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A Comprehensive Review on the Impact of Gap Parameters for Multiple Types of Roundabouts in Different Traffic Conditions

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Abstract

The increasing number of vehicle owners due to population growth has significantly impacted traffic patterns worldwide. Roundabouts have proven to be an effective solution for improving traffic flow, safety, and sustainability. Roundabouts offer operational simplicity and fewer conflict points compared to traditional unsignalized intersections. This study examines the impact of gap parameters, which are key parameters for evaluating roundabout capacity, on various types of roundabouts across diverse traffic scenarios. Beginning with a historical overview of roundabouts and gap acceptance behavior, this comprehensive review explores a range of methodologies, including computer simulations, real-world observations, and mathematical models, to gain insights into traffic flow dynamics and vehicle behavior. Additionally, the review analyzes the evolution of roundabout design and geographical disparities, highlighting the multitude of factors influencing roundabout performance. This review aims to provide valuable insights gathered from previous research on how gap parameters influence the performance of different roundabouts. Finally, it highlights the essential role of gap parameters in maximizing roundabout efficiency to benefit all road users, offering valuable insights for researchers and enthusiasts seeking deeper comprehension of roundabout dynamics.

1. Introduction

A roundabout is a circular intersection in which traffic travels counterclockwise on the right side of the roadway and clockwise on the left side of the roadway around a central island. Entering traffic must yield to circulating traffic. Roundabouts are designed to control motor vehicle speeds throughout the roundabout, typically between 15 mph to 25 mph (24 km/h to 40 km/h) [1]. They also reduce conflict points and severity compared to other intersection types [2].

Roundabouts have become increasingly popular worldwide due to their adaptable design, which addresses various traffic scenarios and provides advantages such as decreased congestion, shorter wait times, reduced emissions, and enhancing road safety. They are especially beneficial in areas with high traffic volumes, contributing to a cleaner and safer environment [3].

However, the effectiveness of roundabouts is significantly influenced by various design and operational parameters, among which the gap acceptance parameter stands out due to its impact on traffic performance. Gap acceptance essentially refers to the minimum time gap between vehicles that drivers are willing to accept for entering the roundabout, a factor that varies widely depending on the type of roundabout and the current traffic conditions. Recent research suggests that optimal gap settings have a significant impact on overall congestion levels at roundabouts [4]. Advances in traffic engineering and behavioral studies emphasize the necessity of conducting comprehensive gap parameter analysis to optimize roundabout design and operation, thereby enhancing vehicle throughput, reducing delays, and mitigating traffic congestion at roundabouts [5].

This paper aims to summarize current knowledge on the impact of gap parameter analysis across different types of roundabouts, including single-lane, multi-lane, and turbo roundabouts. By examining various research findings, simulation studies, and field data, this paper aims to clarify how gap parameter analysis can inform better design practices and improve traffic flow across diverse traffic conditions and roundabout configurations. Furthermore, this comprehensive review explores the methodologies employed in gap analysis, highlighting both traditional approaches and innovative techniques facilitated by emerging technologies. The comparative analysis of gap parameters across different roundabout types offers valuable insights into the nuances of driver behavior, the efficacy of various design features, and the potential for technological interventions to optimize roundabout performance.

The objective of this paper is to offer a thorough examination of gap parameter analysis for roundabouts, highlighting existing gaps in knowledge and suggesting future research directions. Beginning with a review of the historical development of roundabouts and the theoretical foundations of gap acceptance, this paper highlights key models. It then explores methodologies for gap parameter analysis and reviews their impact on different roundabout types. By emphasizing the importance of gap acceptance, the paper aims to improve roundabout performance and identifies gaps for future research.

2. Background

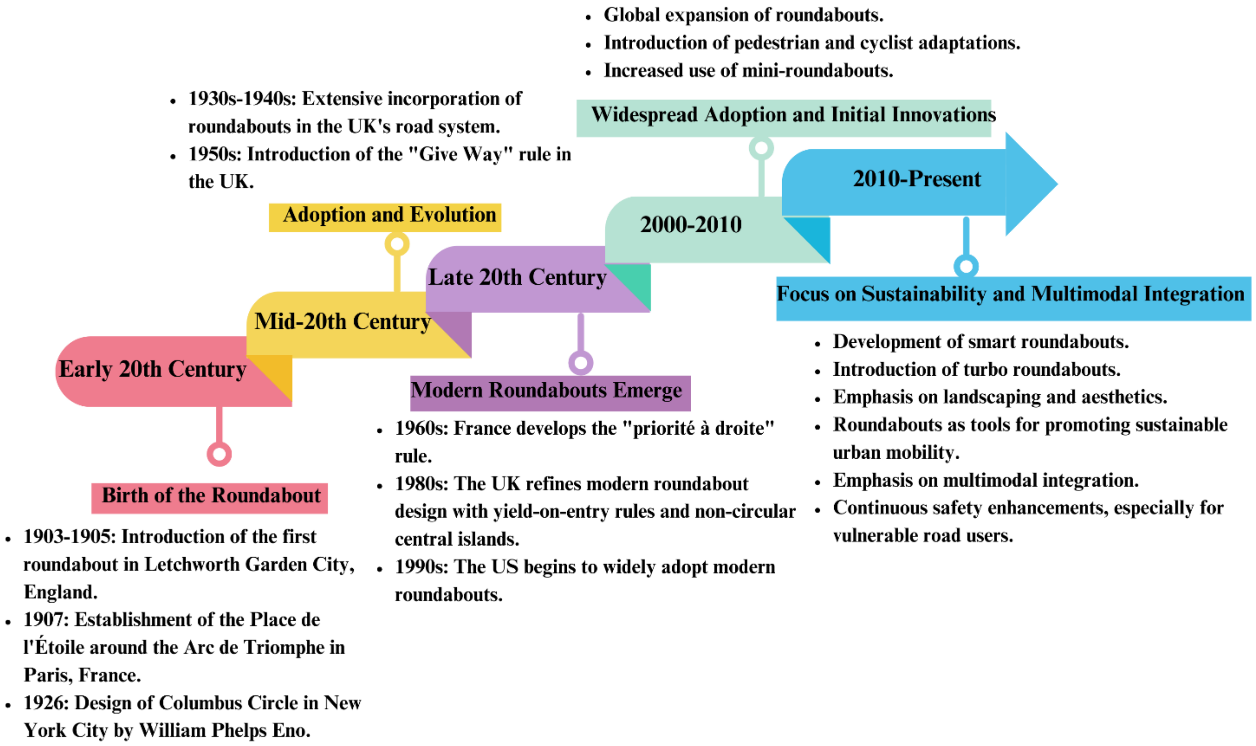
2.1 Historical Development of Roundabouts

The development of roundabouts, also known as traffic circles, represents a fascinating journey through the evolution of transportation engineering, urban planning, and road safety management. This journey, spanning over a century, reflects significant changes in vehicle use, traffic flow theory, and urban design principles.

The concept of the roundabout first emerged in the early 20th century, marking its birth as a pivotal innovation in managing vehicle flow and enhancing safety. The earliest known example dates back to between 1903 and 1905 in Letchworth Garden City, England, where it was integrated into the city’s urban design [6]. Around the same time, the Place de l'Étoile around the Arc de Triomphe in Paris emerged as one of the most renowned early traffic circles [7]. By 1926, Columbus Circle in New York City was designed by William Phelps Eno, further cementing the roundabout’s place in urban traffic management. The mid-20th century saw the United Kingdom play a crucial role in the adoption and evolution of roundabouts. During the 1930s and 1940s, the UK began incorporating roundabouts into its road system extensively, developing rules and designs that greatly influenced their construction worldwide [8]. The introduction of the "Give Way" rule in the 1950s significantly improved their safety and efficiency [9]. The late 20th century marked the emergence of modern roundabouts, with France developing the "priorité à droite" rule in the 1960s and the UK refining roundabout design in the 1980s [10]. These innovations marked the beginning of the modern roundabout era and paved the way for the widespread adoption of roundabouts in the United States during the 1990s, backed by the efforts of the Insurance Institute for Highway Safety (IIHS) and the Federal Highway Administration (FHWA) [11].

From 2000 to 2010, there was global expansion and initial innovations, such as adaptations for pedestrians and cyclists and the introduction of mini-roundabouts for urban areas with limited space [8]. The integration of technology, the spread of turbo roundabouts, and an increased focus on landscaping and aesthetics defined the next decade, showcasing the roundabout’s versatility and its role in urban beautification and biodiversity support.

The most recent developments, from 2020 onwards, emphasize sustainability and multimodal integration, with designs accommodating electric vehicle charging stations, bus stops, bike-share stations, and pedestrian pathways. These enhancements aim to promote sustainable urban mobility and protect vulnerable road users, highlighting the continuous evolution of roundabouts as a crucial component of modern urban transport networks [12], [13]. Fig. 1. illustrates a timeline highlighting key historical developments in roundabouts.



Birth of the Roundabout

- 1903-1905: Introduction of the first roundabout in Letchworth Garden City, England.
- 1907: Establishment of the Place de l'Étoile around the Arc de Triomphe in Paris, France.
- 1926: Design of Columbus Circle in New York City by William Phelps Eno.

Adoption and Evolution

- 1930s-1940s: Extensive incorporation of roundabouts in the UK's road system.
- 1950s: Introduction of the "Give Way" rule in the UK.

Modern Roundabouts Emerge

- 1960s: France develops the "priorité à droite" rule.
- 1980s: The UK refines modern roundabout design with yield-on-entry rules and non-circular central islands.
- 1990s: The US begins to widely adopt modern roundabouts.

Widespread Adoption and Initial Innovations

- Global expansion of roundabouts.
- Introduction of pedestrian and cyclist adaptations.
- Increased use of mini-roundabouts.

Focus on Sustainability and Multimodal Integration

- Development of smart roundabouts.
- Introduction of turbo roundabouts.
- Emphasis on landscaping and aesthetics.
- Roundabouts as tools for promoting sustainable urban mobility.
- Emphasis on multimodal integration.
- Continuous safety enhancements, especially for vulnerable road users.

Fig. 1 *Historical development of roundabouts*

This ongoing evolution highlights the significance of roundabouts in the broader context of transportation infrastructure and urban planning, promoting safer, more efficient, and sustainable urban environment.

3. Theory Of Gap Acceptance for Roundabout

Gap acceptance is a fundamental concept in traffic engineering that refers to the willingness of drivers to accept gaps in traffic to perform maneuvers such as merging or crossing intersections [14]. It involves two main components: critical gap and follow-up time headway [15].

The critical gap, developed in the 1970s, represents the smallest gap that a driver is willing to accept to safely merge or cross traffic streams. It influences driver behavior significantly and is crucial for understanding traffic interactions [16]. However, it is important to note that the critical gap itself is not directly observable; only the accepted or declined gaps are observable.

On the other hand, follow-up headway is the average time interval between queued vehicles in a minor stream as they traverse the intersection during longer gaps in the major stream. This metric helps in understanding how vehicles progress through the intersection under varying traffic conditions [17], [18].

Gap acceptance cycles model roundabout capacity and performance. These cycles comprise a blocked period, where vehicles wait due to a lack of an acceptable gap, and an unblocked period, where vehicles depart when an acceptable gap occurs. This cycle mirrors a signal cycle, with a blocked period akin to the red period and an unblocked period akin to the green period [19].

Fig. 2. shows an illustration of gap parameters for both right-hand and left-hand driving at a four-legged roundabout. Right-hand driving creates a counterclockwise circulating flow around the roundabout, while left-hand driving creates a clockwise circulating flow.

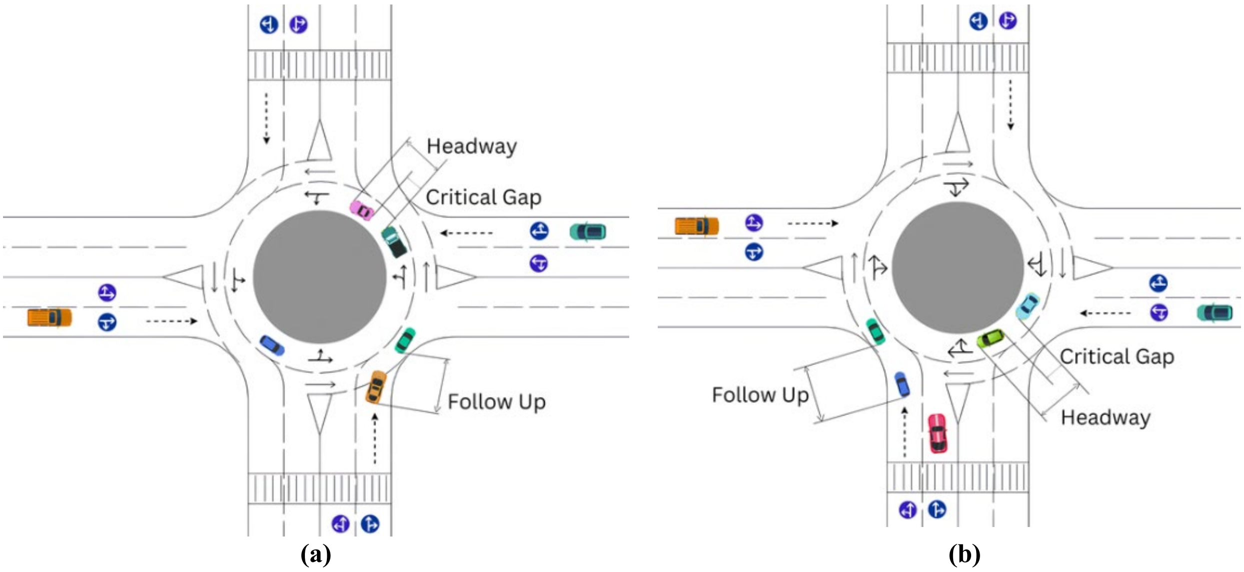


Fig. 2 *Illustration of gap parameters: (a) Right-hand driving; (b) Left hand driving*

Several models have been developed to calculate critical gap and follow-up headway at roundabouts, including the Logit model, Raff's model, Wu's model, Harder's model, the Maximum Likelihood method, Macioszek model, and Ashworth's model. These models offer insights into traffic behavior and aid in estimating capacity at intersections and roundabouts. The calculation of the critical gap and follow-up time using these methods is outlined below:

3.1 Logit Model

Logit model was developed to determine critical gaps at roundabouts using rigorous field observations and data analysis [20]. This model integrates a variety of characteristics, such as gap size, circulating vehicle types, vehicle intensity, and environmental factors, to more accurately and reliably predict driver behaviors while accepting or rejecting gaps. Equation (1) computes the critical gap.

$$t_{cri} = \frac{a_{acc}\, b_{acc} - a_{rej} b_{rej}}{a_{acc} - a_{rej}} \tag{1}$$

where: t_{cri} - critical gap, a_{acc} and b_{acc} - logit function parameters for the cumulative probability accepted gaps, a_{rej} and b_{rej} - logit function parameters for the cumulative probability of rejected gaps.

3.2 Raff's Model

Raff's model became popular because of its simplicity and macroscopic approach to estimating critical gaps at roundabouts [16]. It requires analyzing accepted and rejected gap intervals to calculate the critical gap. However, integrating gaps into intervals may result in approximation and overlooking individual gap acceptance characteristics, impacting accuracy in a variety of traffic scenarios [21]. Equation (2) is used to calculate the critical gap for a major stream.

$$F_a(t) = 1 - F_r(t) \tag{2}$$

where: $F_a(t)$ - cumulative probability of accepted gap, $F_r(t)$ - cumulative probability of rejected gap, t – critical gap of major stream.

3.3 Wu's Model

Wu introduced a model in 2012 [22] for calculating critical gaps at roundabouts, emphasizing macroscopic probability equilibrium to ensure robust results without relying on assumptions about driver consistency or predefined gap distribution. This model, conducive to straightforward calculations without iteration, can be easily implemented in tools like Excel. However, its focus on macroscopic equilibrium may overlook individual driver nuances, potentially limiting its applicability in scenarios requiring detailed analysis of driver behavior for accurate critical gap estimation. Equation (3) is utilized to calculate the critical gap using Wu's model.

$$t_{c\ average} = \sum \left[p_{tc}\left(t_j\right) * t_{dj}^2\right] \tag{3}$$

where: $t_{c\ average}$ – average critical gap, $p_{tc}\left(t_j\right)$ - frequencies of the estimated critical gaps, t_{dj} - the class mean for two consecutive time gaps in seconds.

3.4 Harder's Model

In 1968, Harder [23] developed this model to accurately estimate critical gaps at roundabouts, extending its practical applicability beyond its original context. However, its effectiveness may be constrained in capturing all nuances of driver behavior under specific conditions. The estimation of the critical gap involves two steps, employing equations (4) and (5).

$$a_i = A_i . N_i \tag{4}$$

$$t_{c\ average} = \sum \left[p_{tc}\left(t_j\right) * t_{dj}^2\right] \tag{5}$$

where: a_i - the number of acceptable intervals in interval i, A_i - the frequency or number of acceptable intervals in interval i, N_i - the frequency or number of intervals in interval i, t_c - the critical gap, t_i - the center of each time interval i, a_{i-1} - the number of acceptable intervals in the previous interval $i-1$, $F_c(t_i)$ - the cumulative distribution function of the critical gap at time interval i, $F_c(t_{i-1})$ - the cumulative distribution function of the critical gap at the previous time interval $i-1$.

3.5 Maximum Likelihood Method

The Maximum Likelihood method offers a precise equation (6) for estimating critical gaps at roundabouts, employing drivers' largest rejected and accepted gaps in circulating traffic flow. This approach enables accurate estimations across diverse vehicle types, thereby enhancing traffic characteristic identification and capacity determination. However, despite its effectiveness, the model's applicability may be constrained in scenarios necessitating detailed analysis of factors such as occupancy, vehicle type, and socio-demographics for comprehensive critical gap estimation [24].

$$L = \sum_{i=1}^{n} ln((F(a_i) - F(r_i)) \tag{6}$$

where: L - the average critical gap for all drivers, a_i - the accepted driver's gap observed, r_i - the largest rejected gap observed, $F(a_i)$ - the probability that the critical interval for an individual driver falls below, $F(r_i)$ - the probability that the critical interval for an individual driver falls below.

3.6 Macioszek Model

The Macioszek model, was developed for estimating follow-up headway at urban roundabouts. However, its utility may be confined to particular urban single-lane roundabouts. Moreover, additional research is needed for multilane and turbo roundabouts, where investigations into follow-up headway are relatively limited. Equation (7) facilitates the computation of the follow-up headway value [24].

$$t_f = t_f^{next} - t_f^{previous} [s] \tag{7}$$

where: t_f - follow-up headway [s], t_f^{next} - the crossing time at the edge of the roundabout roadway by the next vehicle driver [s], $t_f^{previous}$ - the crossing time at the edge of the roundabout roadway by the previous vehicle driver [s].

3.7 Ashworth's Model

In 1970, Ashworth [25] developed a model offering a practical method for estimating critical gaps at roundabouts, as described by equation (8). This approach utilizes observed accepted gaps, facilitating capacity analysis. However, the model's reliance on manual data analysis may introduce errors or subjectivity. Additionally, variability in driver behavior and local traffic regulations can affect critical gap estimation accuracy, emphasizing the need for region-specific adjustments.

$$t_c = \bar{t}_a - V_p \sigma_a^2 \tag{8}$$

where: t_c - critical gap (s), V_p - the flow rate of circulating stream (pcu/s), $\bar{t}_a$ - the mean of accepted gaps (s), σ_a^2 - the variance of accepted gaps.

4. Methodologies for Gap Parameter Analysis

Gap parameter analysis is crucial in transportation and traffic engineering for optimizing roundabout efficiency, and capacity. It assesses critical and follow-up headway gaps, influencing driver behavior and decision-making. Methodologies vary from direct observations to simulations, each with unique strengths and limitations, categorized into theoretical models, empirical models, and simulation models. These approaches provide insights into driver gap perception and reaction, guiding design, and operational strategies to enhance roundabout performance. Fig. 3 shows the classification of methodologies for roundabout gap parameter analysis.

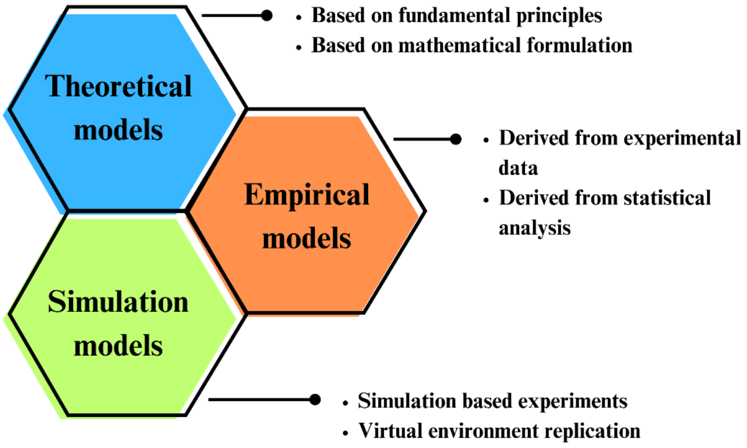


Fig. 3 *Classification of methodologies for gap parameter analysis*

The methodologies for gap parameter analysis in roundabouts have been explored through various studies, focusing on different aspects such as critical gap estimation, the influence of geometric and operational parameters, and the adaptation of models to specific contexts. For instance, studies systematically review critical headways for single and multi-lane roundabouts using maximum likelihood methodologies [26]. Others investigate critical gap analysis for dual-lane roundabouts, demonstrating the underestimation of entry capacity when default gap parameter values are used [27]. Further analyses quantify changes in gap parameters over time, investigate the distribution and calculation of critical gaps, develop empirical models for predicting gap acceptance parameters [28], and introduce new methods for analyzing driver behavior and estimating critical gaps, considering the effects of roundabout geometry [29]. These studies collectively advance the field by offering diverse methodologies and insights into the complex dynamics of gap parameter analysis in roundabouts.

The methodologies for gap parameter analysis in roundabouts and their resulting impact on traffic flow reveal a complex interplay of factors that demand attention. The variation in critical gap estimation methods highlights the detailed nature of gap acceptance behavior and its pivotal role in roundabout entry capacity. This variation not only reflects the diversity in analytical approaches but also hints at the potential for discrepancies in outcomes [30], [31]

The findings further clarify the significance of considering heterogeneous traffic conditions, which are often the norm rather than the exception in many parts of the world. The difference in critical gap values between homogeneous and heterogeneous conditions accentuates the necessity for localized analysis, acknowledging that traffic flow dynamics can vary dramatically based on the specific context of driver behavior, vehicle types, and roundabout design. This is particularly evident in studies conducted in diverse settings such as India [32] and Qatar [33], where local factors distinctly influence gap acceptance and critical gap estimations.

Moreover, the challenges associated with multilane roundabouts, where group gap acceptance behavior becomes a critical factor [29], reveal an additional layer of complexity. These challenges not only affect critical gap estimation but also the overall efficiency of traffic flow through roundabouts. The interaction between drivers in a multilane setting, especially in terms of cooperative and competitive behaviors, necessitates a more sophisticated approach to understanding and modeling gap acceptance [35]. Table 1 shows the comparative overview of roundabout capacity analysis techniques.

Table 1 *Exploration of three distinct methodologies for analyzing the gap parameter*

Model type	Description	Examples
Theoretical	Utilizes fundamental principles and mathematical analysis to predict roundabout capacity.	Interweave theory model: It analyzes weaving movements and capacity based on vehicle paths [35]. Regression model: It predicts roundabout capacity based on geometric parameters and traffic flow theory [18]. Gap acceptance theory: It studies driver behavior in accepting gaps and predicts flow dynamics [19].
Empirical	Relies on real-world data and statistical analysis to establish relationships between parameters.	Sidra intersection software: It employs regression analysis to assess roundabout performance [36]. Macioszek model: It provides lane-based analysis using empirical data to predict roundabout behavior [37]. Arcady: This empirical software tool developed by the UK that analyzes roundabout geometry and performance [38].
Simulation	Simulates individual vehicle movements to analyze roundabout performance under various conditions.	Paramics: It simulates vehicle movement within freeway networks [39]. Vissim: It simulates vehicle movement to assess roundabout operation [40]. Aimsun: It provides detailed analysis of traffic flow and behavior [41].

The exploration into the use of microscopic simulation models for gap parameter analysis in roundabouts reveals a transformative approach to understanding and optimizing traffic flow dynamics. These models stand out for their detailed representation of individual vehicle movements, allowing for a more nuanced analysis of traffic interactions and behaviors at roundabouts.

The advantages of microscopic simulation models are multifaceted, providing deeper insight into the intricacies of vehicle arrivals, departures, and queue formations [42]. Unlike traditional analytical models, these simulations offer a dynamic platform to assess traffic flow characteristics comprehensively. This includes the ability to model the spatial extent of queues and the variability in driver behavior, critical factors in the efficient design and operation of roundabouts.

Calibration and validation emerge as critical steps in leveraging the full potential of microscopic simulation models. The application of driving simulator experiments and genetic algorithms in the calibration process is a testament to the innovative approaches being utilized to align simulation outputs with real-world observations [43]. This meticulous calibration ensures that the models accurately reflect the complex dynamics at play in actual roundabout scenarios, thereby enhancing the credibility and utility of simulation results.

The impact of microscopic simulation models on understanding gap acceptance behavior is particularly noteworthy. By enabling the detailed evaluation of drivers' gap acceptance decisions based on location-specific data, these models provide invaluable insights into how different operational and design alternatives can influence roundabout efficiency.

Furthermore, the feasibility of integrating artificial neural network-based models for gap acceptance into these simulations illustrates the cutting-edge methodologies being adopted to refine our understanding of driver behavior in roundabout contexts [44].

4.1 Advantages and Limitations of Theoretical and Empirical Models

Theoretical and empirical models play vital roles in roundabout analysis, offering distinct advantages and limitations. Theoretical models, grounded in fundamental principles and mathematical analysis, provide systematic approaches to capacity estimation, including interweave theory, regression models, and gap acceptance theory. While theoretically driven, these models may oversimplify real-world complexities, limiting their practical applicability. In contrast, empirical models rely on real-world data and statistical analysis, offering a more practical approach to roundabout analysis [45]. Approaches like Macioszek model leverage field data to predict roundabout behavior [24]. However, empirical models may face limitations due to data availability and generalizability. A balanced approach integrating theoretical insights with empirical observations is crucial for advancing roundabout analysis and enhancing transportation systems' efficiency and safety.

Haitham et al.'s study [28] identifies nine independent parameters and constructes three models: one using the Multivariate Adaptive Regression Spline (MARS) algorithm, another employing Pearson correlation, and the third utilizing Spearman correlation. The MARS model exhibited superior predictive performance, emphasizing circulating traffic flow and distance between neighboring legs as influential parameters for predicting critical gap value. This highlights the practical utility of empirical modeling approaches, particularly when considering real-world factors.

Gap acceptance theory offers valuable insights into driver behavior at intersections, aiding in understanding how drivers decide to enter traffic streams based on available gaps. Regression models further quantify relationships between factors like gap size, vehicle speed, and driver behavior, aiding in gap parameter analysis. While empirical studies suggest integrating gap acceptance dynamics can enhance road safety, determining optimal evaluation models remains challenging. Madena et al.'s study [46] develops a gap acceptance model for roundabouts in India, leveraging critical headway estimation methods like Raff and Ning Wu to shed light on driver behavior and roundabout performance. Their findings underscore the importance of incorporating real-world driver behavior into modeling efforts to improve roundabout efficiency and safety.

Similarly, Ruijun et al. [47] demonstrate Gap acceptance theory's utility in roundabouts for realistic capacity calculations, considering drivers' behavior alongside mathematical modeling. Their study emphasizes the importance of accounting for real-world complexities, such as heterogeneous driver behavior, to accurately assess roundabout capacity. By highlighting the advantages and limitations of theoretical and empirical models, these studies contribute to the ongoing efforts to enhance roundabout analysis and optimize transportation systems.

4.2 Advantages and Limitations of Microscopic Simulation Models

Microscopic simulation models represent a significant advancement from traditional analytical models by incorporating detailed behaviors of individual vehicles, thereby offering a more granular view of traffic dynamics. This approach enables a comprehensive analysis of vehicle arrivals and departures, the spatial extent of queues, and various traffic flow characteristics, providing insights crucial for the effective design and management of roundabouts [48]. Furthermore, the use of driving simulators to study gap acceptance behavior illuminates the critical relationship between vehicle arrival distributions and the acceptance of gaps by drivers, a factor central to the safety and efficiency of roundabout operations [43].

Unlike macroscopic models, which aggregate traffic characteristics over larger time and spatial scales, microscopic models allow researchers to capture intricate interactions between vehicles in real-time, making them particularly suitable for studying complex intersections.

However, it is important to acknowledge the limitations of microscopic simulation approaches. These models require extensive calibration and validation to accurately represent real-world conditions, which can be time-consuming and resource-intensive. Additionally, microscopic simulation models may oversimplify certain aspects of driver behavior or fail to capture the full complexity of traffic interactions, leading to potential discrepancies between simulated and observed outcomes. For instance, variations in driver decision-making and unpredictable environmental conditions can be challenging to replicate in simulation.

Despite these challenges, microscopic simulation remains a valuable tool for understanding and optimizing roundabout performance. Table 2 shows the different features and limitations of microsimulation software and analytical software that are used on gap parameter analysis research, highlighting the strengths and weaknesses of each approach in traffic studies.

Table 2 *Different types of simulation software are used in roundabout gap parameter analysis*

Software	Origin	Year	Functionality	Limitations	Ref.
PARAMICS	UK	1990	Model vehicle movement on freeway networks.	Time-consuming data entry for large networks.	[49]
VISSIM	Germany	1994	Microscopic simulation for multimodal transport.	Powerful but not always cost-effective.	[50]
SIDRA	Australia	1995	Evaluate traffic capacity and signalized intersections.	Requires familiarity with the software for efficient use.	[51]
SYNCHRO v12	USA	1997	Optimizes traffic networks for improved mobility and safety.	The complexity of Synchro Studio v12 may deter inexperienced users.	[52]
AIMSUN	Spain	1997	Generate traffic conditions based on route choice.	Time-consuming data entry for large networks.	[53]
SSAM	USA	2008	Predict collisions using microsimulation.	Inconsistent estimation of unexpected maneuvers.	[54]
TRITONE	Italy	2009	Evaluate traffic safety performance.	Requires rigorous model calibration.	[55]

VISSIM and AIMSUN are renowned for their powerful microscopic simulation capabilities, allowing detailed analysis of traffic dynamics. However, they encounter challenges regarding cost-effectiveness [56] and the time-consuming nature of data entry processes [57]. While these tools offer sophisticated features, their usability may be hindered by these limitations, impacting their practical applicability in real-world transportation planning scenarios.

Conversely, SSAM and TRITONE focus on proactive evaluation of traffic safety, offering valuable insights into collision prediction and safety performance assessment. Despite their potential, these tools require further investigation and meticulous model calibration to ensure consistency and reliability in their outputs [58], [59]. PARAMICS, specializing in modeling vehicle behavior [60], faces challenges related to parametric data entry efficiency, which can impede workflow efficiency, particularly for large networks. Meanwhile, Synchro, while emphasizing traffic flow modeling, may overlook critical factors such as start-up lost time at signalized intersections, potentially leading to inaccuracies in simulation outputs [61]. Thus, there is a clear need for enhancements in data processing efficiency, accuracy of simulation outputs, and consideration of nuanced factors affecting traffic flow and safety to improve the reliability and applicability of these software solutions in transportation planning and management. Critical improvements in model calibration, validation techniques, and user-friendliness are imperative to address these challenges and maximize the effectiveness of these tools in real-world transportation scenarios.

5. Current Research on Roundabout Capacity Models

The evolution of roundabout capacity and gap parameter research over the last two decades has witnessed significant methodological advancements, a deeper understanding of influencing factors, and an increasing recognition of the need for geographic specificity in model development. This comprehensive review synthesizes findings from key studies conducted from 2018 to 2023, shedding light on the progression of the field, emerging trends, and critical areas for future investigation. Understanding the capacity of roundabouts is integral to enhancing traffic conditions, and various capacity models are employed for this purpose, as outlined in Table 3.

Table 3 *Roundabout capacity models: overview*

Origin	Model Name	Approach/Formula Basis	Notes
United States of America (USA)	Highway Capacity Manual (HCM) [62]	Exponential Decay	Widely used in the USA
Australia	Signalized and Unsignalized Intersection Design and Research Aid (SIDRA) [63]	Exponential Decay with Adjustments	Reflects Australian conditions
Europe	German Brilon-Wu, Fortuijn-Harte, E. Macioszek, Kimber, French, Swiss	Various, including Linear and Exponential	Diverse, country-specific models
Other	Linear, Exponential Regression	Linear and Exponential Relationships	Applicable in various contexts
	Wu, Hagring, Mauro-Branco, SETRA, Direct Measure	Complex Formulations	Specific conditions or adjustments

The early part of the last decade focused on empirical and analytical approaches to understanding roundabout capacity. For instance, Mensah et al. [64] provided foundational insights into critical gap reductions on Maryland roads, highlighting the potential for significant improvements in roundabout efficiency through design modifications. However, these early studies were often constrained by the limitations of direct observation and manual data processing techniques, as noted in the work of An et al. [65], where critical gaps for different vehicle types at an intersection in Ahmedabad were analyzed.

The advent of sophisticated simulation tools marked a paradigm shift in research methodologies. Studies like those conducted by Amin et al. [66] and Sandaruwan et al. [67] leveraged VISSIM and AIMSUN, respectively, to model complex traffic scenarios, enabling a nuanced analysis that accounts for a myriad of variables. This shift towards simulation-based studies underscores the field's progression towards capturing the dynamic and complex nature of traffic flow at roundabouts.

A recurring theme across the reviewed literature is the influence of geographic specificity on roundabout capacity and gap acceptance behaviors. The study by Pratelli et al. [68] illustrates the nuanced differences that can arise even within similar traffic conditions, emphasizing the role of local driving behaviors and roundabout designs in influencing capacity estimates. Similarly, research by Khekare et al. [34] and Shaaban et al. [29] highlighted how models' applicability can vary significantly across different regions, underscoring the challenge of developing universally applicable models.

This diversity in findings points to a critical need for localized model calibration or the development of new, region-specific models that can more accurately reflect the unique characteristics of different areas. The work of Chen et al. [69], which focused on Indian traffic conditions, exemplifies the potential benefits of such localized studies in refining existing models or developing frameworks that are more representative of specific geographic contexts.

Common limitations cited across the studies include small sample sizes, limited scope of geographic locations, and the need for more comprehensive datasets. The studies by Khekare et al. [34] and Patnaik et al. [70] specifically note the constraints posed by limited data collection durations and the narrow range of traffic scenarios considered. These limitations highlight the need for future research to adopt broader more inclusive approaches that can capture a wider array of traffic behaviors and roundabout configurations.

Furthermore, the integration of technological advancements offers a promising avenue for overcoming some of these limitations. The exploration of software-defined techniques by Pratelli et al. [68] for faster video processing exemplifies how emerging technologies can enhance data collection and analysis methods. Future research can leverage advancements in machine learning, artificial intelligence, and big data analytics to improve the precision of gap parameter estimations and roundabout capacity models.

Table 4 shows the recent studies and demonstrates a comprehensive overview of the state of knowledge in the field of roundabout capacity and gap parameter estimation. The evolution of research methodologies, the critical role of geographic specificity, and the identified limitations and future directions collectively point to a vibrant and dynamic field. As researchers continue to build on this foundation, the integration of technological innovations and the pursuit of geographically diverse and comprehensive datasets will be crucial in developing more accurate, adaptable, and universally applicable models for roundabout traffic management. The goal remains to enhance the efficiency and sustainability of roundabouts as critical components of our transportation infrastructure worldwide.

Table 4 *Comprehensive summary of selected studies on roundabout capacity and gap*

Author	Year	Main Findings	Limitations	Ref.
Mark T. et al.	2018	Kimber's model without adjustments outperformed the locally adjusted HCM6 model.	Does not test geometrically opposite roundabouts.	[71]
Ashish K. et al.	2018	The ANFIS model is shown to be reliable compared to other models for Indian conditions.	Impact of cross-traffic not researched; dynamic PCU values not used.	[72]
Khaled et al.	2018	Critical gap values for different vehicle types at three-lane roundabouts were identified.	Behavior of cyclists and pedestrians and roundabout geometry not accounted for.	[29]
Marco et al.	2018	Mean values for critical interval and follow-up headways were found.	Lacks detailed estimation methodology and follow-up headway PDF.	[73]
Elżbieta et al.	2018	The average value of follow-up headway is 2.71 seconds; smaller headways increase entry capacity.	Calls for more research on turbo roundabouts under different traffic controls.	[24]
Amila et al.	2019	The critical gap value for the large bus vehicle category increased by more than 1 second with the new method.	Results could be evaluated using simulation software like VISSIM.	[67]
Ashish et al.	2020	The MARS model was identified as the most suitable for roundabout entry capacity and outperformed other models.	Focuses solely on Indian regions; may not be applicable elsewhere.	[74]
Ashish et al.	2020	Critical gap, follow-up time, and lateral distance significantly affect model outcomes.	Mixed traffic conditions and intersecting traffic not considered.	[44]
Riccardo et al.	2020	The simulated environment is reliable for safety and operational analyses, with mean critical gap as a risk measure.	Simulated environment's gap acceptance for unsignalized roundabouts not provided.	[43]
Elzbieta Macioszek	2020	The model considers geometry and traffic factors and aligns closely with previous studies.	Does not exhaust all problems concerning roundabout entry capacity calculation.	[75]
Mohammad et al.	2020	The link between signal timings, phasing designs, and safety levels at roundabouts is explored.	No comparison between performance of signalized roundabouts and intersections.	[76]
Khaled et al.	2020	Overall critical gap varies by roundabout lane count, suggesting lower values in Qatar.	Overlooked factors such as driver age, gender, and behavior.	[33]
Evangelos et al.	2021	The study highlights the risks of higher speeds and questions the single critical gap value approach.	Does not consider diverse traffic conditions or driver behaviors.	[77]
Md. Saddam Hossain	2021	Classifies roundabout capacity estimation methods and uses Akcelik's equation for simulations.	Limited connections between capacity and geometric factors due to small sample sizes.	[78]
Abdulkarim et al.	2021	Critical gap is 31.07% lower for site 1 compared with site 2.	Study conducted with only two sites.	[5]

Madena et al.	2022	Critical gaps changed with a deviation of 10-23%; the Wu method matches Indian conditions well.	Very limited data used. More data needed for higher efficiency.	[46]
Antonio et al.	2022	Examines traffic capacity in unconventional Two-Geometry Roundabouts using Aimsun.	Data for the experiment taken from only two roundabouts.	[68]
Pranav et al.	2022	The difference between calculated and manual follow-up headway is 20%.	Misclassifications by object detector due to limited training data.	[34]
Hong Ki An	2023	Signalized roundabouts with specific cycle lengths can significantly improve capacity and reduce delays.	Did not account for different geometric designs and number of lanes.	[65]

6. Impact of Gap Parameters on Different Types of Roundabouts

The capacity and operational effectiveness of various roundabouts largely depend on critical gap and other gap parameters. Understanding how these parameters impact roundabout operation is crucial for maintaining their performance and vehicle capacity. Research indicates that factors such as roundabout layout, usage, and driver behavior can influence the critical gap, a key parameter in gap acceptance theory [79]–[81]. For example, studies have developed models using real-world data to estimate critical gap values, considering factors like roundabout design and performance. Table 5 presents these models, showcasing different critical gap values for roundabouts based on their type and location.

Table 5 *Overview of critical gap values in roundabouts by type, location, and method based on different studies*

Method	Critical Gap (s)	Location	Roundabout Type	Ref.
Maximum Likelihood Method (Single-Lane)	1.60	Jaipur and Trivandrum, India	Single-Lane	[82]
	3.94	Florida and Maryland, USA	Single-Lane	[83]
	4.80	California, USA	Single-Lane	[84]
Raff's Method (Single-Lane)	2.20	Massachusetts, USA	Single-Lane	[85]
	2.55	Maryland, USA	Single-Lane	[64]
	3.30	Doha, Qatar	Single-Lane	[5]
	2.52		Single-Lane	
Wu Method (Single-Lane)	4.46	Mostar, Bosnia, and Herzegovina	Single-Lane	[86]
The E. Macioszek Model (Single-Lane)	4.69	Tokyo, Japan	Single-Lane	[75]
Maximum Likelihood Method (Multi-Lane)	L 4.36 / R 4.08	Copenhagen, Denmark	Multi-Lane	[87]
	L 4.70 / R 4.40	California, USA	Multi-Lane	[84]
	3.98	Stockholm, Sweden	Multi-Lane	[27]
Raff's Method (Multi-Lane)	2.91	Dalian, China	Multi-Lane	[88]
	3.53	Simulation	Multi-Lane	[89]

6.1 Impact of Gap Parameters on Single-Lane Roundabouts

Various approaches have been employed to comprehensively assess roundabout efficiency, with gap parameters emerging as a key metric. In Qatar, a study utilized Raff's technique to analyze the performance of single-lane roundabouts, revealing crucial follow-up gaps of 3.30 seconds and 2.52 seconds for different intersections [5]. Another study in Qatar examined roundabouts with one, two, and three lanes, observing over 1500 gaps with minimal traffic contact and identifying a total critical gap of 2.24 seconds [33]. Similarly, research in Tokyo employed an empirical method to study drivers' psychotechnical traits at single-lane roundabouts, revealing follow-up times ranging from 2.70 to 3.10 seconds and critical gap values between 3.10 and 6.60 seconds [75]. In Budapest, Python was utilized to analyze roundabouts, highlighting the impact of factors like entry width and approach angle on crucial gap modeling [90]. Additionally, a study in the U.S. explored roundabout efficiency using driver behavior data, introducing "gap utilization" to assess variations between roundabouts. Analyzing 1,181 accepted gaps, the study revealed an average gap of 4.48 seconds and identified state differences in gap utilization [91].

Furthermore, an investigation comparing analytical and empirical models for estimating entry saturation in single-lane roundabouts found that narrower circulatory roadways with larger outer radii enable higher entry capacity. Results suggest that switching from analytical to regression models could increase traffic flow volumes processed at roundabouts by 6% to 15%, potentially extending their service life by 3 to 7 years [92]. Additionally, a study on heterogeneous traffic conditions in Rajshahi, Bangladesh, utilized the Maximum Likelihood Method (MLM) approach to analyze critical gap estimation at unsignalized for three vehicle types, providing critical gap ranges and emphasizing the impact of city demographics and geography on intersection dynamics [93].

6.2 Impact of Gap Parameters on Multi-Lane Roundabouts

Understanding gap parameters in multi-lane roundabouts is crucial in traffic engineering to decipher driver behavior and traffic flow dynamics. Several studies have investigated the impact of critical gap in multi-lane roundabouts.

A study explored relationships between circulating flow, accepted gap, and delay in roundabouts using regression analysis. It found an inverse correlation between circulating flow and accepted gap, and exponential and power relationships between delay, circulating flow, and accepted gap. This suggests longer delays with high traffic. Despite collinearity, robust associations were supported by p-values exceeding 0.05 [46].

Subcontinental nations like India have conducted some studies analyzing headways using the Raff approach. The research determined the odds of accepting and rejecting gaps for each headway, calculating cumulative probabilities. Using the Raff technique, the critical gap was found to be 1.96 seconds. Critical gaps were also computed using the greatest likelihood, Raff, and Wu methods, showing a standard deviation between 10% and 23%. Examination of one-minute interval data revealed an exponential variation in roundabout entry flow with circulating flow [94].

In a study conducted in Malaysia, three methods—Wu's Method, Raff's Method, and Simple Logit Method—were utilized to analyze acceptable and rejected gaps, totaling 710 seconds and 741 seconds, respectively. Gaps larger than 13 seconds, commonly accepted by drivers, were excluded. The critical gap values obtained for Raff's Method, Wu's Method, and Simple Logit Method were 3.45 seconds, 3.60 seconds, and 3.45 seconds, respectively, demonstrating close alignment among the three methods [95]. An Australian study on roundabouts used capacity and flow rates to calculate critical gaps. At a 300 veh/h arrival rate, higher circulating flows decreased critical gaps and follow-up headways. The model linked a slight increase in these parameters at low circulating flows to the entering-to-circulating flow ratio [96].

A study assessed roundabout effectiveness during peak hours, focusing on police presence and traffic congestion. Data from a three-lane roundabout showed an overall critical gap of 2.42 seconds using Raff's method. During police enforcement, the critical gap decreased to 2.13 seconds, determined by intersecting the cumulative distributions of accepted and rejected gaps [18].

The analysis shows that vehicle delays—defined as the waiting time before entering the roundabout—increase as traffic demand rises for all three control systems: traditional yield-regulated control, First Come First Serve (FCFS) control, and the proposed centralized control. Both the traditional yield-regulated and FCFS controls experience significant delays, though FCFS performs better, with delays 52.5% lower than yield-regulated control. The proposed centralized control, however, consistently delivers lower delays, reducing them by up to 87.8% during oversaturation, demonstrating greater entrance lane capacity. This control optimizes vehicle speeds and proactively creates gaps, enhancing overall roundabout efficiency. Despite this, delays in the left lane remain higher due to its smaller capacity and longer internal travel distances. Furthermore, the proposed control reduces fuel consumption by 28.1% compared to traditional yield-regulated control and by 13.4% compared to FCFS. This is attributed to the elimination of full stops and improved operational efficiency [97].

The lane-by-lane turning movement diagram highlights drivers' preference for outer entry lanes, leading to potential conflicts. Lane distribution significantly impacts total volumes, influencing lane choice behavior. Lane preference remains consistent during peak and off-peak hours, affecting roundabout performance. SIDRA simulation shows lane choice impact on roundabout capacity, with theoretical models generally indicating higher capacities than reality. Adjustments to environmental factors balance simulation results with actual field data, improving accuracy in queue length predictions. Theoretical model analysis suggests lane choice impacts queue lengths, emphasizing the importance of strategic lane selection in reducing delays and disputes [98].

Multi-lane roundabouts outperform turbo-roundabouts at medium to low traffic volumes, with turbo-roundabouts showing 2.5 times higher delays at high volumes. Turbo-roundabouts perform better at high volumes but still have 1.5 times higher delays than standard roundabouts. These results show performance uncertainties due to geometric configurations and traffic flow. Unlike some studies, this study found high delays for turbo-roundabouts even with higher main road traffic. Further simulations are needed. Critical gap values average 0.9 s for multi-lane and 1.2 s for turbo-roundabouts, offering 24% to 42% more time for safety [99].

A study introduces a trajectory planner for multilane roundabouts, aiming to enhance capacity through connected automation. It employs bi-level optimization, optimizing passing sequences and speed control to minimize delay and fuel consumption. Simulation on a four-arm roundabout shows significant reductions in delay (69.6% to 87.8%) and fuel consumption (24.7% to 28.6%) compared to traditional yield-regulated control. Compared to FCFS control, delay reduction ranges from 33.5% to 81.9%, and fuel consumption from 7.5% to 18.8%, varying with demand [100].

Urban intersection design necessitates capacity, delay, and queue estimation methods, crucial for traffic control. Many Russian cities employ two and three-lane roundabouts without approved performance estimation methods. Research targets establishing critical headway and follow-up time for multi-lane roundabouts. A study focused on two-lane traffic circles using video records from Bratsk, Petrozavodsk, and Pskov. Linear regression reveals differing values for critical headway and follow-up time between left and right entry lanes, validating separate lane-based capacity calculation methods [17].

6.3 Impact of Gap Parameters on Turbo Roundabouts

Compared to single and multi-lane roundabouts, there are fewer studies on turbo roundabouts. Turbo roundabouts have gained significant traction, with the Netherlands emerging as a leader in their implementation, driven by the concept's origin and a focus on efficient traffic flow and safety [101]. Poland has also witnessed notable growth in turbo roundabout installations, addressing traffic congestion and enhancing overall traffic management [102]. France has increasingly adopted turbo roundabouts across various regions to improve traffic flow and road safety [103]. While Italy, Belgium, Germany, and the United Kingdom have also embraced turbo roundabouts to varying degrees, their prevalence remains higher in Europe. Outside of Europe, countries like Australia, New Zealand, and parts of Asia have begun exploring and implementing turbo roundabouts, albeit on a smaller scale compared to their European counterparts [104].

Gap parameters profoundly impact the operational efficiency and safety of turbo roundabouts. These roundabouts aim to enhance traffic flow and safety by facilitating uninterrupted movement through spiral geometry. Understanding psychotechnical parameters, such as follow-up headways and critical gaps, is essential for assessing the performance of drivers on turbo roundabouts [102]. In a study, Jan et al. [105] demonstrate that the geometric design and gap parameters of turbo roundabouts significantly influence both traffic flow and safety. The physical separation of lanes, a distinctive feature of turbo roundabouts, minimizes the chances of lane-changing conflicts, thereby enhancing overall road safety.

Salvatore et al. [106] demonstrate that gap parameters critically influence the performance of turbo-roundabouts across diverse traffic volumes. The findings reveal that in scenarios with medium to low traffic, multi-lane roundabouts outperform turbo-roundabouts in terms of operational efficiency. Conversely, in high-traffic conditions, turbo-roundabouts exhibit superior performance and enhanced safety, characterized by increased times-to-collision and fewer conflict points. These results highlight the significance of optimizing gap parameter settings to maximize the advantages of turbo-roundabouts, offering vital insights for urban traffic management and the development of safer, more efficient road infrastructures.

Marco et al. [107] shows that gap parameters significantly influence vehicle movement in turbo roundabouts. Specifically, the critical gap (t_c) and follow-up time (t_f) for both light and heavy vehicles play a pivotal role in determining flow efficiency. Heavy vehicles typically exhibit higher critical gap times, ranging from 5.08 to 6.50 seconds, which is 15%-47% greater than that of light vehicles, whose critical gaps range between 4.03 and 5.48 seconds. Similarly, follow-up times for heavy vehicles are 18%-25% longer than those for light vehicles, impacting overall roundabout capacity and performance.

Research by Maksymilian et al. [108] highlights that gap management, particularly at entry points, is crucial for optimizing traffic flow and reducing emissions in turbo roundabouts. These roundabouts, designed to separate lanes and reduce conflict points, improve both safety and efficiency compared to traditional multilane roundabouts. Simulation results indicate that during peak traffic, efficient gap handling in turbo roundabouts significantly reduces vehicle stops, leading to smoother traffic flow and lower emissions—CO2 by 23%, Nitrogen Oxides (NOx) by 16%, and Particulate Matter (PM10) by 23%. The study further emphasizes that turbo roundabouts maintain better traffic fluidity and environmental performance under high traffic volumes by minimizing congestion and emissions spikes.

The efficiency of turbo roundabouts is closely tied to gap parameters, which affect how smoothly traffic flows. Managing these gaps well also leads to fewer stops and lower emissions, contributing to smoother, more eco-friendly traffic.

7. Conclusions

This paper shows the significance of analyzing gap parameters to optimize roundabout design and operation under varying traffic conditions. Among the reviewed approaches, Wu's model emerges as particularly effective in predicting critical gaps, especially in multi-lane roundabouts, due to its balance between accuracy and practicality. The analysis of gap parameters reveals their significant influence on traffic flow efficiency, with smaller gaps improving roundabout capacity and reducing delays. This highlights the necessity of employing customized strategies based on the specific characteristics of each roundabout and traffic scenario. At the same time, advancements in transportation engineering necessitate precise models and localized management for improvement.

Furthermore, integrating gap parameter analysis with the emergence of Connected and Automated Vehicles (CAV) presents an opportunity to gain new insights into how autonomous vehicles interact with conventional vehicles and pedestrians at roundabouts, ultimately affecting roundabout performance. Focusing on future trends, the aim is to promote more sustainable and effective transportation systems, enhancing safety and smoothness for all road users.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

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