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Insights into Simulated Smart Mobility on Roundabouts: Achievements, Lessons Learned, and Steps Ahead

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Abstract: This paper explores the domain of intelligent transportation systems, specifically focusing on roundabouts as potential solutions in the context of smart mobility. Roundabouts offer a safer and more efficient driving environment compared to other intersections, thanks to their curvilinear trajectories promoting speed control and lower vehicular speeds for traffic calming. The synthesis review supported the authors in presenting current knowledge and emerging needs in roundabout design and evaluation. A focused examination of the models and methods used to assess safety and operational performance of roundabout systems was necessary. This is particularly relevant in light of new challenges posed by the automotive market and the influence of vehicle-to-vehicle communication on the conceptualization and design of this road infrastructure. Two case studies of roundabouts were analyzed in Aimsun to simulate the increasing market penetration rates of connected and autonomous vehicles (CAVs) and their traffic impacts. Through microscopic traffic simulation, the research evaluated safety and performance efficiency advancements in roundabouts. The paper concludes by outlining areas for further research and evolving perspectives on the role of roundabouts in the transition toward connected and autonomous vehicles and infrastructures.

Keywords: smart mobility; roundabout; microscopic traffic simulation; road safety analysis; roadway capacity; cooperative driving; sustainable transportation

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1. Introduction

A modern roundabout is a circular intersection where vehicles yield to enter and flow unidirectionally around a central island, creating a continuous flow at a steady pace [1,2]. Roundabouts provide a traffic-calming effect and improved safety and efficiency compared to traditional traffic circles or signalized intersections, reducing the risk of severe collisions [2]. Besides accommodating various vehicles and nonmotorized modes, roundabouts are credited with lowering greenhouse gas emissions [3]. In countries where the introduction of roundabouts is recent, there is still an ongoing adaptation to roundabout navigation, especially at multi-lane sites [4,5]. Driving a roundabout requires the individual user to make the decision to enter, cross, merge, or weave based on the movement of other interacting users [2]. Thus, the curved paths on roundabouts pose challenges for both human drivers and autonomous vehicles [6]. In the evolving landscape of autonomous driving, a likely scenario envisages a cooperative yet competitive interaction between human drivers and autonomous vehicles, each striving for their own advantages on the road [7]. This dynamic interplay signifies scenarios where human intuition should complement the precision of autonomous systems, fostering harmonious coexistence [8]. Beyond automation, the connectivity of vehicles plays a crucial role, serving as a foundational element for smart cities [9,10]. With the increasing prevalence of connected and autonomous vehicles (CAVs) in traffic, the transition toward vehicle-to-everything (V2X) communication underscores the imperative nature of intersection management [11]. Cities now widely employ traffic-responsive and coordinated signals [12]. Approaches for non-signalized intersections, whether centralized (e.g., vehicle-to-infrastructure communication) or decentralized (e.g., relying on vehicle-to-vehicle communication), can optimize crossing sequences and vehicle dynamics through cooperative driving techniques [6]. These considerations extend to roundabouts, introducing complications when accommodating both CAVs and human-driven vehicles (HDVs) simultaneously within their curvilinear design [5,13–15]. Thus, if the potential of roundabout solutions is performing in the context of smart mobility, it is still an open research question.

Smart roads integrate physical infrastructure, software, and big data, with a focus on motorway-like facilities [11]. Highways, thanks to swift data generation, may excel in accommodating smart features, AI-based adaptability, ensuring connectivity and versatile installations for innovative energy production [16,17]. However, it cannot be ruled out that this innovative concept can be extended to urban road networks. If the current emphasis on roads being smart prevails, considering the necessity to accommodate smart mobility, is it possible to extend the smart concept to roundabouts? The term 'smart roundabout' appears fewer times in the Google Trends (2004 to present) time series than smart roads and mobility [18]. Conversely, searching the Scopus database yields a substantial number of documents [19]. Figure 1 illustrates the yearly fluctuation of documents based on data presented in [19] from 2003 to 2023, using the term 'smart roundabout' in the search field. The number of annual papers has recently increased, denoting a significant influence of smart technology development and implementation on the domain of intelligent transportation systems and transportation research.

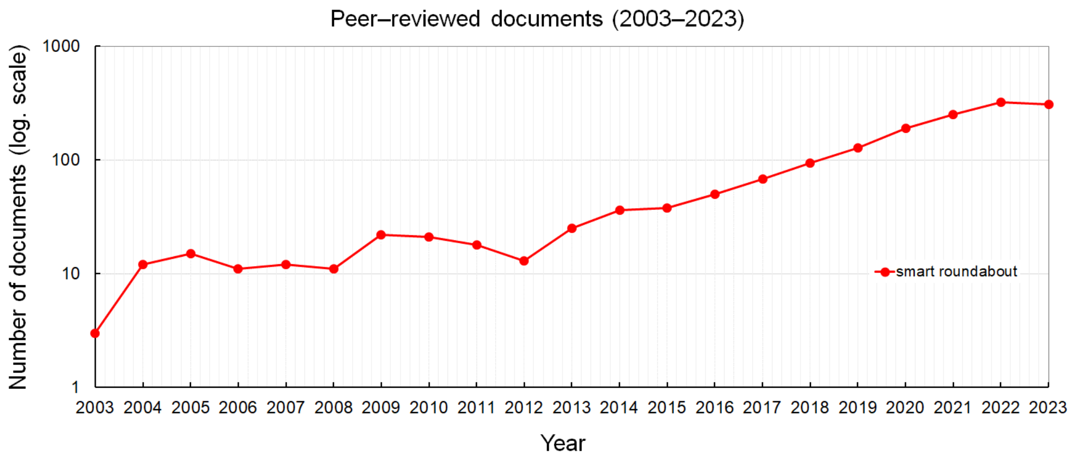

Figure 1. Annual number of documents (log scale) from 2003–2023 based on data presented in [19] using the term 'smart roundabout' in the search field.

By shifting the focus to simulated solutions for smart mobility on roundabouts, insights derived from computer simulations can illuminate noteworthy accomplishments and offer valuable lessons learned and lessons to be learned [20]. Simulations contribute to a nuanced understanding of mobility dynamics, enabling informed decisions to optimize traffic flow in cities, enhance safety, and advance the integration of intelligent systems in roundabout design and operations [21]. It is vital to use microscopic traffic simulation models with CAV logic to analyze potential outcomes under various traffic conditions. Simulations, however, cannot definitively predict the future of widespread CAV use on road networks [5]. A research gap remains in addressing uncertainties in input parameters, particularly when assumptions regarding cooperative driving lack calibration to real operating conditions. The adjustment factors for roundabouts in the *Highway Capacity Manual (HCM)* serve as a practical reference for determining capacity relationships in heterogeneous traffic [5]. As level 4 and 5 CAVs are not yet deployed on actual road infrastructures, adjustment factors for CAVs are derived from microsimulation, assuming reliable operation of all communication elements [5,22]. In light of emerging challenges in the automotive market and cooperative driving technologies, this holds particular relevance for the conceptualization of road infrastructures and the evaluation of their performance efficiency [23–25].

Building upon the considerations outlined above, this paper aims to present the accumulated knowledge in the field of roundabout design through a synthesis review and to highlight emerging issues related to solutions for smart mobility by examining case studies. This necessitated a focused examination of the models and methods used to assess the safety and operational performance of roundabout systems. To assess achievements and advancements, the following questions needed to be addressed:

1. What are the research needs concerning roundabout infrastructure in the transition toward intelligent mobility? This question pertains to identifying similarities or differences in worldwide standards and practices related to roundabout design and assessing the impact of roundabout geometry on efficiency performance. In this view, it addresses models and methods used in safety performance evaluation and operational analysis.
2. Why does microsimulation matter for evaluating roundabout performance? This question is closely intertwined with the versatility of microsimulation tools, which are crucial for assessing choices during changes in roundabout design or traffic patterns.
3. Can connected and autonomous driving efficiently negotiate roundabouts? Is it possible to confirm the existence of 'safety and efficiency-in-numbers' effects with cooperative driving? In this context, the paper draws conclusions to identify areas requiring transitional research and outlines evolving perspectives on the role of roundabouts in a changing context characterized by the widespread integration of smart technologies and digital innovations.

The paper is structured as follows: Section 2 presents a synthesis review of related research on roundabout design requirements, safety performance evaluation, along with models and methods for operational analysis. It also delves into the issues linked with the transition to performing roundabout solutions in the context of smart mobility, aiming to derive valuable insights for roundabout research. Section 3 presents two real-world case studies of roundabouts to demonstrate how advancements in evaluating safety and performance efficiency can be achieved amid the gradual integration of smart mobility features in traffic. Section 4 presents the research results, while Section 5 discusses the findings. At last, Section 6 concludes the paper.

2. Literature-Informed Insights into Roundabout Research

This section reviews roundabout design, crash analysis, safety evaluation, operational analysis, and transitioning to smart roundabouts, while identifying barriers and benefits. The main goal is to answer the question 'what are the research needs concerning roundabout infrastructure in the transition toward intelligent mobility?'. It involves identifying similarities and differences among global standards and guidelines related to the impact of roundabout geometry on traffic efficiency, safety, and operational performance. Thus, the section addresses models and methods currently used in safety performance evaluation and operational analysis and their potential in the transition toward smart mobility.

2.1. Roundabout Design Requirements

Intersections and roundabouts must accommodate various turning vehicles while addressing conflicting traffic demands [26]. Design should prioritize visibility, aiding recognition in the cityscape and road networks, considering factors like position, shape, and approach alignment. Roundabouts, with their curved layout, present challenges in achieving optimal geometric elements while balancing design variables and site constraints, especially in cities [1,26]. This complexity may impede the adoption of standard solutions, complicating the fulfillment of design objectives [4].

Despite design variations, the distinction between single-lane and multi-lane roundabouts is universally acknowledged [1,2]. Strategic planning for single-lane roundabouts should include provisions for seamless expansion if traffic projections materialize within the conventional 20-year traffic horizon. If projected traffic indicates a future need for multi-lane roundabouts, phased implementation as single-lane is prudent, allowing adaptation if traffic demand increases. This approach balances current needs with future scalability, ensuring efficient infrastructure development [2]. Figure 2 illustrates two real-world examples of roundabouts.

(**a**) (**b**)

Figure 2. Real-world roundabout layouts: (**a**) Single-lane roundabout with one circulating lane and one entry lane (latitude 37.660290, longitude 12.609872); (**b**) Two-lane roundabout with two circulating lanes and (at least) one two-lane entry (latitude 38.177443; longitude 13.309095).

Guided by foundational design principles, roundabout conceptualization must adhere to specific objectives [1,2]. These encompass: (a) maintaining uniform speed at entry, within, and exit; (b) determining lane configurations through capacity analysis, ensuring the appropriate number of entry lanes and their continuity through the roundabout, especially in multi-lane settings; (c) aligning paths to prevent overlap in multi-lane setups; (d) considering the design vehicle—anticipated as the largest to use the roundabout—for the effects on the size of geometric elements; (e) ensuring visibility for adequate sight distance to observe conflicting vehicles, pedestrians, or cyclists. Table 1 details the harmonization of design principles and key geometric elements with overarching design goals for roundabouts, fostering a more holistic approach to enhance their design.

Roundabouts generally require more space than traditional intersections, while the approach space needs may be lower. Urban areas favor smaller diameters for speed management, while rural settings need larger ones for truck accommodation [27]. The outer diameter dictates the space requirements for roundabout design [28], which affects vehicle speed. Intersection skew also influences area demands, necessitating the realignment of approaches or larger outer diameters [4]. Table 2 illustrates standard outer diameters, categorized by roundabout type, sourced from guidelines utilized in various countries [2,28–40]. Acknowledging its non-exhaustive nature, this review underscores both similarities and differences among the values of outer diameter applied worldwide [28]. The reported values remain consistent within each roundabout type. The selection of an outer diameter value within a roundabout type will depend on national standards, space requirements, and the built context, which in turn influences the alignment of entry approaches. In this regard, ensuring the efficient operation of a multi-lane roundabout requires assessing not only vehicle speeds, but also the natural alignment of entering lanes with the designated lanes within the circulatory roadway and onward to the appropriate exit lanes [2,26]. Any interference or overlap between lanes can compromise safety and efficiency [1,2].

Table 1. Aligning design principles and geometric elements with overarching design objectives.

Design Elements	Roundabout Design Principles				
	Speed Management	**Lane Arrangements**	**Path Alignment**	**Design Vehicle**	**Visibility**
Central island	Rural design wider than urban design	Traversable only for mini roundabouts	Sized based on design circle and ring width	Apron to accommodate large vehicles	Raised islands to enhance driver recognition
Ring width	Minimized based on design vehicle and context	Narrow enough to prevent side friction between adjacent lanes	Matching the maximum entry width or extending up to 120%	Large enough to accommodate the design vehicle	Landscaping within the central island without obstructing sightlines
Entry design	Curved versus tangential design balances capacity and safety for all modes while minimizing costs	Entry width of not more than the ring width and based on the design vehicle's paths	Approach alignment through the center (or to left of center) for increased deflection	Providing curvature sufficient enough to guide drivers into the circulatory roadway	20° to 40° entry angles capture the effects of entry path curve, alignment, and left-side visibility
Exit design	Radial alignment encourages slower speeds	Reduced exit radius promotes lane discipline	Radial alignment avoids path overlap	Verify curved versus tangential design	Ensure proper widths for large vehicle turns
Splitter islands	Plant material for funneling effect to reduce speeds	Maximizing width to deflect and slow entering traffic and ensure pedestrian refuge	Extension separates entering from exiting traffic, aiding speed control	Large enough width to comply with requirements for trucks	A recommended 15 m length ensures visibility and refuge
Design objectives	Adequate deflection and tightening entry curvature and width to slow speeds	Traffic channelization and lane continuity from the entry to the desired exit	The legs should be aligned at 90° to promote slow speeds through the entries and the exits	Requirements of design vehicle's swept path for roadway types and land use	Ensure adequate visibility for drivers to view entering traffic from adjacent entries or circulating vehicles

Table 2. Outer diameter ranges from international literature.

Country	Outer Diameter [m] by Roundabout Type			
	Mini	**Compact**	**Conventional**	**Large**
Australia [29]	-	20 to 54 [1]	multi-lane: 34 to 62 [1] (see also [28])	
Croatia [30]	14 to 25	30 to 40	multi-lane: 50 to 90	
France [27,31]	15 to 24	≥30.0 [2]	2-lane (urban): 40 to 50	2-lane (rural) > 50
Germany [32,33]	13 to 24	26 to 35 (urban); 35 to 45 (rural)	2-lane (rural): 40 to 60	55 to 80
Italy [34]	14 to 25	25 to 40	40 to 50	>50
The Netherlands [35,36]	10 to 20	32 (urban); 36 (rural)	2-lane: 40 to 56 (urban or rural)	-
Poland [37,38]	14 to 25	Small sized: 26 to 40 (urban), 30 to 40 (rural) Medium sized: 41 to 45 (urban), 41 to 50 (rural)	Small sized: 37.5 to 45 [3] (urban); 40 to 45 m (rural); Medium sized: 45 to 55 (urban), 45 to 65 (rural)	>55 m (urban), >65 m (rural)
Sweden [39]	28	30.8 to 36 (small sized: urban or rural)	53 to 90 (normal sized: urban or rural)	
UK [40]	15 to 28	28 to 36	36 to 100	
US [2]	13 to 27	27 [4] to 46 (urban and rural)	46 to 55	61 to 76 [5]

[1] To be determined by designer; [2] 24.0 to 30.0 m on secondary road network; [3] preferred range also for suburban areas; [4] D_{outer} needs to be at least 32 m at single-lane roundabouts to accommodate large design vehicles; [5] 61 to 91 m preferable range of outer diameter to accommodate large design vehicles (3 or 4 entry lanes).

Similar observations regarding the outer diameter values in Table 2 can also be extended to the entry lane widths in Table 3 [2,28–40]. While the former addresses space requirements relative to traffic demand, the latter determines entry capacity issues. Assessing capacity is essential for proper functionality, especially during peak periods.

Among other factors, the geometric shape of roundabouts significantly influences safety and efficiency, affecting potential crashes and capacity. This impacts the development of predictive models relying on empirical data, alongside issues of transferability between countries, complicating the identification of universally applicable performance evaluation methods, especially for alternative roundabout layouts [41,42].

Clear recommendations for single-lane and multi-lane roundabouts should be also established to consider the functional requirements of cooperative driving [5,10]. In urban areas, prioritizing cyclists and ensuring unimpeded pedestrian access is paramount, while outside built-up areas, such privileges may differ.

Table 3. Standard entry widths for mini, single-lane, and multi-lane roundabouts.

Country	Entry Lane Width [m] by Roundabout Type		
	Mini Roundabout	**Single-Lane Roundabout**	**Multi-Lane**
Australia [29]	-	3.5 to 4 (min 5 m for curb-to-curb lane)	3.5 to 4 m (by lane)
Croatia [30]	-	3.25 to 3.5	3.5 to 4
France [27,31]	2.5 to 3 m	3 to 4 (urban); 4 (rural)	2-lane: 6 to 7 (urban); 6 to 9 (rural)
Germany [32,33]	3.25 to 3.5 m	3.25 to 3.5 m (urban); 3.5 to 4 (rural)	-
Italy [34]	≥3.5 m	≥3.5 m	≥6 m (2 entry lanes)
The Netherlands [35,36]	3.5 to 4 m	not recommended but permitted for 2 lanes	
Poland [37,38]	3 to 3.5 m	3.5 to 4 m	6.0 to 7.0 (2-lane approaches)
Sweden [39]	≥3.5 m	≥3.5 m	7.0 m (2-lane approaches)
UK [40]	3 to 4 m	4 to 11 m (curb-to-curb, 1 lane)	7 m to 15 m (curb-to-curb, 2 lanes)
US [2]	3 m	4.2 to 5.5 m	7 to 9 (2-lane [1]); 11 to 14 (3-lane); 25 (urban) or 40 (rural)

[1] 25 m entry flare length at 2-lane entries.

2.2. Findings from Crash Research and Safety Performance Evaluation

The safety effectiveness of a roundabout depends on its geometry [43,44]. Prioritizing speed harmony while maintaining sight distances is essential [26,45].

An optimal combination of deflection and entry width in roundabouts results in lower speeds compared to signalized or unsignalized intersections [2,26]. The central island curves vehicle trajectories, reducing relative speeds between entering and circulating vehicles, thus lowering crash incidence [2,44]. The leftward shift of approach alignment at the roundabout center enhances entry deflection and improves horizontal curvature. However, while beneficial for entry dynamics, exit deflection is reduced, failing to maintain low speeds, especially at crosswalks [45]. A right offset alignment at the roundabout center reduces entry curvature and deflection but increases through-speeds, playing a pivotal role in loss-of-control and entering–circulating crashes, especially with less yielding drivers [46]. This design allows drivers additional time to accurately assess headways and react to sudden or potential conflicts [2]. Conflicts occur where vehicle paths intersect, merge, diverge, or weave within the circulatory roadway [46]. Figure 3 illustrates these conflict points at the roundabouts in Figure 2.

Crash prediction models play a crucial role in evaluating the safety performance of roundabouts [47]. Roundabout and approach-level models estimate crash frequencies and assess safety benefits for design alternatives. However, challenges still persist in localized data, regression modeling, and transferability issues, fueling ongoing research in the field [48].

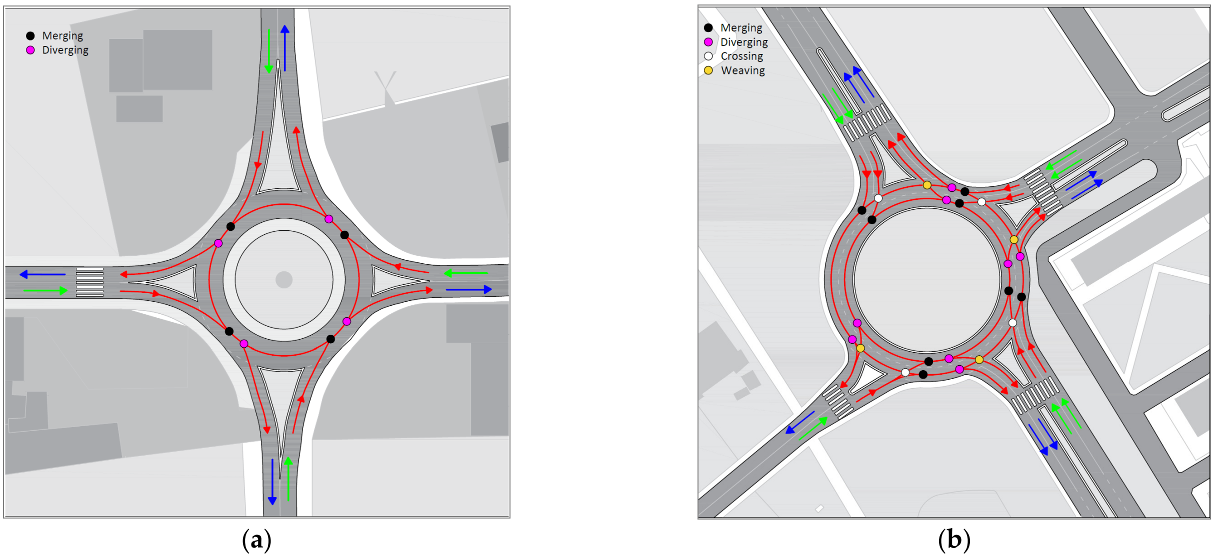

Figure 3. Conflicts points at roundabouts: (**a**) Single-lane roundabout; (**b**) Two-lane roundabout.

Safety performance functions (SPFs), key to count data models such as Poisson or Negative Binomial regression, correlate crash frequency with site characteristics like traffic volume, lane configuration, roundabout dimensions, and pavement conditions [49]. These models establish a log-linear relationship between the expected annual crash count at a site and explanatory variables, enhancing our comprehension of safety implications for diverse roundabout configurations and crash types [43,49]. Decisions regarding model shape, sample sites, and explanatory variables significantly impact calibration and estimate efficiency in network screening or project-level applications [47]. Advancements in safety performance function (SPF) modeling tackle temporal, spatial correlations, and regression-to-the-mean bias. However, transferring safety experiences across countries or contexts encounters challenges. Variations in road safety stem from differences in crash reporting, roundabout crash definitions, climate, design standards, driver traits, and user familiarity with roundabouts [47]. For instance, the Maycock and Hall model [50], predicting roundabout crash rates in the UK, may lack transferability to regions with distinct driving norms and user familiarity. Moreover, models with numerous explanatory variables might lack predictive effectiveness [43,49].

A comparative analysis of intersection-level (exposure-only) models for 4-leg roundabouts has been conducted, emphasizing annual injury crash frequency and total entering traffic flow as explanatory variables (refer to Figure 4) [44,45,51–55].

The figure illustrates the correlation between injury crash frequency and total entering traffic flow, calculated through annual average daily traffic (AADT). Notably, the Central European model [44] forecasts fewer crashes than the Swedish [45], New Zealand [54], and American [52] models as traffic flow increases. Established roundabouts maintain consistent crash frequencies within manageable limits with rising traffic flow. American roundabouts [52], benefiting from global experiences, demonstrate minimal disparities from Swedish [45] and New Zealand models [54]. Higher crash predictions occur in areas with newer roundabouts, lacking the benefits of evolving global geometric design expertise, except for Northern Italy [55] and Oregon [53], which utilized more recent data. The Southern Italian model [51], tailored for traditional roundabouts, is less safe than modern ones [2]. Pedestrian and bicycle crashes at roundabouts are rare, making up less than 1% of total crashes, as reported by [47], and are influenced by factors such as land-use context and geometric features.

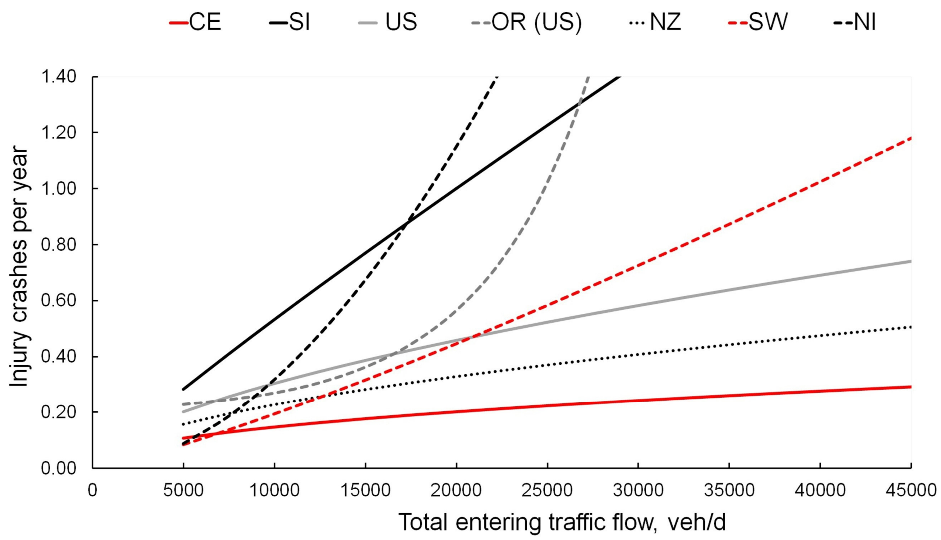

Figure 4. Comparative study for roundabout crash models. Note: The acronyms refer to the countries (or regions) in which the models have been developed: CE stands for Central Europe [44]; SI stands for Southern Italian model [51]; US stands for Unites States of America [52]; OR (US) stands for Oregon (USA) [53]; NZ stands for New Zealand [54]; SW stands for Sweden [45]; NI stands for Northern Italy [55].

There is growing research interest in employing surrogate measures for safety performance evaluation [56]. Safety performance can be assessed using traffic microsimulation models to anticipate alternative scenarios and evaluate the potential of roundabout solutions that are useful, integrable, and sustainable in smart urban contexts [57]. Accurate calibration of these models should ensure that simulated safety measures reflect real-world traffic conditions. Saulino et al. [58] explored the use of simulated conflicts as a surrogate safety measure and their ability to predict roundabout crashes. Additionally, the surrogate safety assessment model (SSAM) estimates traffic conflicts based on vehicle trajectories from microscopic traffic simulation models [57,59,60]. In this perspective, surrogate safety measures offer a basis for comparing different intersection types under varying geometry and traffic conditions, aiding in their performance evaluation. An application is shown in Section 3.

2.3. Models, Methods, and Implications for Roundabout Operational Analysis

Various investigations have explored the operation of existing or planned roundabouts. However, the ongoing debate between gap acceptance theory and empirical regression models defines the prevailing situation in estimating the capacity of unsignalized intersections and roundabouts [61]. Different countries employ both empirical and analytical models to assess roundabouts under stable conditions, each method offering distinct advantages and drawbacks. Empirical regression models, derived from on-site data, establish connections between capacity (or delay) and geometric factors. However, they necessitate extensive data from congested entries for reliable results [62,63]. Analytical models, based on gap acceptance principles, can be devised from uncongested scenarios but necessitate specific criteria for estimating critical and follow-up headways.

All methodologies for analyzing the capacity of unsignalized intersections and roundabouts trace back to a basic queuing model observing the interaction of two one-way streets [64]. The prevailing assumption is that drivers exhibit consistent behavior, yet this overlooks the variability of headways over time, among drivers, and in diverse traffic situations, rendering the gap acceptance process stochastic. In multi-lane roundabouts, uncertainty arises regarding entry lane choices and circulatory roadway curvature, challenging precise quantification [62]. While regression models may implicitly consider these factors, evidence suggests that they might not adequately address the distribution of entry and opposing flows. Silva and Vasconcelos [65] highlighted the inadequacy of regression models for new layouts, particularly when detailed lane-by-lane analyses are necessary. Conversely, more complex capacity formulas based on gap acceptance may be influenced by the traffic distribution among entry and circulatory lanes [66]. Gap acceptance models, relying on (fixed) critical and follow-up headway values, provide entry capacity approximations under average conditions. Thus, assuming constant values may lead to inaccurate estimates due to driver population heterogeneity. Recognizing the stochastic nature of time headways, capacity models should treat them as distributions. Additionally, specifying the probability distribution of headways between vehicles in each major stream is crucial for gap acceptance-based capacity models [67,68]. Figure 5 shows the most commonly used single-lane roundabout gap acceptance capacity models globally for the purpose of comparison [66,69–73].

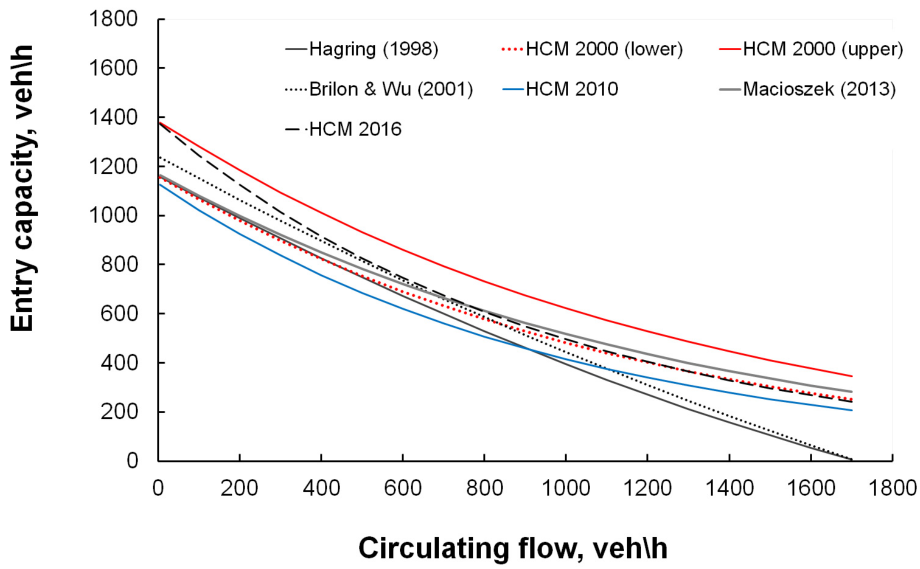

Figure 5. A comparison among gap acceptance capacity models for single-lane roundabouts. Note: the capacity models in the graph are referenced as follows: Hagring (1998) [66] calibrated based on meta-analytical estimates of critical and follow-up headways by [68]; HCM 2000 (lower) and HCM 2000 (upper) stand for the lower bound model and upper bound model, respectively, proposed by the *Highway Capacity Manual* [69]; Brilon & Wu (2001) stands for the model proposed by [70]; HCM 2010 stands for the capacity model by the *Highway Capacity Manual* 5th edition [71]; Macioszek (2013) stands for the capacity model by [72]; HCM 2016 stands for the capacity model by the *Highway Capacity Manual* 6th edition [73].

From the graph, it can be inferred that an operating range is entirely comparable among the considered models, where differences are predominantly attributable to users' behavioral parameters and variations related to different driving situations and codes adopted in the countries where the models were developed. These models have long been used in their reference contexts, facilitating steady-state capacity assessments even in other areas where roundabout schemes and the corresponding traffic patterns are entirely comparable.

Understanding operational conditions at roundabouts requires recognizing them as a series of states with probabilistic characteristics [1]. The probability associated with each state is crucial. A roundabout system is transient if state probabilities change over time, whereas it is in a steady state when the probability of each state remains constant [1]. In a steady state, the statistical values for the variables remain constant, evolving randomly with operating conditions. Traffic demand also stays constant at entries during undersaturation. Morse's inequality [74] is relevant here, stabilizing traffic conditions around constant mean values of the state variables. Alternatively, if conditions do not stabilize, time-dependent solutions should be considered. Steady-state models serve as approximations, applicable when the analysis period surpasses the time duration resulting from Morse's expression. For comprehensive steady-state entry capacity models at roundabouts refer to [1], where further capacity model insights, including regression approaches, can be also found. Advancements in computer technologies, software engineering, and intelligent transport systems have elevated traffic simulation to a critical role in traffic analysis. Its capacity to replicate traffic variability is essential for comprehending complex traffic systems. In this context, microscopic traffic simulation, emulating traffic flows from individual vehicle motion governed by specific rules such as car following, lane changing, and gap acceptance, is increasingly favored [75]. These models are also crucial for evaluating roundabout efficiency, offering insights into diverse design scenarios [14]. Over time, microsimulation studies on roundabouts have increased, employing various criteria for performance evaluation, including safety, mobility, environmental impacts, social effects, and economic factors. Calibration methods, as discussed by various studies, should ensure accurate predictions [75,76]. A concise overview of select peer-reviewed studies from 2019 to 2023, primarily using PTV Vissim [77] and Aimsun [78], is provided in Table 4 [76,79–98]. However, research on roundabouts has significantly expanded, reflecting the increasing interest in integrating smart features for enhanced functionality [11]. This underscores the necessity for innovative approaches to roundabout design to accommodate evolving transportation paradigms. With the introduction of automation and communication between vehicles, which can significantly alter vehicle behavior on a microscopic level, there is a clear need for microscopic models, including cooperative driving technologies, to perform what-if analyses of infrastructures and traffic scenarios in transition [5,14].

Table 4. Summary of past research using a microsimulation-based method to assess roundabout performance.

Authors	Analysis Tool	Subject	Scope of Application			
			Design	Environment	Mobility *	Safety
Brilon et al. [79]	Vissim	Novel application of fundamental diagram of traffic flow to an urban single-lane roundabout			✓	
Ištoka Otković et al. [76]	Vissim	Applying neural networks to calibrate the employed microsimulation model with field data on urban single-lane roundabouts			✓	
Tumminello et al. [80]	Aimsun	A methodological framework for assessing the safety and efficiency effects of a dedicated lane for CAVs on a two-lane roundabout			✓	✓
Šarić et al. [81]	Vissim	Evaluation of geometry's impact on emissions with zero-emission vehicles in traffic at two-lane roundabouts, turbo roundabouts, and signalized intersections	✓	✓		
Cantisani et al. [82]	Vissim	BIM-based methodology to develop a benefit–cost analysis between alternative configurations	✓	✓	✓	✓
Alozi and Hussein [83]	Vissim	Multi-criteria assessment to compare elliptical, two-lane roundabouts, turbo roundabouts, and signalized intersection	✓	✓	✓	✓
Boualam et al. [84]	Vissim	Assess the impact of autonomous vehicles on the capacity of single-lane roundabouts			✓	
Acuto et al. [85]	Aimsun	Integrating the vehicle-specific power model as referred by [85] and microsimulation to estimate instantaneous vehicle emissions at two-lane roundabouts		✓		

Table 4. *Cont.*

Authors	Analysis Tool	Subject	Scope of Application			
			Design	Environment	Mobility *	Safety
Ciampa et al. [86]	Vissim	A comparative study between atypical and modern roundabout layouts through swept path analysis	✓		✓	
Severino et al. [87]	Vissim	Safety assessment with autonomous vehicles in traffic by microsimulation			✓	✓
Mądziel et al. [88]	Vissim	Emissions analysis at a multi-lane roundabout and turbo schemes under varying traffic patterns	✓	✓	✓	
Gallelli et al. [89]	Vissim	Comparison of safety and operations in converting priority intersection to roundabouts			✓	✓
Osei et al. [90]	Vissim	Simulated signalized roundabout, assessing capacity, delay, and queue length			✓	
Zakeri & Choupani [91]	Aimsun	Operational evaluation to prioritize public transport at standard roundabouts			✓	
Bulla-Cruz et al. [92]	Vissim	Compare the safety evaluation of two-lane roundabout vs. proposed basic turbo roundabout				✓
Bulla-Cruz et al. [93]	Vissim	Event-based road safety microsimulation in roundabouts				✓
Granà at al. [94]	Aimsun	Estimating passenger car equivalents for two-lane and turbo roundabouts			✓	
Mądziel et al. [95]	Vissim	Methodology to model traffic and compare emissions in selected roundabouts		✓		
Guerrieri & Sartori [96]	Aimsun	Case studies of underground roundabouts to assess mobility needs in cities	✓		✓	
Mohamed et al. [97]	Vissim	Innovative methodology for capacity and level of service for elliptical roundabouts	✓		✓	
Virdi et al. [98]	Vissim	Estimation of conflicts under mixed fleets				✓

* Mobility stands for mobility aspects including operational metrics as delay time, travel time, speed, or vehicle kilometers traveled [77,78].

2.4. Where Is the Research on Smart Roundabouts Headed?

Recent studies have concentrated on impact assessment in the "smart roundabout" domain (see Figure 1) and have delved into the potential of incorporating smart technologies into existing or planned roundabouts [14,15]. The goal is to leverage the benefits of integrating cutting-edge technological advancements into these infrastructures to fulfill the needs of sustainable traffic management [99]. Although not aiming for exhaustive coverage but rather to highlight key issues amenable to a common analytical approach, a search was conducted in the Scopus database, focusing solely on the term 'smart roundabout' within a 'title, abstract, and keywords' search. This yielded approximately 70 peer-reviewed papers published between 2019 and 20 January 2024 [19].

The abstracts of all papers underwent meticulous evaluation for relevance, resulting in the exclusion of around 13 conference proceedings due to unclear author identification. Additionally, several papers not aligned or consistent with the study's focus were removed, while conference papers, books, or book chapters were retained in the absence of duplicates. No additional papers were found through hybrid research. Ultimately, 30 peer-reviewed papers consistent with the study's aims were thematically analyzed by the authors.

Common research themes emerged, shaping three primary study trajectories, reflecting solely the authors' perspective, as detailed below:

- Optimization of traffic flow, to reduce congestion, enhance throughput, and improve overall traffic efficiency at roundabouts in the transition toward smart mobility [100–109];
- Enhancement of safety measures [110–115];
- Integration with sustainable transportation solutions [85,116–128].

It should be emphasized that the boundary between topics such as traffic flow optimization, road safety, and sustainability of transportation solutions was not always clear. This ambiguity arises due to mutual implications among these research areas, especially in the ongoing transition within the mobility sector.

2.4.1. Optimization of Traffic Flow at Roundabouts in the Transition toward Smart Mobility

Research on traffic flow optimization, particularly concerning roundabouts, predominantly concentrates on evaluating the efficacy of novel assessment techniques integrating intelligent technologies into road infrastructure to enhance mobility [100–109]. In this regard, Elmanaa et al. [100] developed a compact system for real-time processing of camera images, showing promise when applied to a three-leg roundabout for traffic surveillance, especially in resource-limited settings. In line with this, Deveaux et al. [101] explored how knowledge model networking can minimize duplicate transmission and processing of comparable data. By analyzing vehicle exit probability distribution in a roundabout, they showcased the advantages of context-aware knowledge dissemination over context-independent methods, including improved precision, reduced delays, and lower overhead. Duan et al. [102] established a criterion for implementing metering at roundabouts using a signal-based strategy. Through a case study, they demonstrated that this approach reduced delay by up to about 26 percent. However, pedestrians and non-motorized traffic were excluded so that further demand combinations could be included to reach more generalizable results.

Despite the promising outcomes in the areas highlighted above, escalating traffic volumes and population growth pose significant global challenges, exacerbating road congestion, especially in extensive networks. Future endeavors may delve deeper into real-time adaptive control systems and comprehensive data analytics to enhance roundabout performance within intelligent mobility frameworks. From this perspective, Belhaous et al. [103] introduced a novel approach for roundabout navigation, prioritizing alternative paths to alleviate congestion. Their aim was to provide efficient routes, yet real-time adjustments posed challenges in congestion mitigation. Similarly, research in [104] underscored the advantages of combining a laser simulator-based method with fuzzy logic algorithms for the detection of roundabout presence and navigation through roundabout settings under multiple scenarios. However, the authors stressed the need to eliminate noise and improve path automation. Additionally, Li and Li [105] proposed managing smart vehicles by weighing camera versus electromagnetic sensor usage, while research in [106] showcased Tabu search's effectiveness in roundabout avoidance. Potential limitations of managing smart vehicles through cameras versus electromagnetic sensors still include limited visibility under adverse conditions and susceptibility to interference. Also, effectiveness in roundabout avoidance may vary due to computational complexity and real-time implementation challenges. In another study, Mohammed and Ismail [107] contrasted signalized intersections with roundabouts for managing heavy traffic using a micro-analytical evaluation tool. Roundabouts encountered significant delays and a low level of service. As a consequence, further alternatives should mitigate delays for current and future traffic volumes. In this context, Zyner et al. [108] proposed a forecasting method employing recurrent neural networks with Lidar-based tracking data, akin to future smart vehicles. Despite being validated in urban roundabouts, further research is needed to ensure broader applicability. Meanwhile, the authors in [109] introduced a novel technique enhancing learning efficiency based on traffic density in a roundabout. Simulations using real-world data demonstrated enhancements in Internet of Vehicles technology and privacy preservation in high-traffic scenarios.

A common aspect of the research on optimization of traffic flow at roundabouts in the transition toward smart mobility is the absence of extensive real-world applications that should support field validation. This suggests prolonged timelines for the extensive application of the proposed methods, particularly considering the computational efforts required relative to the expected benefits. Furthermore, the optimization of traffic flow at roundabouts in the transition toward intelligent mobility faces numerous challenges. One key issue is the need to balance efficiency with safety and sustainability. Barriers to achieving this balance include outdated infrastructure, limited integration of advanced technologies, and varying global standards. To address these challenges, future studies should focus on enhancing roundabout design to accommodate smart traffic management systems and ensuring seamless interoperability in the evolving mobility landscape. This includes improving infrastructure and implementing vehicle-to-infrastructure communication to mitigate risks and ensure safer interactions between different types of road users. Additionally, efforts should be made to promote the integration of advanced technologies and the adoption of standardized practices to facilitate the transition toward intelligent mobility.

2.4.2. Enhancement of Safety Measures

Regarding the second study trajectory, enhancing roundabout safety through smart technologies involves integrating advanced systems for vehicle-to-vehicle communications, real-time monitoring, and control. These technologies aim to mitigate risks by detecting potential hazards, optimizing traffic flow, and providing timely alerts to drivers, thus improving overall safety at roundabouts [110–115]. Lee [110] raised doubts about the reliability of smart systems and stressed the importance of conducting practical assessments to gauge their effectiveness. This highlights the necessity for engineers to strike a balance between innovation and practicality when integrating new smart technologies. Research should revolve around aspects such as smart software, driver behavior, and redundancy, particularly focusing on enhancing safety at crossroads and roundabouts. Nonetheless, this subject remains an ongoing area of research. Also, advanced warning systems and vehicle-to-infrastructure communication have been proposed to prevent crashes and enhance safety, especially at complex road sections such as intersections and roundabouts [111]. Kácovský et al. [112] examined the influence of design parameters on safety, validating hypotheses through crash and conflict data, thus contributing to defining safe design parameters and enhancing road safety. However, safety constraints pose challenges for autonomous vehicles in assessing cornering at roundabouts. Another study [113] analyzed vehicle behavior across curved trajectories, particularly focusing on a passenger car navigating a constant roundabout turn. Stability was observed within speeds of 10 to 74 km/h, with a critical zone beyond. Nonetheless, the anticipated safety advantages of cooperative driving, compared to traditional systems, seemed to diminish in scenarios exclusively involving CAVs at roundabouts [80]. This decline was largely attributed to assumptions of assertive driving behavior in simulations, which could potentially decrease the safety margin among CAVs. Conclusions on CAV conflicts in mixed traffic, and their severity, are uncertain due to analytical tool limitations. Further research must address methodological constraints to better integrate conflict characteristics into decision support tools, crucial for managing CAV-related conflicts effectively. Advancing analytical techniques is key for enhanced understanding and management.

Gruden et al. [114] explored the influence of digital distractions on pedestrian behavior, particularly focusing on social media's effect on reaction times and crossing behavior at roundabouts. Through eye-tracking, participants navigated designated routes while facing distractions. The findings revealed an 84 percent increase in reaction time with phone usage, minimally affecting crossing duration. Attention-catching elements also corroborated previous studies. Additionally, Doniec et al. [115] demonstrated the ability to detect drivers' activities solely through electrooculography data, regardless of driving experience or style. These findings suggested potential advantages in objectively assessing driving skills and enhancing driving safety.

Despite advancements in observation systems, future research should explore integrating smart technologies to enhance safety for both motorized and non-motorized traffic. This includes developing advanced warning systems and improving infrastructure. Additionally, there is a need to objectively assess driving skills and monitor user behavior under dynamic driving conditions for further safety enhancements.

2.4.3. Integration with Sustainable Transportation Solutions

Regarding the third key issue, integrating smart roundabouts with sustainable transportation solutions shows promise [85,116–128]. Intelligent transportation systems have become crucial for smart city development, necessitating vehicle awareness, especially in high-risk areas like intersections and roundabouts [116,117]. This also involves creating virtual systems using information and communication technologies to monitor and control traffic flow for intelligent transportation systems users, while also promoting the Internet of Vehicles and eco-friendly travel modes [118,119]. Eleuch et al. [120] devised a feature-based vehicle tracking system within visual sensor networks tailored for roundabouts. While requiring further generalization, the system adeptly tracked vehicles, even when partially occluded. In turn, Ornelas-Gutierrez et al. [121] utilized vehicular ad hoc networks to integrate the Internet of Vehicles with advanced wireless technology in smart cities. Their research highlighted the crucial role of dynamic beamforming in effectively managing the complexities of roundabouts and ensuring reliable communication. Despite the computational demands involved, they advocated for the adoption of machine learning to predict and simulate interference among various road users.

In a related study, Guerrieri and Parla [122] introduced a computer vision and deep learning approach for detecting, recognizing, and tracking pedestrians, vehicles, and cyclists along tramway infrastructure in urban environments. Their experiments, conducted on segments intersecting a roundabout with a 24 m outer diameter, utilized a survey vehicle equipped with a video camera. The results demonstrated accurate localization and tracking of road users near tram rails, validated through neural network training. Integrating this method into advanced driver assistance systems (ADAS) could significantly enhance the safety of autonomous and high-speed trams. However, additional testing is essential to ensure the reliability and applicability of these findings. Meanwhile, Pauca et al. [123] introduced a cyber-physical framework for vehicle access control at roundabouts, incorporating two cyber-centric levels where vehicles constitute the physical aspect. The edge-computing layer utilized multivariable optimization to minimize waiting times and ensure safe crossing, while the cloud-computing layer stored vehicle data for long-term analysis. The simulation results confirmed the efficacy of this approach, feasible for real-time implementation on embedded devices, pending extensive application to validate the procedure. In a related study, Zhang et al. [124] investigated traffic noise modeling using deep learning techniques. Their objective was to determine the most effective machine-learning model for predicting traffic noise from real-world data incorporating various traffic features. The results favored a multivariate bi-directional GRU model for its accuracy and computational efficiency, offering real-time traffic noise predictions solely based on city sensor-collected data, beneficial for policymakers in noise mitigation decisions.

By evaluating the integration of smart roundabouts with sustainable transportation solutions, researchers can assess their potential benefits in reducing carbon emissions, promoting active transportation, and facilitating the transition toward a more sustainable urban mobility system. García-Suárez et al. [125] proposed a hybrid model merging cellular automata and agent-based modeling to analyze electric vehicle (EV) charging station deployment through microscopic traffic simulations. Their study compared three charging station arrangements in a city setting, highlighting the effectiveness of a distributed network. Smart routing was emphasized to balance EV distribution among stations. Further research stressed the significance of crowd-sensing logic in evaluation methods of environmental performance at roundabouts [85]. In this regard, Alkhaledi [126] simulated the impact of a smart roundabout on vehicle fuel consumption and emissions, contrasted with traditional roundabouts and signalized intersections. While smart roundabouts reduce signal equipment maintenance expenses, actual costs may differ based on site-specific conditions and design elements, landscaping, and road pavement [2].

In the tech-savvy era, road infrastructure is advancing with smart sensors and connected vehicles, shaping intelligent transportation networks. In this view, Tumminello et al. [127] proposed a holistic framework to assess urban road network designs integrating traffic-calming measures and cooperative driving technologies for energy-efficient public transportation. Micro-simulation analysis of limited traffic zones and mini roundabouts demonstrated improved operational and safety conditions, with reduced emissions during restricted time slots. In light of promising technical advancements, it is imperative to consider the long-term implications of urban mobility. Conducting comprehensive cost analyses is crucial to support decision making. These assessments are essential not only for ensuring the sustainability of transportation solutions but also for making informed decisions about infrastructure development, resource allocation, and environmental impact mitigation strategies in urban areas [2].

Transitioning to CAV driving, Chalaki et al. [128] introduced a real-time control framework that coordinated robotic CAVs in multi-lane roundabout scenarios and transportation corridors. They validated its effectiveness with nine CAVs in a roundabout and 15 CAVs in a corridor featuring roundabouts, intersections, and merging roadways. Ongoing research should address uncertainty in vehicle surroundings, errors in vehicle-to-vehicle communication, and explore methods for indirectly controlling human-driven vehicles, potentially forming CAV platoons.

2.5. Findings from Research on Roundabout Solutions in the Context of Smart Mobility

The related research on roundabout design, safety evaluation, and operational analysis provided the necessary preface for understanding where the research on roundabouts is headed, while also identifying the benefits and barriers to implementing roundabout solutions in the transition toward smart mobility. Specifically, the synthesis review allowed us to aggregate and analyze findings from multiple studies, serving as a starting point to reconsider the potential of roundabouts as effective solutions in the context of smart mobility. Despite the potential benefits outlined in the research trajectories, implementing smart technologies in modern roundabouts faces various barriers and challenges [113,114]. One concern is the cost of deploying and maintaining these systems, although the long-term benefits may outweigh initial costs [2]. However, studies often overlook the construction cost of new smart roundabouts. While smart roundabouts reduce signal equipment maintenance expenses, actual costs may vary based on site-specific conditions, design elements, landscaping, and road pavement [126]. Interoperability and compatibility with existing infrastructures and vehicle systems pose additional issues [107,111]. Smart roundabouts should rely on interconnected networks and communication protocols, necessitating seamless integration with other smart transportation initiatives for efficiency and reliability [105,110,111,121]. Privacy and data security concerns also arise from sensitive information collection. Implementing robust privacy safeguards and encryption mechanisms is crucial [108]. Additionally, exploring data mining and artificial intelligence methods is imperative to understanding traffic dynamics, crucial for ensuring the safe navigation of roundabouts by CAVs amidst potential environmental awareness challenges [98,100,101,110]. In this regard, microsimulation techniques are invaluable for forecasting the safety and operational implications of integrating CAVs into traffic [21]. As introduced in the previous section, these tools enable detailed modeling of driving behavior and interactions among vehicles. They allow engineers to assess CAV impact on traffic, congestion, road safety, and other critical transportation parameters. Microsimulation also remains crucial in transitioning scenarios incorporating cooperative vehicles and communication technology systems (e.g., [76,80,84]). Despite calibration needs, driving simulation technology offers clear advantages over real-scale measurements in evaluating safety, operational performance, and driving behavior [57,75,82]. Building infrastructural and traffic scenarios streamlines roundabout design optimization and enables a thorough assessment of various design solutions and their impact on traffic flow, safety, and overall efficiency (e.g., [14,84,93]).

To ensure smooth and safe traffic flow, engineers increasingly favor modern roundabouts over conventional intersections for their safety and efficiency [2,5]. Roundabouts, accommodating vehicles of all sizes and non-motorized transportation, are credited with reducing environmental impacts [129]. They also offer aesthetic appeal and cost-effectiveness, complementing road engineering efforts and aligning with transportation objectives like corridor access management and multimodal networks. The continuous adaptation and integration of roundabouts underscore their pivotal role in traffic management and urban planning [21]. However, they must face the new demands of cooperative driving. Also, the evaluation methods themselves must be tailored to them.

From this perspective, the case study outlined in Section 3 illustrates the literature-informed methodological approach to estimating the operational and safety performance of two roundabouts with CAVs in traffic.

Despite the specific objective of the application, the results of each research phase, together with the overall findings, will enable the authors to provide more informed answers to the key questions posed in Section 1. From a scientific standpoint, this study identifies the parameters of cooperative driving that can realistically replicate real-world situations on roundabouts. It aims to examine the effects of changes in driving behavior on safety and efficiency as the proportion of CAVs in traffic increases. From a societal perspective, the paper underscores a broad performance enhancement with CAVs on roundabouts compared to the base case with human-driven vehicles, offering insights to evaluate the anticipated safety and operational benefits of CAV driving in meeting future mobility solutions.

3. Materials and Methods

3.1. Geometric and Traffic Analysis of the Case Studies

The roundabouts in the study are situated at the rural–urban interface in different Sicilian provinces, Italy. In Figure 2, the schematics of these roundabouts are depicted; they are labeled as R1 and R2, subsequently. Both roundabouts adhere to Italian standards for intersections and interchanges [34]; the urban speed limit is equal to 50 km/h at both sites. R1 is a compact single-lane roundabout with an outer diameter of 39 m; it features a 7.00 m wide circulatory lane, single-lane entry and exit lanes are 4.50 m wide (north–south direction), and 4.00 m wide entry and exit lanes (east–west direction). R2, on the other hand, is a larger roundabout with a 71.00 m outer diameter, a two-lane circulatory roadway 8.00 m wide, and 4.00 m wide entry and exit lanes. Both roundabouts have deflection angles exceeding 43 degrees. The two roundabouts boast radial approach alignments intersecting at a 90° angle. Their ample space and level terrain facilitate unhurried traffic flow, aiding driver perception and reaction to potential conflicts. This geometric setup ensures smooth entry, circulation, and exit while maintaining appropriate sight distances [2]. At the roundabouts, entering vehicles give way to counterclockwise circulating traffic. Drivers choose the entry lane, waiting for suitable gaps in circulating vehicles. Priority rules govern vehicle negotiation at conflict points, where entering vehicles merge with circulating traffic toward their desired exits. Yield conditions, influenced by lane count, impact traffic interactions and entry capacity. Two cameras were set up on sidewalks to track traffic volume and turning movements at each roundabout in Figure 2, supported by manual counts. Traffic was evenly spread across all approach legs. At R1, data were collected during morning peak hours (8:00 to 9:00 a.m.) and afternoon peak hours (7:00 to 8:00 p.m.) over three weekdays in March 2023. Afternoon peak data were chosen for Aimsun initialization due to their longer duration and steadier flow. This revealed a total afternoon entering flow of 1355 vehicles per hour, mainly cars (83%), with motorcycles

(3%), vans (7%), bicycles (2%), buses, and trucks (5%). At R2, surveys were conducted during morning and afternoon peaks (6:30 to 8:30 a.m. and 6:30 to 8:00 p.m.) from Tuesday to Thursday in November 2023. Afternoon data showed an entry flow of 3422 vehicles per hour, including 11% trucks; pedestrian and bicycle traffic were minimal due to the roundabout's suburban location.

Field surveys revealed three designated entry lane paths (ELPs) for vehicles entering the roundabouts, each outlining the expected trajectory for entry vehicles as follows:

- ELP 1: A single-lane entry path conflicts with one circulating lane at the single-lane site (i.e., R1);
- ELP 2: The entry path from the left lane of a two-lane entry conflicts with two lanes circulating in the two-lane site (i.e., R2);
- ELP 3: The entry path from the right lane of a two-lane entry conflicts with two lanes circulating in the two-lane site (i.e., R2).

To address varying proportions of vehicles with cooperative adaptive cruise control systems, target capacity curves were utilized. Each entry lane path (ELP) was simulated with a fleet entirely comprising human-driven vehicles to establish baseline capacity curves for each roundabout; meta-analytic estimates for critical and follow-up headways were applied [68]. Subsequently, capacity curves were developed to integrate CAVs at market penetration rates (MPRs) of 20%, 40%, 60%, 80%, and 100%. Each mixed traffic fleet included a percentage (x) of CAVs ranging from 0% to 100%, with the corresponding $(1 - x)$ percentage of HDVs. Increases of 20% were applied incrementally. These defined entry lane paths (ELPs) were then employed in the subsequent Aimsun simulations to determine right-of-way at conflict points and simulate gap acceptance behaviors. The capacity of an entry lane (or either lane of a two-lane entry) opposed by one circulating lane (or by two conflicting lanes) was expressed by the general equation 33-1 in [5], utilized for model roundabouts with up to two lanes without CAVs. Parameter A, controlling the intercept of the capacity curve, yielded values of 1380 for ELP 1, 1350 for ELP 2, and 1420 for ELP 3. Parameter B, governing the slope of the capacity curves, resulted in values of 0.00102 for ELP 1, 0.00092 for ELP 2, and 0.00085 for ELP 3. Both parameters A and B, which control the intercept and slope of the capacity curves for the ELPs without CAVs, were adjusted using the respective factors proposed by Exhibit 33-13 [5] to accommodate CAVs. The adjustment factors were determined via microsimulation [5], using engineering principles and knowledge of vehicle-to-vehicle communication technology. They were calculated for different combinations of entry and circulating lanes.

After establishing roundabout models in Aimsun (version 20.0.3) [78], using field geometry and contextual data, simulations were conducted. To replicate all turn directions in each roundabout in Figure 2, traffic demand was set in the Demand Data folder as an origin-destination matrix (O_iD_j), with $O_{i=1,\ldots,n}$; $D_{j=1,\ldots,n}$; n = 4). The time interval for applicable traffic demand was defined by setting the initial time to 6:30 pm. To assess capability in replicating field traffic, 10 simulation runs were initiated in Aimsun, each comprising initialization (15 min), simulation (60 min), and completion (15 min) to clear the system without compromising simulation quality. The results indicated consistent simulated traffic data with field-detected traffic at entries during each 15 min sampling period in the afternoon peak hour. The total traffic matrix was divided into two OD matrices: one for human-driven vehicles and another for CAVs, based on the MPRs outlined previously. To simulate saturated traffic conditions, seven subsequent OD matrices for R1 and nine for R2 were generated and assigned to the designated entry lanes (specifically, the west entry in R1 and south entry at R2 in Figure 2) until saturation. Circulating traffic flow increased from 0 to 1200 pc/h at R1 and 0 to 1800 veh/h at R2, incrementing by 200. The simulation transitioned from free-flowing traffic to capacity, matching the capacity values recorded by the detectors on each roundabout network model.

3.2. Enhancing Simulation Accuracy

Calibrating the model parameters was necessary to improve alignment between the target capacity values and simulated capacity data under default settings. Aimsun simulated various vehicular fleets involving CAVs at different MPRs, assuming high reliability in all communication components [5]. Insights from [5] informed assumptions about CAV behavior during the transition to fully CAV-operated traffic systems. Microscopic traffic simulation models clarify vehicle interactions through car-following, lane-changing, and gap-acceptance principles [75,78], aiding in understanding and optimizing traffic dynamics. Car following regulates longitudinal behavior, lane changing manages lateral movement and driving style adjustments [78,130], while gap acceptance controls yielding at entry points [75,78]. Cooperative adaptive cruise control (CACC) allows CAVs to share data, aiding decisions at roundabout entries based on CAV or human-driven vehicle presence [5]. CACC activates when CAVs encounter each other, assessing conflicting vehicle data for gap acceptance. Facing human-driven vehicles, CAVs rely on adaptive cruise control (ACC) [5]. Lane change varies between R1 and R2; while R1 lacks such opportunities, vehicles can switch lanes within R2's circulatory roadway.

Microscopic models entail numerous parameters, often appearing similar yet differing in calibration success. This complexity may obscure crucial parameters for specific studies. Effective approaches entail selecting minimal necessary parameters, tuning them based on their impact on outcomes, and iteratively running calibrated simulations for robust results. Barcelo [75] suggested preliminary sensitivity analysis and manual calibration for each parameter, followed by iterative adjustments until outputs closely align with target values. These methods bolster model accuracy and reliability.

The model parameters for the baseline case were previously calibrated by the authors, focusing on single-lane and two-lane roundabouts with human-driven cars typical in Italian traffic [131,132]. In vehicular fleets without CAVs, the vehicle modeling parameters included: (1) the driver reaction time, or the duration required for a driver to react to changes in the speed of the vehicle in front, which increased to 0.86 s for ELP 1, 0.95 s for ELP 2, and 0.94 s for ELP 3 (from the default of 0.80 s); (2) the speed acceptance reflecting driver compliance with speed limits, which was reduced to 1.00 for ELP 1, 0.97 for ELP 2, and 0.95 for ELP 3 (from the default of 1.10), affecting adherence to the speed limit; and (3) the gap, or the time between vehicle rear and front bumpers, which was increased to 1.58 s for ELP 1, 1.33 s for ELP 2, and 1.00 s for ELP 3 (from the default of 0.00 s), modifying the headway. The default headway uses front bumper-to-front bumper measurements; modified values affect deceleration in car-following models. These adjustments aimed to better reflect real-world driving behaviors and improve the accuracy of modeling in mixed traffic conditions.

Refining the model parameters was also essential to capture the cautious or assertive behavioral tendencies of CAVs in gap acceptance; thus, the impacts of parameter adjustments in mixed traffic fleets were examined. The behavioral framework for CAVs in Aimsun was drawn from ACC and CACC trials, diverging from the model for human-driven vehicles [78]. It was presumed that all CAVs were equipped with CACC, while only 30% of HDVs had ACC. Sensitivity analysis identified suitable parameter values to validate the model's ability to replicate target capacity curves for the case studies. Vehicle length and width were assumed to be uniform in the simulations, though driving behavior varied depending on the preceding vehicle type; shorter gaps occurred exclusively if a CAV met another CAV. Aimsun's CACC-equipped vehicle modeling parameters, tuned for calibration purposes, were as follows: (1) the maximum acceleration was increased to 4.00 m/s^2 for ELP 1 and ELP 2 and to 3.50 m/s^2 for ELP 3 from the default value of 3.00 m/s^2, enhancing vehicle performance; (2) the safety margin factor was reduced to 0.50 for ELP 1 and ELP 2 and to 0.40 for ELP 3 from the default of 1.00, indicating assertive driving at priority junctions; (3) the sensitivity factor, allowing the follower to estimate leader deceleration, was set at 1.00 for ELP 1 and reduced to 0.50 for the other ELPs (from the default of 1.00), reflecting cautious and assertive driving behaviors respectively, expressed a trade-off to simulate the interactions among different vehicles and to evaluate CAV skills in mixed traffic [78].

Similarly to human-driven vehicles, the calibration also regarded the reaction time used by CAVs to adapt their speed to the speed variation of the next vehicle. The driver reaction time, or the time it takes for a CAV to respond to speed changes in the CAV ahead, was reduced to 0.63 s for ELP 1, 0.67 s for ELP 2, and 0.70 s for ELP 3 (from the default value of 0.80 s). Shorter reaction times may increase capacity, enabling drivers to identify and safely accept smaller gaps before entering the roundabout. Aimsun's car-following parameter could be set uniformly for both CAVs and HDVs, matching the simulation timestep. This ensured immediate response to speed changes in preceding vehicles during subsequent simulation intervals. However, CAVs demonstrate shorter reaction times compared to HDVs. Therefore, a weighted average of reaction times calibrated for each user class was computed, with weights assumed to be equal to the proportions of each user class (CAVs or HDVs) expressed by every MPR. The sensitivity analysis also considered additional parameters, including clearance (the distance in meters maintained by a vehicle when stopped) and lateral clearance (the minimum lateral spacing between vehicles), but they were found to have minimal impact on longitudinal and lateral behavior. Also, the cooperative gap creation parameter was set to 0.50, affecting ELP 2 and ELP 3 at the two-lane roundabout only. This parameter, ranging from 0.00 to 1.00 (where 1.00 signifies high aggressiveness), allows vehicles to collaborate in creating lane-change gaps. A moderate aggressiveness of 0.50 was selected in line with roundabout speed limits. Other parameters, such as normal and maximum deceleration, as well as headway aggressiveness, had minimal impact due to uniform vehicle size. This fine-tuning maintained realistic headway sizes without unrealistically increasing capacity. The GEH statistic in [75] confirmed the model's ability to reproduce the target capacity values for each ELP. Specifically, the deviation of the simulated capacity data from the target values was less than 5 in over 85% of cases across MPRs. Consequently, the model was deemed 'calibrated' as the simulated capacity closely matched the target values. The results of the root mean squared normalized error, as referenced in [75], which provides information on the magnitude of the error relative to the average measurement, confirmed the aforementioned considerations.

A two-sample *t*-test was conducted to verify the significance of the average difference between the two subsets of data: the capacity target values and simulated data for each ELP across CAV-based MPRs. The t-statistic was utilized to test the null hypothesis of no significant difference between the means of the two samples, or to reject the null hypothesis if $|t| >$ the critical value of the t-distribution with N degrees of freedom at a significance level of 0.05. Additionally, the F-statistic was calculated to test the equality of sample variances. Since the t-values of the *t*-test for each entry lane path were below their respective critical values, and the *p*-values were well above 0.05, there was insufficient evidence to reject both the null hypothesis that the means were equal and the null hypothesis that the sample variances were equal at the 0.05 significance level. For synthesis purposes, Table 5 presents the summary statistics comparing CAV-based target capacities with simulated data at various market penetration rates of CAVs for ELP 1.

The environmental impact was further evaluated by analyzing the estimated carbon dioxide (CO_2) emissions during the simulations of both R1 and R2. The London emission model (LEM) in Aimsun estimates CO_2 emissions using the calibrated average speed model [78]. It adapts to variable vehicle activity, providing more precise estimates for short links. By considering the average speed for each vehicle type, the LEM calculates emissions, determining individual vehicle emissions from their average speed over micro-trips. Each R1 approach had a total flow of 900 veh/h, while each R2 approach had 1800 veh/h. CO_2 emissions were simulated in Aimsun, assuming a zero-emission rate for CAVs, consistent with their market penetration rate. For example, if the MPR of CAVs is 40%, 40% of CAVs are electrically driven and 60% are petrol-powered. Thus, an MPR of 100% CAVs would imply that all CAVs are electrically driven.

Table 5. Comparison of CAV-based target and simulated capacities at varied CAV MPRs for ELP 1.

	Market Penetration Rate (MPR) of CAVs (%)					
Capacity (pc/h)	**0**	**20**	**40**	**60**	**80**	**100**
μ_1 (s.e.) [1]	822.0 (61.23)	876.4 (63.20)	944.0 (66.0)	1047.0 (72.0)	1129.0 (73.1)	1211.6 (72.1)
μ_2 (s.e.) [1]	810.39 (72.4)	883.3 (76.0)	954.3 (77.34)	1020.18 (79.7)	1061.0 (80.0)	1115.05 (78.0)
$t_{\alpha,N}$ statistic [2]	0.12	0.07	0.1	0.25	0.63	0.92
t-critical value [3]	2.005	2.006	2.006	2.005	2.004	2.004
$p(\alpha)$-value [4]	0.91	0.94	0.92	0.8	0.54	0.41
F-statistic [5]	1.4	1.44	1.4	1.24	1.21	1.2
F-critical value [6]	1.905	1.905	1.905	1.905	1.905	1.905
F-probability [7]	0.4	0.35	0.41	0.6	0.6	0.7
GEH (%) [8]	93	93	100	100	96	93
R^2 [9]	0.991	0.993	0.997	0.996	0.995	0.996

[1] μ_1 and μ_2 are the mean values of equally sized samples, while s.e. is the corresponding standard error; [2] $t_{\alpha,N}$ statistic from the *t*-test on N = 54 degrees of freedom and significance level of α = 0.05; [3] t-critical value is the critical value of the t-distribution; [4] $p(\alpha)$-value is the probability under the null hypothesis of equal means (α = 0.05); [5] F-statistic from the two-tailed F-test: the hypothesis that the two variances were equal is rejected if F-statistic is greater than F-critical value; [6] F-critical value of the F-distribution (α = 0.05); [7] F-probability under the hypothesis of equal variances; [8] the Geoffrey E. Havers' statistic (GEH) reported by [75]; [9] R^2 is the coefficient of determination of the scattergram analysis to compare target versus simulated capacities at various market penetration rates of CAVs.

Safety performance analysis was conducted by integrating the surrogate safety assessment model (SSAM) [56,57] with Aimsun. To assess the impact of cooperative driving on roundabout safety in a mixed traffic setting, the mean values of parameters tuned for HDVs and CAVs were selected for each entry lane path. Balanced flow patterns, as described earlier, were assigned. The SSAM analyzes trajectory files from Aimsun, evaluating conflict probabilities using metrics such as time-to-collision or post-encroachment time. It systematically lists conflict events, accumulating conflicts from previous steps. Ten trajectory files per layout (i.e., R1 and R2) were processed, and conflict counts were extracted. Filters, consistent with previous studies [59], were used to ensure realistic and suitable outcomes. It was necessary to consider conflicts within a 30 m radius from entries to avoid recording conflicts that occurred far from the entry line. Sensitivity analysis revealed that parameters such as time-to-collision (TTC) and post-encroachment time (PET) significantly impacted potential conflicts [59]. Smaller TTC and PET values increase the likelihood of conflict, with TTC = 0 indicating collision potential; TTC should be shorter than PET [57]. A maximum TTC threshold of 1.5 s was established for R1 and R2 as the TTC default value; lower values can reduce the overlap for the vehicle pair in the projected timeframe, resulting in a new maximum TTC threshold [57,59]. The SSAM updates the TTC values for each vehicle pair until the projection timeline is free from overlaps. In turn, a crash occurs when the projection is zero and the vehicles can overlap. The conflict occurs when the TTC value rises above the threshold again [56,57]. The post-encroachment time (PET) threshold, denoting the time gap between a vehicle exiting and another entering the conflict zone, was set to 2.5 s for R1 and 1.9 s for R2, with a default of 5.0 s [57]. Each conflict's PET was linked to a timestep, with the final PET value recorded post conflict, even if the TTC may be below its threshold. Minimum TTC and PET values of 0.10 s were established to manage processing errors. The SSAM also recorded the maximum vehicle speeds during conflicts, typically near the urban speed limit. Conflict angle, indicating the hypothetical collision direction, ranged from 0° (direct rear approach) to around −135° (approach from the left). Based on the absolute value of the conflict angle, the SSAM also categorizes conflicts by type: rear end (angle < 30°), crossing (angle > 85°), or lane changing (in between). Rear-end conflicts involve vehicles in the same lane simultaneously, while lane-changing conflicts involve lane-switching vehicles. For conflicts at roundabout entry or exit, SSAM differentiates them based on the conflict angle and lane configuration. Other surrogate safety measures remained at default to prevent unrealistic maneuvers. The potential conflict points at R1 and R2 are illustrated in Figure 3a,b, respectively. Simulation outputs are detailed in the subsequent section.

4. Research Results

Based on the fine-tuning of model parameters, the results of the performance analysis for the examined roundabouts are reported in Figure 6. Specifically, Figure 6a–c depict the percentage differences in the values of (a) entry capacity (pc/h), (b) delay (s/km), and (c) travel time (s/km) as market penetration rates of CAVs increase compared to the starting condition featuring only human-driven vehicles. Figure 6d illustrates the CO_2 emissions in grams generated during simulations conducted for each entry lane path as MPRs increase compared to the scenario with 100% HDVs. Entry capacity represents the maximum number of vehicles exiting to the yield line at the subject entry during saturation, while delay time indicates the time loss compared to free-flowing traffic, calculated based on the total possible routes experienced by all vehicles during simulations [2,5]. The simulations illustrated how CAV penetration influenced entry capacities, with higher MPRs correlating to increased efficiency, as seen in Figure 6a. Higher MPRs enabled the acceptance of shorter gaps, enhancing entry capacity in the Aimsun simulations, reflecting the impact of CAVs on traffic dynamics and efficiency. For instance, in a single-lane entry reaching capacity (i.e., at R1 for ELP 1), capacity rose by 15% at 40% CAVs (MPR 2) and by 27% at 80% CAVs (MPR 4) compared to the base case with 100% HDVs (Figure 6a).

These findings corroborated those of previous studies [14,84] on the effect of autonomous driving on roundabout capacity. Introducing CAVs notably improved roundabout performance, gradually reducing delays and travel times with higher CAV penetration rates. At MPR 4 (80% CAVs), delays and travel times decreased by approximately 15.0% and 13.0%, respectively (Figure 6b,c at R1 for ELP 1). However, as only CAVs operated on R1 (ELP 1), the percentage differences in entry capacity, delays, and travel times tended to stabilize (Figure 6a–c) compared to mixed traffic. Similar trends were demonstrated in [133], concerning situation-aware CAVs on signalized intersections. Similar outcomes were observed for both ELP 2 and ELP 3 on R2 compared to the base case (100% HDVs). Higher CAV penetration rates enhanced their capability to accept narrower gaps, thereby improving entry capacity and reducing delay times. For instance, at 60% CAVs (MPR 3), capacity rose by 24% in the left entry lane (ELP 2) and by 17% in the right entry lane (ELP 3) compared to the base case (Figure 6a). Delays and travel times gradually reduced with higher CAV penetration rates. At MPR 4 (80% CAVs), delays decreased by approximately 13.0% (ELP 2) and 12.0% (ELP 3), respectively; in turn, at MPR 4, travel times decreased by approximately 26.0% (ELP 2) and 14.0% (ELP 3), respectively (Figure 6b,c). When only CAVs operated on R2 (MPR 5), the percentage differences in entry capacity increased to 29.0% (ELP 2) and 25.0% (ELP 3), while the percentage differences in delays slightly decreased for both ELP 2 and ELP 3 compared to MPR 4, given the absence of competition with human-driven vehicles. In terms of travel times, the simulations showed significant differences between the values of ELP 2 and ELP 3 across MPRs, especially when only CAVs operated on the two-lane roundabout. These differences are primarily attributable to the assumptions of assertive behavior we adopted in Aimsun, prompting CAVs to enter the roundabout from the left lane, accept smaller gaps in the circulatory roadway, and adopt more efficient driving styles (Figure 6c). Consistently with field observations, the simulations at R2 showed that the left entry lane of a two-lane entry approach truly conflicted with two circulating lanes, while vehicles entering from the right lane mainly tended to make right turns at the next approach. Consequently, the differences in percentage changes of travel times observed between the two lanes aligned with the real driving mode of a two-lane roundabout. It is also worth emphasizing that these trends, overall, aligned with what is reported in the literature on the subject [5,134]. Vehicle type also affects driving behavior, with closer gaps often showed during simulation between connected autonomous vehicles in leading and following positions, thus shaping overall traffic dynamics and gap acceptance tendencies. Additionally, there is potential for lane changes in the two-lane circulatory roadway, allowing vehicles to advance side by side or switch lanes based on the availability of suitable gaps. Regarding estimated emissions, there was a progressively increasing percentage reduction across different MPRs. The trend of CO_2 emissions in Figure 6d is decreasing for each ELP, as expected, due to the increasing presence of CAVs in traffic [3,10]. It is also noted that, the percentage reduction of pollutant emissions across different MPRs was greater in the case of ELP 2 and ELP 3 than in ELP1; in the three ELPs, the environmental advantage achievable was similar in the case of MPR 4 and a fully CAV fleet. However, we suggest considering the results in Figure 6d as projections of future scenarios with widespread CAV usage on road networks. It should also be noted that the CAV assumptions were simulation-based and not calibrated to actual traffic conditions. These results concerning emissions cannot be generalized without comparing them to real-world data, which are currently unavailable. This is because the rate of replacing old vehicles with cooperative vehicles does not keep pace with current technological development.

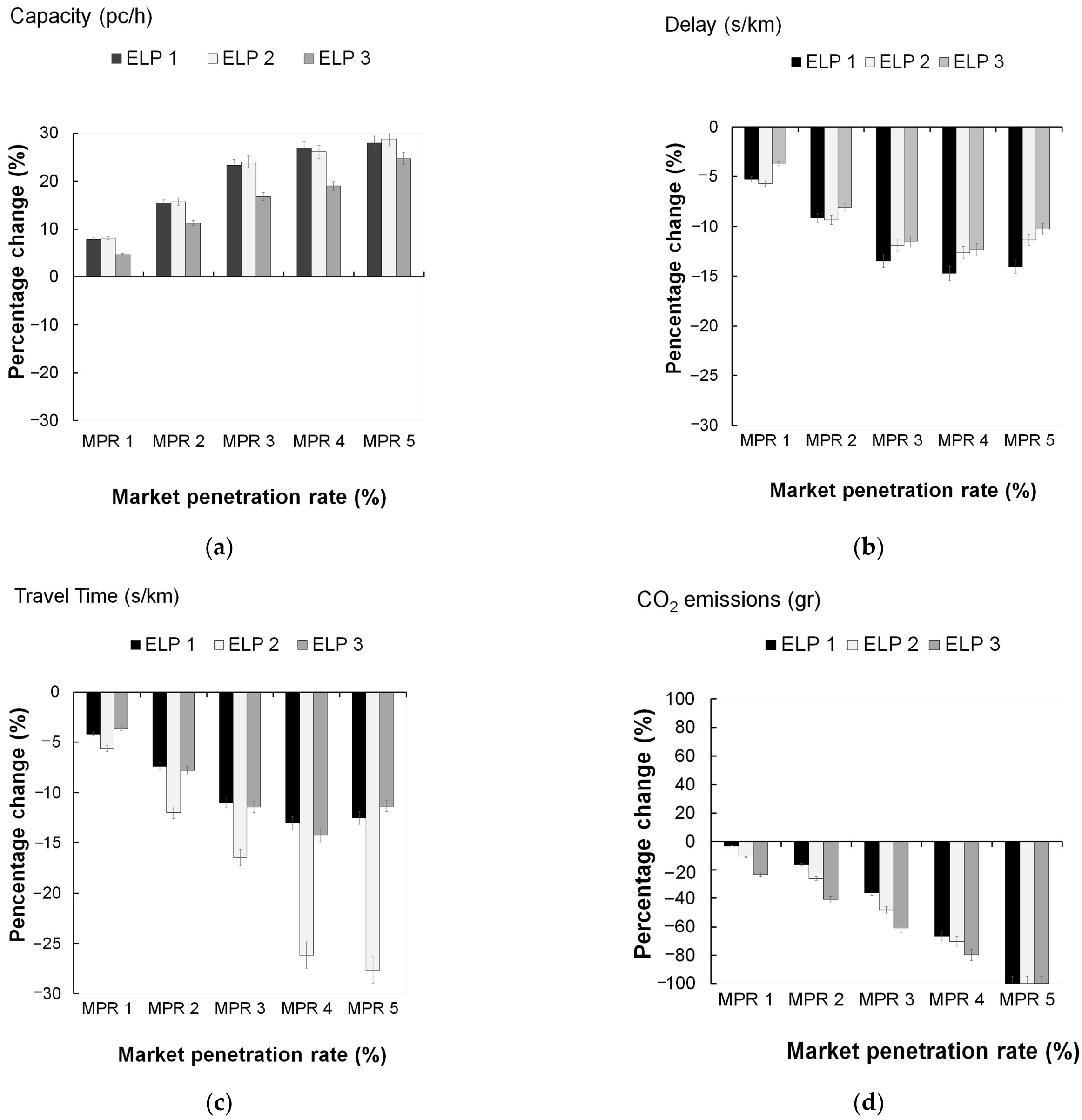

Figure 6. Percentage changes in the market penetration rates (MPRs) compared to the starting condition featuring only human driven vehicles: (**a**) entry capacity; (**b**) delay; (**c**) travel time; (**d**) carbon dioxide (CO_2) emissions. Note: (1) MPR 1: 20% CAVs; (2) MPR 2: 40% CAVs; (3) MPR 3: 60% CAVs; (4) MPR 4: 80%; (5) MPR 5: 100% CAVs.

The assumption of assertive behavior appears to compromise the safety performance in the two examined schemes in terms of total conflicts. It is important to note that the total number of conflicts represents the average value for each ELP, based on data from 10 trajectory files analyzed by the SSAM. The safety analysis was also conducted with reference to an approach saturation degree of 0.6 at every roundabout. While the safety analysis results were consistent with the assertive behavior assumptions for CAVs, the total conflicts percentage rates for each entry lane path, evaluated concerning the total conflicts simulated for each ELP, increased with higher MPRs because of the growing competition among vehicles in traffic regarding the gaps to be utilized (see Figure 7).

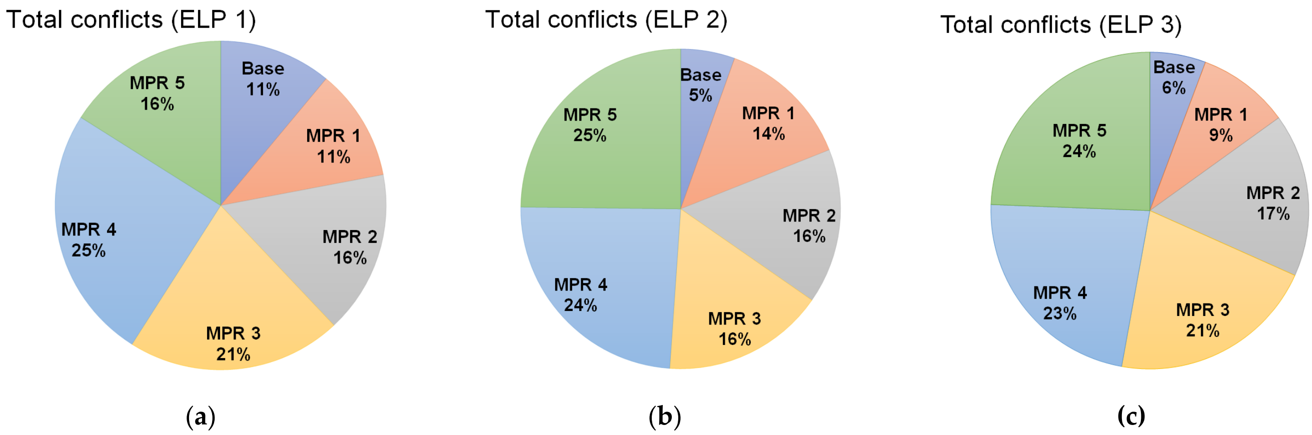

Figure 7. Simulated total conflicts at roundabouts R1 and R2 for increasing CAV market penetration rates (MPR 1, 2, 3, 4, to 5 corresponding to 20%, 40%, 60%, 80%, and 100%): (**a**) Total conflicts for entry lane path 1 (ELP 1) and the case of 0% CAVs; (**b**) Total conflicts for entry lane path 2 (ELP 2) and the case of 0% CAVs; (**c**) Total conflicts for entry lane path 2 (ELP 3) and the case of 0% CAVs.

The simulations also uncovered a considerable number of rear-end collisions, which were prevalent at both roundabouts. Roundabout R2, in particular, showed a noteworthy percentage of lane change conflicts (around 25 percent at each MPR), given the size of the circular roadway and the possibility of lane changes. Furthermore, it is crucial to acknowledge that the analysis conducted in this study was limited to conceptualizing roundabout network models as isolated nodes within the road network. Assumptions regarding assertive behavior led to an operational efficiency advantage at the expense of road safety, as indicated by the frequency of conflicts identified in the simulations, especially for the two-lane roundabout (R2). Based on the findings concerning the two-lane roundabout, dedicated lanes for CAVs with turbo-like configurations, featuring a spiraling layout and curbs for separating vehicular movements, may offer greater adaptability in implementing the V2X features typical of smart infrastructure [13,80]. Additionally, cautious CAV behavior should also be simulated in order to identify the most appropriate behavioral trade-off, especially in mixed traffic. Although the transition to a fully autonomous vehicle fleet, assuming assertive behavior, brought notable operational advantages, progressively enhancing roundabout traffic conditions, the simulations in Aimsun [78] employing CAV logic should be conceived as illustrative scenarios, providing insights for CAV traffic management rather than definitive forecasts. Further research on diverse traffic patterns and roundabout layouts is essential to evaluate the suitability of roundabout geometry for gradual CAV integration, refine design standards, and enhance traffic efficiency.

5. Discussion

Building upon the considerations outlined above, this paper presents accumulated knowledge in the field of roundabout design and performance evaluation, considering the transition toward intelligent mobility. Existing research helped the authors to address achievements and future steps while acknowledging the limitations of the study, initiating responses to key questions in Section 1.

Strategic planning for single-lane roundabouts always aims to enable seamless expansion if traffic forecasts align with the standard 20-year horizon. If projected traffic indicates a future need for multi-lane roundabouts, a phased approach starting with single lanes should ensure adaptability, balancing current requirements with future scalability [2]. These assessments are essential not only for ensuring the sustainability of transportation solutions but also for making informed decisions about infrastructure development, resource allocation, and environmental impact mitigation strategies [2]. From this perspective, conducting comprehensive cost analyses is crucial to support decision making [82]. One major concern is the cost of deploying and maintaining smart systems, although the long-term benefits may outweigh initial costs [2]. However, studies often overlook the construction cost of new smart solutions for future mobility. While smart roundabouts reduce signal equipment maintenance expenses, actual costs may vary based on site-specific conditions, design elements, landscaping, and road pavement [126].

Identifying analogies or differences in globally implemented roundabout design standards and practices was necessary to answer key question 1 (see Section 1) and to evaluate the impact of curved geometry on operational performance. Despite aligning design principles and geometric elements with overarching objectives, models and methods used in the safety performance evaluation and operational analysis for roundabouts must now consider the functional requirements of cooperative driving [5,10,11].

Findings from crash research and safety performance evaluation highlight the growing research interest in employing surrogate measures [48,56]. However, they require the use of microscopic traffic simulation models, the interests of which intertwine with their versatility, which is crucial for assessing choices during changes in roundabout design or traffic patterns. Accurate calibration of microscopic traffic simulation models should ensure that the simulated measures can predict roundabout safety performance based on vehicle trajectories from microscopic traffic simulation models and reflect real-world traffic conditions [57–59]. From this perspective, surrogate safety measures may offer a basis for comparing different intersection types under varying traffic conditions, aiding in performance evaluation.

Microscopic traffic simulation models are also crucial for assessing roundabout efficiency, providing insights into different design and traffic scenarios [14]. Driving simulation technology offers a clear advantage over real-scale measurements in evaluating vehicle performance and driving behavior. By eliminating the need for real-world driving data or data that cannot be observed, it streamlines roundabout design optimization and enables a thorough assessment of various design features and their impact on driver response to changes in geometry and traffic settings. This explains why microsimulation matters for evaluating roundabout performance, addressing key question 2 (see Section 1). Over time, microsimulation studies on roundabouts have increased, using various criteria for evaluation, including safety, mobility, environmental impacts, social effects, and economic factors [75,82,85]. From this perspective, Table 4 offered a concise overview of selected peer-reviewed studies on this subject.

Microsimulation techniques are also invaluable for forecasting the safety and operational implications of integrating CAVs into traffic, thus addressing key question 3 (see Section 1). Thus, these tools aid in evaluating the interaction between novel vehicles and geometric design, aiming for a balance between efficiency and safety. Microsimulation allows for controlled analyses across traffic scenarios with CAVs in traffic [5]. However, integrating simulation and real-scale measures would optimize assessments, enhancing roundabout design standards and guidelines [21,83,85]. Additionally, literature-informed insights into smart roundabouts highlighted primary study trajectories, thus emphasizing the importance of integrating smart features, promising enhanced functionality [11,110]. This underscores the need for innovative approaches to roundabout design to accommodate evolving transportation paradigms. Additionally, exploring data mining and artificial intelligence methods becomes imperative to understand traffic dynamics, particularly crucial for ensuring the safe navigation of roundabouts by CAVs amidst potential environmental awareness challenges [9,10]. Nevertheless, concerns such as physical constraints, realism, driver fatigue, and reliability still persist [21].

Roundabouts simulated in Aimsun [78] in Section 3 were conceptualized as illustrative scenarios, providing insights for traffic management amidst CAV presence, rather than definitive predictions. These simulations do not conclusively determine the appropriateness of roundabout geometry for CAV integration. However, the case studies in Section 3 allowed for demonstrating how to assess roundabouts in the transition toward a fully autonomous vehicle fleet. Assuming assertive behavior, the roundabouts exhibited notable operational benefits, gradually enhancing efficiency but at the expense of road safety, particularly in the two-lane roundabout (R2) rather than the single-lane counterpart (R1). Based on the findings concerning two-lane roundabouts from the literature [13,41,80], dedicated lanes for CAVs with turbo-like configurations, featuring a spiraling layout and curbs for separating vehicular movements, may offer greater adaptability in implementing the V2X features typical of smart infrastructure. Additionally, assumptions about cautious CAV behavior should be also tested to assess the most appropriate behavioral trade-off, especially in mixed traffic.

Regardless of the assertive behavior assumptions made in the calibration process, it should be noted that the combination of various levels of connectivity and automation can influence the contribution of these technologies to future benefits at transport system level [10]. Additionally, net energy savings at the vehicle level, depending on vehicle design or operations, can reach approximately 23 percent with fully CAVs, excluding the energy demand by automation and connectivity [3,10]. Despite energy savings, the potential impact on energy efficiency remains uncertain [10]. Overall, there is a possibility of heightened travel demand by individual cars, potentially exacerbating road congestion and energy-related CO_2 emissions instead of promoting shared mobility also with CAVs [10,11]. Further exploration of various traffic patterns and roundabout configurations is also essential for evaluating the suitability of roundabout geometry for the gradual integration of CAVs, refining design standards, and improving traffic efficiency across the road network, all while incorporating resilience as a guiding principle [135]. In this context, few methods have been investigated to incorporate efficiency and resilience into the performance assessment of roads and intersections. Although not the primary focus of the study presented in this paper, it is crucial to emphasize the importance of future research focusing on developing criteria to assess how specific intersection or roundabout projects can impact crucial aspects related to their ability to respond to extreme events. At last, Figure 8 outlines the proposed study path and provides a comprehensive overview of the research methodology employed in this study. This framework offers a roadmap, delineating the key steps and methodologies used to address the research objectives effectively. Through it, readers can gain insight into the structured approach undertaken to investigate the research questions and achieve meaningful outcomes.

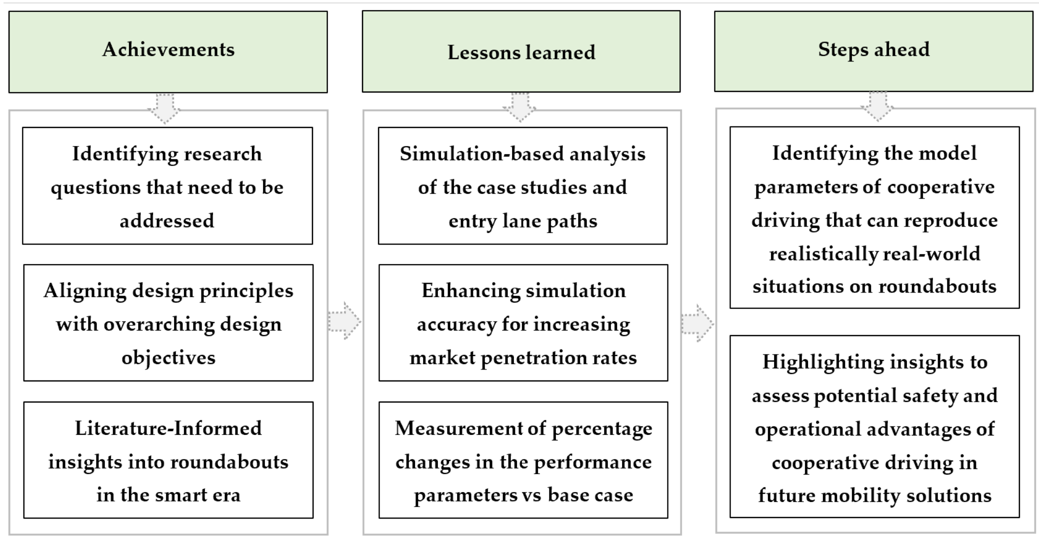

Figure 8. Summary framework outlining the proposed study path.

6. Conclusions

To ensure smooth and safe traffic flow, engineers increasingly favor modern roundabouts over conventional intersections for their performance. The importance of roundabouts lies in their geometric design and the traffic-calming effect they provide, especially as conventional vehicle fleets are gradually replaced by new driving technologies. This shift will impact road network design criteria, leading to continued research in the field. Additionally, evaluation methods must be tailored to the new demands of cooperative driving to align with traffic management and urban planning objectives.

This paper aimed to review current knowledge and identify emerging needs in the design and evaluation of roundabout systems, particularly considering new challenges from the automotive market and vehicle-to-vehicle communication. The literature-informed approach allowed the authors to evaluate safety and efficiency advancements using microscopic traffic simulation methods, with the aim of informing further research and shaping the role of roundabouts in the transition to cooperative driving. Utilizing Aimsun through case studies, the research explored the impact of connected and autonomous vehicles equipped with cooperative adaptive cruise control. Coupling Aimsun with the SSAM allowed the use of surrogate measures for the safety analysis. Given the limited real-world data on CAVs, assumptions were vital for modeling their impact on road performance. The latest *Highway Capacity Manual* [5] has introduced innovative techniques to predict capacity enhancements across diverse road infrastructure types, including roundabouts. These methods account for varying proportions of CAV-equipped vehicles, offering insights into potential performance improvements. The main conclusions of the study can be summarized as follows:

- Acknowledging that the results are influenced by the assumptions we made, simulations of roundabouts in Aimsun were only illustrative scenarios, offering insights into traffic management with CAVs on roundabouts rather than definitive predictions.
- The case studies do not decisively determine how roundabout geometry is suitable for CAV integration but demonstrate how to evaluate roundabouts in transitioning to fully autonomous vehicle fleets.
- Despite the advantages in terms of capacity and reduced delays for each entry lane path examined, simulations revealed significant differences in travel times across different market penetration rates of CAVs, particularly when only connected and autonomous vehicles operated on the two-lane roundabout. These discrepancies primarily stem from assumptions of assertive CAV behavior, such as utilizing the left lane for entry, accepting smaller gaps in the circulatory roadway, and adopting more efficient driving styles. Additionally, potential lane changes in the two-lane

circulatory roadway allowed vehicles to move side by side or switch lanes based on available gaps.

- Roundabouts, assuming assertive behavior, showed operational benefits but compromised safety, especially in two-lane roundabouts where dedicated lanes for CAVs with spiral layouts and curb separation could enhance adaptability for implementing V2X features.
- Testing assumptions about cautious CAV behavior is also crucial for mixed traffic to assess the most appropriate behavioral trade-off with CAVs in traffic. Thus, further research on diverse traffic patterns and roundabout layouts is essential for refining design standards and enhancing traffic efficiency.

In the transition toward cooperative driving, several research challenges in roundabout design and evaluation are anticipated:

- Firstly, there will be a need to develop new design standards and guidelines that accommodate the interaction between cooperative vehicles and traditional vehicles. This includes determining optimal lane configurations, entry and exit designs, and traffic control strategies to facilitate efficient cooperation between vehicles.
- Secondly, assessing the safety implications of cooperative driving at roundabouts will be essential. Researchers will need to investigate how cooperative vehicles interact with vulnerable road users such as pedestrians and cyclists, and how to minimize potential conflicts.
- Thirdly, there will be challenges in modeling and simulating cooperative driving behaviors accurately. This involves developing sophisticated simulation models that can replicate the complex interactions between cooperative vehicles and their environment, considering factors such as communication delays and varying levels of cooperation between vehicles.

Despite the computational hurdles, the goal is to attain sustainable traffic control at roundabouts by enhancing their safety and capacity in the face of advancing vehicle technologies. Additional case studies are necessary to identify cooperative driving parameters that faithfully replicate transition scenarios. This will empower analysts to evaluate how alterations in driving behavior affect the safety and efficiency of CAVs in traffic. Nevertheless, the research provides crucial insights for assessing the expected safety and operational benefits of CAVs in tackling future mobility challenges. This highlights the importance and relevance of the study's outcomes for transportation planners and engineers. Overall, addressing these challenges will require interdisciplinary collaboration between transportation engineers, computer scientists, and policymakers to ensure the successful integration of cooperative driving technologies into roundabout design and evaluation practices.

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