

Roundabout Safety Benefits, Design Considerations and Safety Evaluation Techniques: A Review

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Abstract

Roundabouts are increasingly replacing conventional signalized intersections due to their potential to enhance traffic safety and operational efficiency. This paper examines and reviews the safety benefits, design considerations, and evaluation methods for roundabouts. Studies consistently show significant reductions in crashes at roundabout relative to other at-grade intersections control systems, particularly severe injury crashes, with reductions ranging from 37% to 88%. Roundabouts reduce conflict points, lower vehicle speeds, and improve safety for both motorized and vulnerable road users. The methodology for this paper involved a comprehensive review of literature on roundabout design and safety evaluation techniques. Data from global studies were analyzed to identify key design elements such as geometric layout, signage, and pedestrian provisions, which contribute to roundabout safety. Various safety evaluation methods, including crash data analysis, traffic conflict techniques, and surrogate safety measures, were also assessed for their effectiveness in evaluating roundabout performance. Findings indicate that proper geometric design, clear signage, and the use of innovative features like right-turn bypass lanes and roundabout metering systems can enhance safety and traffic flow. Based on these findings, the paper recommends integrating these design elements, prioritizing the safety of vulnerable users, and utilizing advanced safety evaluation techniques, including simulation modelling and intelligent transportation systems (ITS) to further optimize roundabout performance.

Keywords: Roundabouts, Roundabout Benefits, Design Considerations, Safety Evaluation Methods.

Introduction

Traffic safety and operational efficiency are critical challenges faced by transportation authorities, particularly at at-grade intersections where multiple traffic streams converge. These intersections are major sources of congestion and collisions, leading to significant delays and an increased risk of accidents (Akcelik *et al.*, 2022; Khan & Das, 2024; Leonardi & Distefano, 2023b). Conventional traffic control methods, such as signalized intersections and stop signs, though effective in managing traffic flow, often contribute to higher crash rates, especially during turning movements (Gazder *et al.*, 2023; L. Li *et al.*, 2024; Modupe

& Ben-Edigbe, 2024; Otto & Okafor, 2023; TRB, 2000, 2010d; Vinayaraj & Perumal, 2022). These systems are prone to certain types of crashes, including rear-end, left-turn, and right-angle collisions, which often result in severe injuries or fatalities (Gazder *et al.*, 2023; Khan & Das, 2024; Modupe & Ben-Edigbe, 2024).

Roundabouts are gaining significant recognition as a safer and more efficient alternative, for managing at-grade intersections (Modupe *et al.*, 2021; TRB, 2010e, 2022; Vinayaraj & Perumal, 2022). They are circular intersections with central island aimed at channeling conflicting traffic continuously either clock-wise or counter-clock-wise in one direction requiring yielding from entering vehicles, with approaching traffic yielding to circulating traffic (TRB, 2000, 2010e, 2010b, 2016b, 2016a, 2022, 2023). This design eliminates conflicting traffic phases within signalized intersections, reducing potential collision points (Al Hasanat & Janos, 2023; Bari & Dhamaniya, 2022; Kehagia *et al.*, 2022).

Historically, the concept of circular intersection with channeled traffic flow has a long history, with evidence of roundabout-like structures found in archaeological sites dating back to Roman times, whereas, the modern roundabout design recognized today originated from Europe during the early 20th century (Fathullah *et al.*, 2023). The first documented modern roundabout was built in 1905 in Paris, France (TRB, 2010d). Therefore, roundabouts have a rich history and have seen a significant increase in use in recent years due to their safety and operational benefits. Originating from Europe and Australia, roundabouts were introduced in North America much later and have since gained popularity for their ability to improve traffic flow and reduce congestion (Hétu, 2000), with their modern form emerging from Europe (Fathullah *et al.*, 2023). Their safety and operational benefits have fueled a significant rise in implementation worldwide; including a recent surge in the United States. This historical background strengthens the focus of the review paper by highlighting how the safety advantages of roundabouts have driven their increasing popularity as a modern intersection control method.

Safety remains primary reason for the increased use of roundabouts, with research demonstrating reductions in severe crashes compared to other conventional at-grade intersections. Improved traffic flow and reduced congestion, particularly at low volume intersections, make roundabouts an attractive option (complements the safety aspect). The use of roundabouts in the United States has grown rapidly in the past few years, with their benefits becoming increasingly recognized (Hétu, 2000). In the United Kingdom and mainland Europe, roundabouts have been in widespread use for over half a century, and their safety and flexibility have been well-documented (Llewellyn, 2015). The introduction of traffic signal control at certain roundabout sites has further improved safety and capacity (Llewellyn, 2015).

Recent studies have shown that roundabouts can be designed to accommodate heavy vehicles and oversized or overweight vehicles in rural areas with high-speed approaches. Additionally, roundabouts have been found to have a positive impact on traffic performance, with one study comparing the performance of a through-about to standard

roundabouts and conventional intersections, demonstrating the through-about ability to improve travel time for both public and private transport (Zakeri & Choupani, 2021). The use of spiral markings at roundabouts has further optimized traffic flow, directing traffic efficiently around the junction through the optimal use of road space. However, the reliance on drivers adhering to lanes can sometimes lead to an increased risk of accidents and reduced capacity due to sub-optimal flow (Llewellyn, 2015).

Studies consistently report significant safety advantages of roundabouts compared to conventional traffic control systems at intersections. These benefits include reductions in crash rates, particularly severe injury crashes (Awadalla & Albuquerque, 2021; Elzaher & Albuquerque, 2021; Qawasmeh *et al.*, 2023; TRB, 2010d, 2010b). A case study in Sicily, Italy compared the operational and safety performance of multi-lane roundabouts and turbo-roundabouts, revealing that at medium or low traffic volumes, multi-lane roundabouts are significantly superior in terms of operational performance (Leonardi & Distefano, 2023b). Besides, the potential of roundabouts to significantly improve safety compared to signalized intersections, as they help reduce severe crashes, particularly head-on and right-angle collisions, due to the elimination of conflicting traffic movements within conventional intersections have been reported (Fromme, 2010; Khan & Das, 2024; Nnabuihe, 2020). Also, a study investigated the operational benefits of modern roundabouts for high-speed locations that serve heavy vehicles, finding that roundabouts can be designed to accommodate not only heavy vehicles but also oversized (overweight) vehicles in rural areas with high-speed approaches (Brewer *et al.*, 2023). On the other hand, the safety performance of roundabouts was also studied, with results showing an increase in safety indices such as minimum Time-to-collision (TTC) and Post-Encroachment-Time (PET), reduction in maximum speeds and decelerations, and a significant decrease in conflict points (Leonardi & Distefano, 2023b). Beyond safety benefits, roundabouts can enhance traffic flow and operational performance; capacity and reduce delays, particularly at low to medium traffic volumes, and can lead to smoother traffic flow and shorter travel times compared to signalized intersections (Gathungu, 2022; Muhammad & Jamaludin, 2022; Osei *et al.*, 2021). They have emerged as a safer and more efficient alternative to traditional traffic control methods. Their design eliminates conflicting traffic phases and reduces vehicle speeds, significantly lowering the risk of severe crashes, particularly right-angle and head-on collisions (TRB, 2023).

Therefore, in contrast, roundabouts offer a design solution that significantly mitigates the major challenges associated with traditional and conventional signalized intersections, which are prone to delays and higher crash frequencies, especially during peak hours (Awadalla & Albuquerque, 2021) by reducing conflict points, controlling vehicle speeds, and enhancing safety for all users (TRB, 2016b, 2022, 2023). However, there is still the need for further research and comprehensive reviews that address how design considerations, such as geometric layout, signage, and capacity analysis, can be optimized to maximize the safety benefits of roundabouts. Thus, addressing the following fundamental research

questions; (i) how do roundabouts compare to conventional signalized intersections in terms of safety and operational performance? (ii) what are the critical design elements that contribute to the improved safety and efficiency of roundabouts? (iii) which safety evaluation techniques are most effective for assessing the performance of roundabouts in diverse traffic conditions?

This paper aims to provide a comprehensive review of roundabout safety benefits, design considerations, and evaluation techniques to address the following objectives:

- i. To analyze the safety benefits of roundabouts in comparison to conventional signalized intersections, focusing on crash reduction, particularly in severe injury and fatality cases.
- ii. To identify key design considerations, including geometric layout, signage, and capacity analysis, that enhance the safety and operational performance of roundabouts.
- iii. To review and assess existing techniques for evaluating roundabout safety performance and operational efficiency.

While this review provides a comprehensive analysis of roundabout safety and evaluation methods, the following limitations were acknowledged:

- i. Geographic and Cultural Variability

The reviewed studies came from a range of geographical locations, which may introduce variability in terms of traffic laws, driver behavior, and road user demographics. Roundabout designs and safety outcomes may differ significantly between regions due to these factors. Therefore, some of the findings may not be universally applicable.

- ii. Limited Longitudinal Data

Many studies included in the review are based on short-term evaluations of roundabout safety, which may not capture long-term performance trends, such as changes in driver behavior or infrastructure wear and tear.

- iii. Data Gaps and Reporting Bias

As with most reviews, there is a potential for data gaps, particularly where crash data is underreported or traffic conflicts are not adequately captured.

Methodology

The methodology employed by this study is a comprehensive literature review method to analyze the safety benefits, design considerations, and safety evaluation techniques related to roundabouts. The review synthesizes existing research to identify trends, gaps, and findings that can inform the design and assessment of roundabouts for improved safety and efficiency.

The data for this review were collected through an extensive search of peer-reviewed journal articles, conference proceedings, technical reports, and institutional publications. The primary sources of data include studies that focus on roundabout safety performance, design elements, and evaluation techniques. Databases such as Google Scholar,

ScienceDirect, and the Transportation Research Board (TRB) were used to identify relevant researches. The keywords used during the search include “roundabout safety,” “traffic conflict points,” “roundabout design,” “safety evaluation methods,” and “vulnerable road users at roundabouts.”

The review prioritized studies published within the last two decades to capture the most recent advancements in roundabout design and evaluation, although foundational research was also included where relevant. Studies from different geographic regions were considered to ensure that the review reflects diverse traffic conditions and regulatory environments, including high-income countries such as the United States and European nations, as well as low- and middle-income countries where roundabout implementation may face unique challenges (Alshannaq & Imam, 2020; Brewer *et al.*, 2023).

Literature Review

Roundabouts have gained global recognition as a safer and more efficient alternative to traditional signalized intersections, especially for managing at-grade intersections where multiple traffic streams converge. Several studies have highlighted the key safety and operational benefits of roundabouts, including significant reductions in crash rates and congestion (Akcelik *et al.*, 2022; Khan & Das, 2024; Leonardi & Distefano, 2023b). This section reviews the literature on the safety advantages of roundabouts, design considerations, and safety evaluation techniques, structured into theoretical and empirical findings to enhance clarity.

Theoretical Foundations of Roundabout Safety

The fundamental safety advantages of roundabouts stem from their ability to reduce conflict points and control vehicle speeds. Roundabouts eliminate conflicting traffic phases, such as left turns and cross-traffic movements, which are common sources of right-angle and head-on collisions at conventional intersections (Al Hasanat & Janos, 2023; Bari & Dhamaniya, 2022). Studies consistently report that roundabouts reduce crash rates by 37% to 88%, particularly for severe injury crashes (Guo *et al.*, 2024; TRB, 2010d, 2010a). The theoretical framework supporting these safety benefits is grounded in the principles of traffic flow management, which emphasize the importance of minimizing conflict points and reducing vehicle speeds to prevent accidents (Brewer *et al.*, 2023).

Additionally, roundabouts contribute to smoother traffic flow and shorter travel times by minimizing the need for vehicles to stop completely, as is required at signalized intersections. This operational efficiency, combined with their safety benefits, makes roundabouts an attractive option for improving both traffic performance and road safety (Leonardi & Distefano, 2023b; Gathungu, 2022; Osei *et al.*, 2021).

Empirical Studies on Roundabout Design and Safety

Empirical studies have further confirmed the safety benefits of roundabouts, especially in reducing severe collisions. Awadalla and Albuquerque (2021) found that roundabouts significantly reduced crash severity for all road users, including pedestrians and cyclists. Other studies have corroborated these findings, emphasizing that roundabouts can lower vehicle speeds, thereby reducing the frequency and severity of crashes (Spanou *et al.*, 2015; Yannis *et al.*, 2023).

However, the design of roundabouts plays a crucial role in maximizing these safety benefits. Key design elements, such as geometric layout, signage, and pedestrian crossings, must be optimized to ensure safe maneuvering for all road users. Ahac and Dragcevic (2021) highlight the importance of clear sight areas at roundabout entry points, while Ahac and Kipa (2022) underscore the role of appropriate lane widths and deflection angles in reducing accident risks. Furthermore, incorporating features such as right-turn bypass lanes and roundabout metering systems can enhance both safety and operational efficiency, particularly during peak traffic periods (Guerrieri *et al.*, 2015; TRB, 2010d).

The results and findings from the studies reviewed, are presented thematically, based on the relevant theme and sub-themes in accordance with the objectives of this review paper aimed at addressing the formulated research questions.

Safety Evaluation Methods at Roundabouts

To effectively assess the safety performance of roundabouts, various evaluation techniques have been developed. The most commonly used method is crash data analysis, which examines historical crash data to identify trends and assess the impact of roundabout implementation on safety (Awadalla & Albuquerque, 2021). While crash data analysis provides valuable insights, it is limited by underreporting and the time lag between crash occurrences and data availability (Elzaher & Albuquerque, 2021).

Proactive safety assessment methods, such as traffic conflict techniques, have emerged as a more effective approach to identifying potential safety risks before crashes occur. These techniques analyze near-miss events or "conflicts" as indicators of traffic safety issues (Kácvoský, 2019). Studies using traffic conflict analysis, such as those by Alshannaq and Imam (2020), demonstrate that this method can provide early warnings of safety concerns, particularly in high-traffic areas where crashes are more likely to occur.

In addition, surrogate safety measures, such as Time-to-Collision (TTC) and Post-Encroachment-Time (PET), offer an innovative way to predict the likelihood of crashes by analyzing vehicle trajectories and interactions at roundabouts (Leonardi & Distefano, 2023b; Nnabuihe, 2020). These measures are particularly useful in evaluating newly constructed roundabouts or those with limited crash history, allowing transportation authorities to assess safety performance without waiting for crashes to accumulate.

Design Considerations for Vulnerable Road Users

The safety of vulnerable road users, including pedestrians and cyclists, is a critical concern in roundabout design. Several studies emphasize the need for dedicated lanes, pedestrian crossings, and refuges to ensure the safety of non-motorized users (Singleton & Poudel, 2023; Giuffrè *et al.*, 2017a). Research also suggests that roundabouts with optimized geometric designs can reduce crash risks for these users by minimizing conflict points and ensuring safe crossing opportunities (FHWA, 2022). For instance, a study by Alkaissi (2022) demonstrated that well-designed pedestrian crossings and appropriate signage can significantly reduce pedestrian accidents at roundabouts.

Recent advancements in intelligent transportation systems (ITS) and autonomous vehicles (AVs) have further enhanced the potential for roundabout safety. Studies indicate that integrating ITS and AV technologies into roundabout design can optimize traffic flow and reduce human errors, which are a leading cause of accidents (El Ganaoui-Mourlan *et al.*, 2023; Khakifirooz *et al.*, 2024). By improving vehicle-to-infrastructure communication and automating decision-making processes, these technologies can further reduce conflict points and enhance safety for all road users.

Benefits of Roundabouts

Generally, roundabouts offer a range of safety benefits compared to conventional signalized intersections (Awadalla & Albuquerque, 2021; Brewer *et al.*, 2023), including reduced conflict points, lower vehicle speeds, reduced crash severity, safer merges, environmental benefits, operational efficiency, and cost-effectiveness (Araslan *et al.*, 2022; ASCE, 2021; El Ganaoui-Mourlan *et al.*, 2023; Németh *et al.*, 2023).

Safety Benefits of Roundabouts

Safety is a top priority in designing and operating roundabouts. Research consistently shows significant safety advantages compared to other conventional intersections. The key advantages comprise of reduced crash rates and lower conflict points.

- (a). *Reduced Crash Rates*: Roundabouts generally experience fewer crashes, particularly severe injury crashes, compared to traditional signalized intersections (Awadalla & Albuquerque, 2021; Elzahr & Albuquerque, 2021; Qawasmeh *et al.*, 2023; TRB, 2010d, 2022). A basic analysis on some earlier studies revealed reduction in fatal and severe injury crashes in the range of 37% to 88% (Guo *et al.*, 2024; TRB, 2010d, 2010a).
- (b). *Reduced Conflict Points*: Roundabouts eliminate conflicting traffic phases present at signalized intersections, reducing potential collision points (Al Hasanat & Janos, 2023; Bari & Dhamaniya, 2022; Guerrieri *et al.*, 2015; Kehagia *et al.*, 2022). In addition, they also eliminate the need for left turns, which can significantly reduce the number of potential conflict points between vehicles, pedestrians, and other road users (ASCE, 2021; Hossain & Rahman, 2023; Spanou *et al.*, 2015)

- (c). *Lower vehicle speeds*: Roundabouts are designed to reduce vehicle speeds, which can lead to fewer and less severe crashes (ASCE, 2021; Spanou *et al.*, 2015).
- (d). *Reduced crash severity*: Studies have shown that roundabouts can reduce crash severity for all users, including pedestrians and cyclists (ASCE, 2021; Distefano & Leonardi, 2019; Pan *et al.*, 2023). Yannis *et al.*, (2023) investigated various road safety measures in Greece and reported a 20% reduction in fatalities at roundabout relative to other forms of intersections. This emphasizes the potential safety benefits of roundabouts.
- (e). *Safer merges*: Roundabouts provide more time for all users to detect and correct mistakes, allowing for safer merges into the circulating traffic (ASCE, 2021; Brewer *et al.*, 2023; Distefano & Leonardi, 2019).

Environmental Benefits

Roundabouts can reduce delays and the number and duration of stops, which can have positive environmental impacts in terms of reduced noise, air quality, and fuel consumption (Distefano & Leonardi, 2019). Studies have shown that roundabouts are more environmentally friendly compared to other types of intersections, as they substantially reduce the amount of carbon monoxide (CO) emissions relative to other at-grade priority intersections (Gazder *et al.*, 2023; Pan *et al.*, 2023). Furthermore, the integration of intelligent transportation systems (ITS) and autonomous vehicles (AVs) further enhances these benefits by optimizing traffic flow and reducing idle times, leading to lower emissions and fuel consumption (Shen *et al.*, 2023). Additionally, the implementation of countdown signals has been proposed to improve traffic safety and efficiency, which indirectly contributes to environmental benefits by minimizing stop-and-go traffic patterns (Pan *et al.*, 2023). Moreover, advancements in the recognition of occluded pedestrians from the driver's perspective help extend sight distance and ensure driving safety at signal-free intersections, contributing to smoother traffic flow and reduced environmental impacts (Qie *et al.*, 2024). The integration of these technologies demonstrates the potential for significant environmental improvements, aligning with the broader goal of sustainable transportation.

Operational Efficiency and Cost-Effectiveness

Roundabouts can improve traffic flow and reduce queues, which can lead to increased safety by reducing the likelihood of rear-end collisions (Brewer *et al.*, 2023). Due to queues reduction, road users travel time can also be shorter as against those traversing other conventional intersections that require a complete stop. In terms of construction cost, roundabouts are often less expensive to construct and maintain than traditional signalized intersections (Karunarathne *et al.*, 2021; Tarhuni *et al.*, 2024; TRL, 2018).

Design Considerations for Improved Safety at Roundabouts

Traffic safety at roundabout intersections can be enhanced through some available measures highlighted as follows:

- (a). **Geometric Design:** Several studies emphasized the importance of proper geometric design for roundabout safety. This includes providing clear sight areas, appropriate lane widths, deflection angles, and pedestrian crossings as they are crucial for safe maneuvering and reducing accidents (Ahac & Dragcevic, 2021; Ahac & Kipa, 2022; Čudina Ivančev *et al.*, 2023; Kadeha, 2016; Kehagia *et al.*, 2022; Spanou *et al.*, 2015). For instance, clear sight triangles at entry points minimize accidents (Ahac & Dragcevic, 2021; Ahac & Kipa, 2022) while, appropriate lane widths, deflection angles, and pedestrian crossings influence safety outcomes (Mark & Lin, 2018; Qie *et al.*, 2024; TRB, 2010d). Therefore, optimizing roundabout geometry can enhance safety and efficiency (TRB, 2022). Ahac & Dragcevic (2021) studied the geometric design of suburban roundabouts, providing insights into the design process and the factors that influence roundabout safety and operational performance. The study emphasized the importance of considering sight distance, road alignment, and traffic flow when designing roundabouts. Another study; Ahac & Kipa (2022), examined the clear sight areas on suburban roundabouts and found that the optimal sight distance for improved safety of roundabouts depends on factors such as the roundabout's size, traffic volume, and road alignment.
- (b). **Signage and Markings:** Clear and consistent signage and lane markings are essential for guiding drivers and help in reducing confusion (Ahac & Dragcevic, 2021; Alshannaq & Imam, 2020; Fernandes *et al.*, 2020; TRB, 2010b, 2016b, 2016a, 2022; Wang *et al.*, 2024). These measures helps ensure that drivers can navigate the roundabout safely and efficiently, minimizing the likelihood of accidents due to misunderstandings or misinterpretations of the road layout.
- (c). **Capacity Analysis:** Roundabout capacity estimation helps optimize traffic flow and indirectly improves safety by reducing congestion (Al Hasanat & Janos, 2023; H. M. Majid & Jabari, 2023). In addition, the capacity estimation models shall consider diverse traffic compositions to ensure accurate capacity estimation, which is necessary for safe roundabout operation (Al Bashaireh *et al.*, 2005; Giuffrè *et al.*, 2017a). Studies explore methods for capacity estimation in single-lane and multi-lane roundabouts (Adeke *et al.*, 2020; Al Hasanat & Janos, 2023; H. M. Majid & Jabari, 2023; TRB, 2010b, 2016b, 2016a, 2022).
- (d). **Safety for Vulnerable Users:** The vulnerable road users involve pedestrians and cyclists, while roundabouts generally improve safety; specific design features like dedicated cycling lanes and pedestrian crossings are essential for the enhanced safety of these vulnerable users (Singleton & Poudel, 2023; Tiwari & Mohan, 2016). Pedestrian refuges, proper lighting, and optimized design for cyclists are essential for safety (FHWA, 2022; Singleton & Poudel, 2023). According to (Giuffrè *et al.*, 2017a), pedestrian refuges and optimized crossing designs enhance safety for

pedestrians. Whereas, a study suggested a "Through-about" design prioritizing public transport for potential improvement of the safety of cyclists and pedestrians (Zakeri & Choupani, 2021). Besides, considering cyclist comfort in roundabout design can encourage cycling and indirectly improve safety (Singleton & Poudel, 2023). Also, pedestrian considerations in the design of roundabouts are recommended, because well-designed pedestrian crossings are vital for safety, especially in mixed traffic conditions (Alkaissi, 2022; ASCE, 2021).

- (e). **Safety Decisions Prioritizing Driver Behavior:** Driver behavior, particularly the gap acceptance at roundabout entry, plays a vital role in safety. For example, clear and consistent signage reduces driver confusion leading to improved safety (ASCE, 2021; Fernandes *et al.*, 2020). Whereas, police enforcement can influence critical gaps accepted by drivers (Shaaban & Hamad, 2021). On the other hand, driver behavior estimation systems can aid in conflict resolution at roundabouts (Sharma *et al.*, 2023), as such, studies were carried out to investigate driver behavior, particularly the follow-up headway, the critical gaps, and the gap acceptance models (Alkheder *et al.*, 2020; H. Majid & Mohammed Ali, 2023; Radović *et al.*, 2022; Shaaban & Hamad, 2020, 2021).
- (f). **Speed Management:** Operational speed is among the most important factors for ensuring appropriate safety and capacity conditions at roundabouts, available research showed that accidents related to roundabouts primarily result from exceeding operational speed (Klobučar *et al.*, 2022). Therefore, limiting the approach speeds is essential for safe roundabout operation (Anagnostopoulos *et al.*, 2022; Klobučar *et al.*, 2022; TRB, 2010b, 2010c, 2022).
- (g). **Right-Turn Bypass Lanes:** These lanes can potentially reduce weaving conflicts and improve safety, particularly for heavy vehicles (Guerrieri *et al.*, 2015; Suh *et al.*, 2018; Vichova *et al.*, 2021). The environmental and functional benefits of right-turn by-pass lanes at roundabouts was evaluated and found that right-turn by-pass lanes at roundabouts can improve environmental performance by reducing emissions and fuel consumption (Guerrieri *et al.*, 2015).
- (h). **Roundabout Metering:** Often during peak periods, flow from one entry may dominate downstream entries leading to insufficient available gaps, and causing excessive delays and queues at the downstream entry, in these cases, entrance metering can provide significant operational benefits during these peak periods, in some cases, metering may be a more economical than geometric improvements, especially if the traffic condition requiring metering is of a short duration (TRB, 2010d). Therefore metering techniques can manage traffic flow and potentially improve safety and operational efficiency (Aldohuky, 2023; Karkee *et al.*, 2023).
- (i). **Intelligent Transportation Systems (ITS):** Intelligent transportation systems include the deployment of a variety of modern technologies, such as traffic reporting by radio or mobile phones, computerized highway systems, parking

guidance and intelligence, traffic counters navigation systems, transit enhancements, and digital charging (Ogunkan & Eyitola, 2022). It also involves the integration of human driving models into autonomous vehicle trajectory planning for roundabouts and could enhance safety (El Ganaoui-Mourlan *et al.*, 2023; Khakifirooz *et al.*, 2024; Leonardi & Distefano, 2023a; Németh *et al.*, 2023).

- (j). **Roundabout Design Variations:** Recently, research on alternative designs like Elliptical and turbo roundabouts are being explored for potential safety improvements, although, they can be effective safety interventions in specific situations; however, they require further research (Alkaissi & Kamoon, 2021; Fathullah *et al.*, 2023; Qawasmeh *et al.*, 2023; Spanou *et al.*, 2015; Tarhuni *et al.*, 2024; TRB, 2010d, 2016b). Often, the elliptical roundabout is considered a superset for the modern roundabout type (Mohammed Ali & Majid, 2023). Tarhuni *et al.*, (Tarhuni *et al.*, 2024) regard the turbo-roundabout as a novel approach to the two-lane roundabout, it was implemented in the late 1990s, as a more secure and effective replacement for conventional multi-lane roundabouts, In turbo-roundabout, traffic flows independently before entering the roundabout occupying different lanes within the circulatory route, and traffic flows depart the roundabout individually as well and the structural separation is achieved using delineators, which are specially shaped components that prevent traffic lanes from changing within the roundabout. The challenges faced by motorcycles at roundabouts in mixed traffic conditions in Vietnam was studied, revealing that motorcycles tend to operate at lower speeds and exhibit different lane-changing behaviors compared to cars. This highlights the need for design considerations and potentially dedicated lanes for motorcycles at roundabouts with high motorcycle volumes around 20% of traffic (Trinh *et al.*, 2021)
- (k). **Traffic Flow and Management:** This involves calibrating capacity models for diverse traffic compositions, which can improve safety (Ahmad & Rastogi, 2019). Complementary roundabout metering may positively impact operational performance and safety (Karkee *et al.*, 2023). In addition, proper lane markings, signage, and deflection radii are crucial for safe operation (TRB, 2010d).
- (l). **Public Transport Integration:** This includes designs that prioritize public transport, like "through-about", which has been found to improve safety for vulnerable road users (Žura, 2022).
- (m). **Driver Education:** Although, driver behavior such as violating the traffic rules, lack of clear lane markings in the circulating area, and inadequate signage at the roundabouts entries are the main causes of roundabout accidents (Alshannaq & Imam, 2020). However, Studies reported that educating drivers as well as pedestrians on roundabout etiquette along with proper signage can improve safety (Alshannaq & Imam, 2020; Anagnostopoulos *et al.*, 2022; Deveaux *et al.*, 2024). Another study examined driver behavior at roundabouts in Kuwait and evaluate

their performance. The study found that drivers tend to follow the inner lane when entering a roundabout, which can lead to congestion. The authors suggest that improving driver education and signage could help improve roundabout safety and performance (Alkheder *et al.*, 2020).

- (n). **The Safe Systems Pyramid:** This framework emphasizes designing infrastructure to forgive human error and can be applied to roundabout design for further safety improvements (Chen, 2018; Chen & Hourdos, 2018; Ederer *et al.*, 2023).
- (o). **Emerging Technologies:** Integrating human driving models into autonomous vehicle trajectory planning for roundabouts can potentially improve safety (Leonardi & Distefano, 2023a). Research into how autonomous vehicles and connected car technology will interact with roundabouts is important for future safety considerations (Guerrieri, 2023; L. Li *et al.*, 2024; TRB, 2016a).

Safety Evaluation Methods at Roundabouts

Roundabouts are a proven safety countermeasure at intersections as they are increasingly replacing traditional traffic signals due to their potential for improved safety and efficiency, it is also believed that evaluating roundabout safety is crucial for optimizing design, operations, and maintaining efficient and safe intersections (Deveaux *et al.*, 2024). The common safety metrics frequently used as safety indices include crash frequency, severity (fatalities, injuries), and types of crashes (Alshannaq & Imam, 2020). While, surrogate safety measures like traffic conflicts are also valuable indicators (Kácvoský, 2019; L. Li *et al.*, 2024). In addition, driver behavior is another crucial aspect to consider with respect choice of indices for roundabout safety (Alkheder *et al.*, 2020; H. Majid & Mohammed Ali, 2023).

Safety evaluation is beyond just crash data analysis, therefore, various safety evaluation methods are reviewed highlighting their strengths, limitations, and considerations for effective implementation (Alshannaq & Imam, 2020). The choice of safety evaluation method depends on specific objectives and data availability (Alshannaq & Imam, 2020). Traditionally, these methods have been categorized into common, advanced techniques and indirect methods briefly as follows:

- (a). *The common methods* include Crash data analysis, although prevalent but limited by underreporting (Awadalla & Albuquerque, 2021; Elzaher & Albuquerque, 2021), Conflict analysis, a proactive approach using near-miss events (L. Li *et al.*, 2024; Nnabuihe, 2020), Traffic simulation, models traffic flow to assess performance and safety (Adeke *et al.*, 2020; Gracanin *et al.*, 2023; Zehawi, 2018), Driver behavior modelling, an emerging area with potential for safety evaluation (H. Majid & Mohammed Ali, 2023).
- (b). *The Advanced techniques* involve the use of LiDAR data analysis for proactive safety analysis (Bhattarai, 2003; L. Li *et al.*, 2024), Deep learning for conflict prediction (Y. Li *et al.*, 2024), Geographically weighted regression models for high-risk locations (Ling *et al.*, 2023), Driver behavior estimation (Sharma *et al.*, 2023), Drone

technology for traffic safety assessment (Shawky *et al.*, 2023) and Virtual driving simulators for driver training and assessment (Rehm *et al.*, 2024).

- (c). *Indirect safety indicators* might include Roundabout capacity estimation linked to safety through optimized traffic flow (Akçelik *et al.*, 2022; Al Hasanat & Janos, 2023), Traffic flow efficiency (Fathullah *et al.*, 2023), Noise emission levels (Distefano & Leonardi, 2019; Fernandes *et al.*, 2020; Mirzahosseini *et al.*, 2020; TRB, 2016a).

Categories of Methods for Safety Evaluation at Roundabouts

As earlier highlighted, the selection of an appropriate method depends on the specific objectives and available data (Alshannaq & Imam, 2020). These methods can be systematically categorized into; traditional methods, Proactive Safety Assessment Methods, Emerging Techniques, and Indirect Safety Measures as presented in Table 1.

Table 1: Categories of Methods for Safety Evaluation

Broad Category	Safety Evaluation Method
Traditional Methods (Reactive)	(a). Crash Data Analysis: This prevalent method analyses historical crash data (frequency, severity, types) to identify patterns and trends (Awadalla & Albuquerque, 2021; Elzahr & Albuquerque, 2021). It offers insights but can be limited by underreporting and data availability (Treiber & Kesting, 2013; Vinayaraj & Perumal, 2022). (b). Highway Capacity Manual (HCM): The HCM provides a framework for roundabout safety evaluation (TRB, 2000, 2010a, 2010c, 2010d, 2010e, 2010b, 2016a, 2016b, 2022). However, it may not capture the full picture, and further research is needed (Vinayaraj & Perumal, 2022).
Proactive Safety Assessment Methods	(c). Traffic Conflict Techniques: These techniques identify near-miss events (potential collisions) as indicators of safety risks (Kácvský, 2019; Y. Li <i>et al.</i>, 2024). They are valuable for proactive safety assessment (Alshannaq & Imam, 2020). (d). Traffic Simulation: Traffic simulation models traffic flow to assess roundabout performance and potential safety concerns (Adeke <i>et al.</i>, 2020; Gracanin <i>et al.</i>, 2023; Zehawi, 2018). It is useful for evaluating design changes and future scenarios.
Emerging Techniques	(e). Driver Behavior Modeling: This emerging field explores how driver behavior impacts safety at roundabouts (Farman Majeed Salam & Majid, 2022; Majid & Mohammed Ali, 2023; Sharma <i>et al.</i>, 2023). (f). Advanced Techniques: Methods like LiDAR data analysis and deep learning show promise for conflict prediction (Bhattarai, 2003; Han, 2022; Y. Li <i>et al.</i>, 2024). Other techniques include geographically weighted regression models, driver behavior estimation, and drone technology (Ling <i>et al.</i>, 2023; Sharma <i>et al.</i>, 2023; Shawky <i>et al.</i>, 2023).

Indirect Safety Measures	(g). Roundabout Capacity Estimation: Optimize traffic flow through capacity estimation models can be indirectly linked to safety (Akçelik <i>et al.</i>, 2022; Al Hasanat & Janos, 2023; Anagnostopoulos <i>et al.</i>, 2021; Čudina Ivančev <i>et al.</i>, 2023; Giuffrè <i>et al.</i>, 2017b; Karimov <i>et al.</i>, 2023; A. Khan <i>et al.</i>, 2022; Khekare <i>et al.</i>, 2022; Mahesh <i>et al.</i>, 2016; Majid & Mohammed Ali, 2023; Patnaik <i>et al.</i>, 2020; Pratelli <i>et al.</i>, 2022; Pratelli & Brocchini, 2022; X. Qu <i>et al.</i>, 2014; Z. Qu <i>et al.</i>, 2014; Radović <i>et al.</i>, 2022; Sharma <i>et al.</i>, 2023; Žura, 2022). (h). Other Indirect Indicators: Traffic flow efficiency, noise emission levels, and gap acceptance models can also provide insights into safety (Alkheder <i>et al.</i>, 2020; Anai <i>et al.</i>, 2024; Distefano & Leonardi, 2019; Fathullah <i>et al.</i>, 2023; Fernandes <i>et al.</i>, 2020; Kalašová <i>et al.</i>, 2021; Radović <i>et al.</i>, 2022; Shaaban & Hamad, 2020, 2021).
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Future Research Needs

This review identified several areas for further research to optimize roundabout safety:

- (a). Investigate driver behavior and gap acceptance decisions in detail.
- (b). Quantify the safety benefits of emerging safety measures like bypass lanes and alternative designs.
- (c). Optimize roundabout design for the safety of vulnerable users like pedestrians and cyclists.
- (d). Explore the integration of emerging technologies like ITS and autonomous vehicles with roundabouts.
- (e). Conduct long-term safety performance studies and develop robust evaluation methods.
- (f). Analyze the cost-effectiveness of different roundabout designs, safety measures, and evaluation methods.

Addressing these research needs, transportation engineers, planners, and researchers can continue to improve the safety and efficiency of roundabouts for all users, making them a widely adopted and beneficial intersection design.

Summary of Key Findings

In summary, the literature provides robust evidence of the safety and operational benefits of roundabouts, particularly in reducing crash rates and improving traffic flow. However, these benefits are highly dependent on the proper design and implementation of roundabouts, as well as the use of effective safety evaluation techniques. Geometric design, signage, and provisions for vulnerable users are crucial elements that must be optimized to maximize the safety potential of roundabouts. Furthermore, advanced evaluation methods, such as traffic conflict analysis and surrogate safety measures, offer valuable tools for proactively assessing and improving roundabout performance.

By addressing these design and evaluation considerations, transportation authorities can further enhance the safety and efficiency of roundabouts, making them a more widely adopted solution for managing traffic at intersections.

Conclusion

Roundabouts have gained widespread recognition as a safer and more efficient alternative to conventional signalized intersections. This review paper discusses the various safety benefits of roundabouts, including significant reductions in crash rates, particularly for severe injuries and fatalities, by minimizing conflict points and reducing vehicle speeds. The design of roundabouts has proven to be effective in enhancing traffic flow, reducing delays, and providing environmental benefits through lower emissions and fuel consumption.

In addition to safety benefits, roundabout design plays a critical role in their operational efficiency. Key design elements such as geometric layout, clear signage, lane markings, and the incorporation of innovative features like right-turn bypass lanes and roundabout metering systems are essential for ensuring the safety of both motorized and non-motorized road users, including pedestrians and cyclists. The review also stresses the importance of using robust safety evaluation methods, such as crash data analysis, traffic conflict techniques, and surrogate safety measures to continuously assess and improve roundabout performance.

However, challenges remain; including variability in design standards across regions, limitations in long-term safety data, and the need for more focused research on vulnerable road users. Addressing these challenges through more standardized design practices and advanced evaluation techniques will further enhance the safety and efficiency of roundabouts.

Recommendations

Based on the findings of this review, the following practical recommendations are proposed for enhancing roundabout safety and performance:

- i. **Geometric Design:** Ensuring that roundabouts are designed with proper geometric features, including clear sight triangles at entry points, appropriate lane widths, deflection angles, and pedestrian crossings. This will enhance safe maneuvering and reduce potential accidents.
- ii. **Signage and Markings:** Use of clear, consistent signage and lane markings to guide drivers and reduce confusion. Ensure proper placement of yield signs and speed limit signs to enhance safety at entry and exit points.
- iii. **Capacity Analysis and Traffic Flow Management:** Conduct regular capacity analysis to optimize traffic flow, particularly in multi-lane roundabouts. Adjust lane configurations and add right-turn bypass lanes where necessary to reduce weaving conflicts and improve efficiency.

- iv. Safety for Vulnerable Road Users: Prioritize the safety of pedestrians and cyclists by including dedicated cycling lanes, pedestrian refuges, and well-marked crossings. Ensure proper lighting for pedestrian areas to enhance visibility, especially during low-light conditions.
- v. Speed Management: Implement speed control measures such as speed humps, rumble strips, and signage at roundabout approaches to ensure that vehicles enter the roundabout at safe speeds, minimizing the risk of crashes.
- vi. Roundabout Metering Systems: Consider the use of roundabout metering during peak periods to manage traffic flow and prevent excessive delays at downstream entries. This technique can enhance safety and reduce congestion without major geometric changes.
- vii. Advanced Evaluation Techniques: Utilize emerging technologies like traffic simulation models, drone-based traffic assessments, and LiDAR-based conflict analysis to proactively assess safety risks and improve roundabout design.
- viii. Integration of Intelligent Transportation Systems (ITS): Integrate ITS solutions such as autonomous vehicle guidance, connected car technology, and real-time traffic monitoring to improve safety and efficiency at roundabouts. This includes adaptive traffic signals and dynamic lane management.

Author(s) Contributions

The authors confirm contribution to the paper as follows:

- A. Batari: Study conception and design, literature collection, summarization, analysis and interpretation of results, draft manuscript preparation.
- M. N. Ibrahim: Study conception, analysis and interpretation of results, design and supervision, manuscript critical review and proofreading.

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Conflict of interest

The authors declare that they have no conflict of interest.

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