no monuments); thus, they can also serve as a landmark in the city [65]. They can also be constructed at the boundary of two roads of different classification or areas with different functions, so that drivers are properly alerted to adjust their speed. In this context, roundabouts are considered to constitute an organizational landscape feature. Hence, beyond its basic functions, a roundabout with the appropriate central island arrangement is an aesthetic and easily identifiable place that characterizes the architecture of the local area [66].

4.2. Autonomous Vehicles and Roundabouts

The relationship between roundabouts and the autonomous driving mode, which is expected to become increasingly prevalent in the near future, is another noteworthy observation. It is important to mention that the majority of communities across the globe are currently grappling with the transition to an autonomous driving future, whereby new mobility patterns are anticipated. Truck platooning, connected autonomous vehicles (CAVs), and autonomous vehicles (AVs) are terms that both scholars and practitioners are starting to use more frequently. The scientific community, industry, and automation technologies are collaborating to improve the efficiency of the movement of people and products. The deployment of AVs has led to the development of new research studies examining modifications to road markings, lane width, roadway capacity, and pavement design elements [67–69].

Investigating the role of AVs on the status of current road infrastructure provides a unique opportunity for the transportation engineering community. Among others, the contribution of AVs on the roundabout capacity and safety have attracted a lot of research interests [11]. Autonomous driving in roundabouts requires the understanding of complex relationships between road design features, traffic rules, and the performed maneuvers of various road users [70]. According to Figure 8, in a fully autonomous vehicle driving environment, the Internet of Things will be responsible for any kind of decision maneuvers, where the driving behavior and drivers' perception will have no impact.

For the theoretical case of full AV dominance, it is currently impossible to evaluate the real performance of a roundabout against AVs in terms of safety and capacity; therefore, field tests and observations can be replaced by microscopic traffic simulations and driving simulator tests in order to gain further insights into this area. The research so far does not produce consistent remarks. Double-lane roundabouts were assessed in a study [71] through microsimulation with the Vissim software [72]. Different penetration rates of CAVs into the routine traffic flow were assumed, and it was found that for higher rates, significant benefits occur for the maximum queue length, travel times, and delays. For a fully CAV-based traffic scenario, it was claimed that the roundabout performance of the road network worsens [71]. On the other hand, Friedrich [73] reported a disproportional increase in the capacity of the road network as the share of AVs increases. Nevertheless, reaching the maximum possible speeds will become feasible, once AVs appear at a rate of 100% within traffic composition [74].

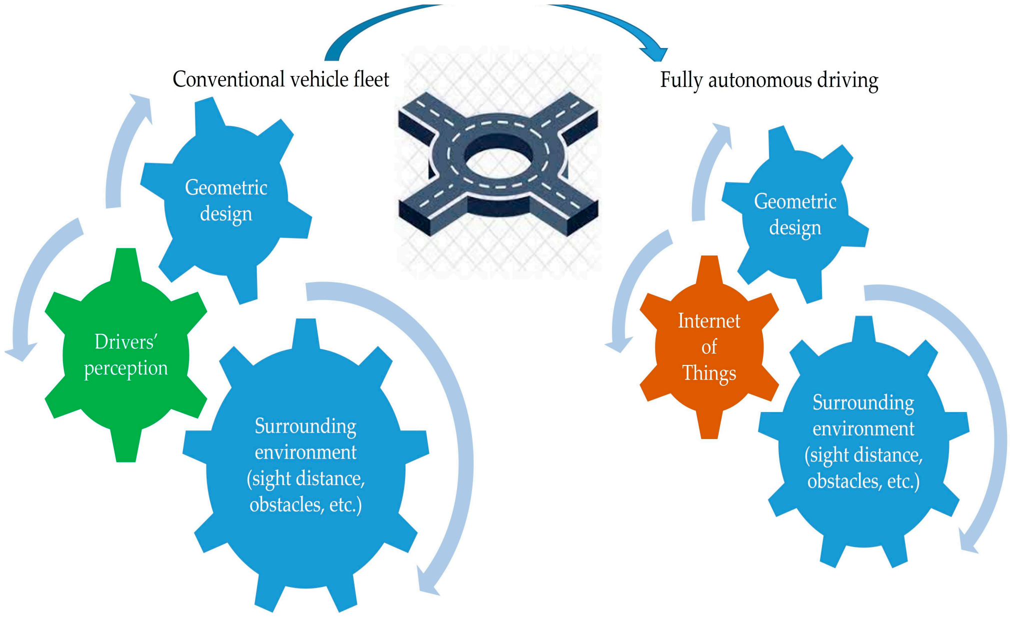

Figure 8. Pillars affecting vehicle movement at roundabouts for a conventional fleet and a fully autonomous fleet.

A path planning strategy for autonomous vehicle driving was developed by Gonzalez et al. [75] to better comprehend the patterns of AVs traveling at a roundabout. They proposed a system that generates continuous paths, dividing the driving process into three stages as follows: (a) entrance maneuver, (b) driving within the roundabout, and (c) exit maneuver. In their parametric study, they considered double-lane roundabouts, but with different exit scenarios. Their contribution was to allow for rational real-time planning, easily adjustable to any AV architecture [75].

Overall, the international literature agrees that a roundabout is safer than a traffic signalized intersection for AVs [74,76], since the progress in vehicles' sensors will help them better manage merges in different lanes of traffic. Further to this, the aspect of connectivity enables a better operational management of lateral distances, time gaps, etc., thereby increasing the traffic capacity and the quality of traffic flow at a roundabout [77]. Nevertheless, the major challenges until the full absorption of AVs into a typical traffic composition is achieved include the joint consideration of conventional vehicles with autonomous vehicles at different rates [74].

4.3. The Role of Simulation

Real-scale measurements on the vehicle performance at roundabouts does not offer the opportunity of design optimization; rather, they offer a reactive potential instead of a proactive one. At the same time, it is not feasible to strictly overview the impact of multiple features of road design (e.g., the width and radius of entry lanes, the diameter of the inscribed circle, sight distance, etc.) and assess how the drivers' response to changes in the roundabout's geometric design is affected [78]. In order to investigate how the safety and operational characteristics of the traffic will change when AVs are added, traffic micro-simulation appears to be a valuable approach. At the same time, it is necessary to explore data mining and artificial intelligence techniques to find an effective method of understanding traffic behavior at roundabouts [79,80]. This is even more important in the case of AVs, where despite the general trend of safer vehicle movements at roundabouts, there is a risk of some self-driving cars to enter a roundabout without a complete realization of the driving environment.

Using driving simulation technology appears to be an effective means to evaluate driving behavior, without taking risks as per the real driving activities [81]. Thanks to their use, it becomes feasible to evaluate the liaison between drivers and geometric design principles. This is important in order to achieve a balance between capacity and safety and maximize the performance of roundabouts. Besides, the joint effect of geometric elements is more important than their individual impacts [2]. Related research should be directed towards the accuracy improvement of safety performance models through the consideration of geometric parameters of the road design process, the use of automated video analysis for the description of traffic incidents, and the use of reliable simulators. Of course, it has to be acknowledged that the problems of considering physical limitations or obstacles, the lack of realism, the case of drivers' fatigue, as well as the validity challenges are among the major shortcomings of driving simulators [78,82].

In the same context, Alozi et al. [20] highlighted the role of simulation for a balanced design of roundabouts by jointly considering three pillars: (i) the separation of particular movements, (ii) the achievement of desirable speed profiles, and (iii) the satisfaction of geometry constraints. Neglecting traffic design elements implies that any enhancement in road safety will not necessarily be accompanied by better mobility and vice versa [20]. Hence, the authors developed a novel multi-criteria approach to simultaneously incorporate the different evaluation criteria in a meaningful way. Micro-simulation enabled them to conduct analyses in a controlled environment and assume multiple scenarios with different volumes for traffic and pedestrians. They considered modern, elliptical, and turbo roundabout design. They concluded that a turbo roundabout excels for low to medium traffic congestion as well as for the total vehicle emissions. Elliptical roundabouts were found to be more prone to incidents and safety was better only for cases of higher congestion rates.

Thanks to simulation studies, one can obtain useful implications about the speed profiles at roundabouts. In addition, maintaining suitable speeds for all vehicles while travelling in a roundabout is the most crucial design goal. However, because of the non-common consensus on the roundabout design, it is rather difficult to quantitively evaluate the effect of alternative safety measures on the resulted speed and the related control parameters. Of course, speed surveys can prove beneficial, since speed provides a link between roundabout safety and geometry [6]. However, direct observation and geometrical parameter measurements that may lead to the collection of other variables related to driving behavior do not necessarily guarantee consistent and solid remarks. Therefore, the joint analysis of using simulation analysis and real-scale supportive measures would enable an optimized assessment. To this end, robust research efforts should be targeted to ameliorate the design standards and guidelines of roads and roundabouts towards the optimization of the design parameters that have conflicting effects.

5. Conclusions

Roundabouts have been advocated by many transportation professionals as an effective alternative to conventional intersection designs. They provide a convenient solution by reducing vehicle delays and enhancing safety among other presumed benefits. The most predominant safety benefits are usually attributed to the geometry and priority rules of roundabouts, which force approaching vehicles to reduce their speeds and, subsequently, face a lower risk of collisions.

Roundabout implementation, integrated design, and proper evaluation are a necessity to achieve beneficial results. Despite this fact, limited literature exists focusing on roundabout quality evaluation (level of service versus quality of service); this is something that could be rather useful for transportation engineers and policymakers during the design stage, maintenance, or while deciding on the construction of a new roundabout [10].

The criticality of roundabouts in terms of their geometric design as well as the provided road safety lies upon the fact that roundabouts are currently used for the conventional vehicle fleet, which will be gradually replaced by new vehicle technologies. Such an action will directly impact the criteria for road network design and/or redesign, thereby continuously fostering new research initiatives. Towards this direction, the role of micro-simulation studies was highlighted. Related research is ongoing aiming at shedding light on the optimized geometric design of roundabouts with an efficient traffic flow, enabling both "safety" and "capacity" potentials to become maximized, thereby offering sustainable traffic management at roundabouts.

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