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SIMULATION-BASED PERFORMANCE EVALUATION FOR SMART ROAD SYSTEMS

Summary. With the growing integration of smart technologies in transportation, the study of roundabout operational efficiency and safety remains a pertinent research area. This paper presents a novel method for evaluating roundabout performance using simulation-based techniques. By analysing two roundabout case studies in Aimsun, the study explores the implications of increasing market penetration of cooperative, connected, and autonomous vehicles on traffic dynamics. The study involves processing geometric and traffic data, categorizing entry lane types, developing benchmark capacity functions, processing micro-simulator input data, and conducting sensitivity analysis for model calibration. The findings advance roundabout design and management in smart road systems and offer insights into the intersection of roundabout research and smart mobility solutions.

Keywords: smart road operational efficiency, Aimsun, road safety cooperative driving

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1. INTRODUCTION

Modern roundabouts enhance traffic flow and safety while reducing vehicle conflict points [1]. Challenges persist for newer adopters of roundabouts, especially at multi-lane sites, which require nuanced decisions regarding curved paths [1, 2, 3]. As autonomous driving advances, integrating human intuition with precise automation becomes crucial. Connectivity, essential for smart cities, gains significance with the rise of connected and automated vehicles (CAVs) [4, 5]. Accommodating both CAVs and vehicles driven by humans in circular intersections presents complexities, underscoring ongoing research aimed at optimizing roundabouts within the context of smart mobility [6].

Smart roads blend physical infrastructure, software, and big data for enhanced connectivity and energy generation [4, 7, 8]. While highways excel in smart features, extending this to urban roads is feasible but complex [7]. In turn, smart roundabouts have limited experiences supporting their potential integration into smart mobility frameworks [8, 9, 10]. Research has explored real-time control methods and data analysis to enhance traffic safety within smart transportation systems, which is particularly crucial for various traffic scenarios [9, 10, 11]. Achieving a balance between efficiency, safety, and resilience in roundabouts is challenging due to the need for infrastructure upgrades and technological limitations [12]. Future research should focus on improving design and technology integration to achieve seamless intelligent mobility. The adoption of standardized practices and vehicle-to-infrastructure communication can support this transition [13]. Continued progress highlights reliability concerns, necessitating practical evaluations. Addressing methodological limitations in analysing autonomous vehicle behaviour is crucial, alongside exploring advanced warning systems and infrastructure upgrades for safety and eco-friendly mobility [4].

Incorporating roundabouts into innovative sustainable transportation solutions also holds promise for addressing urban design challenges [14, 15]. Crucial for smart city evolution, intelligent transportation systems should enhance vehicle awareness, especially at intersections and roundabouts, through information and communication technologies [3, 9]. Cooperative driving frameworks and traffic-calming measures integration can optimize roundabout operations, offering environmental benefits [4]. Real-world validation is also vital, requiring cost analyses for decision-making [16]. Thus, additional research is needed to refine these frameworks, despite facing implementation and performance evaluation barriers.

Microsimulation techniques are increasingly vital for evaluating the impact of CAVs on traffic, offering advantages over real-scale measurements [17]. They facilitate roundabout design optimization and thorough assessment of various design solutions. However, uncertainties persist, especially in calibrating cooperative driving assumptions to real conditions [18].

Starting from the above considerations, this paper assesses smart solutions for two roundabout systems, emphasizing the research needs in the shift toward intelligent mobility. It presents a novel microsimulation-based methodology for evaluating roundabout performance, and guiding design decisions and traffic patterns' adjustments under diverse traffic conditions. The study aims to assess capacity, delay, travel times, and conflicts at roundabouts across different CAV proportions. Aimsun software allows for modeling mixed traffic patterns with human-driven vehicles (HVs) and CAVs, by configuring microsimulation setups, and conducting sensitivity analysis [19]. The model calibration validated simulation output against benchmark data [18]. Integration with the SSAM software enabled the safety analysis by using surrogate measures [11]. At last, the performance evaluation offered insights into roundabout research and smart mobility intersections.

The proposed research method is depicted in Figure 1 and detailed in Section 2. The research results are discussed in Section 3, while Section 4 concludes the paper.

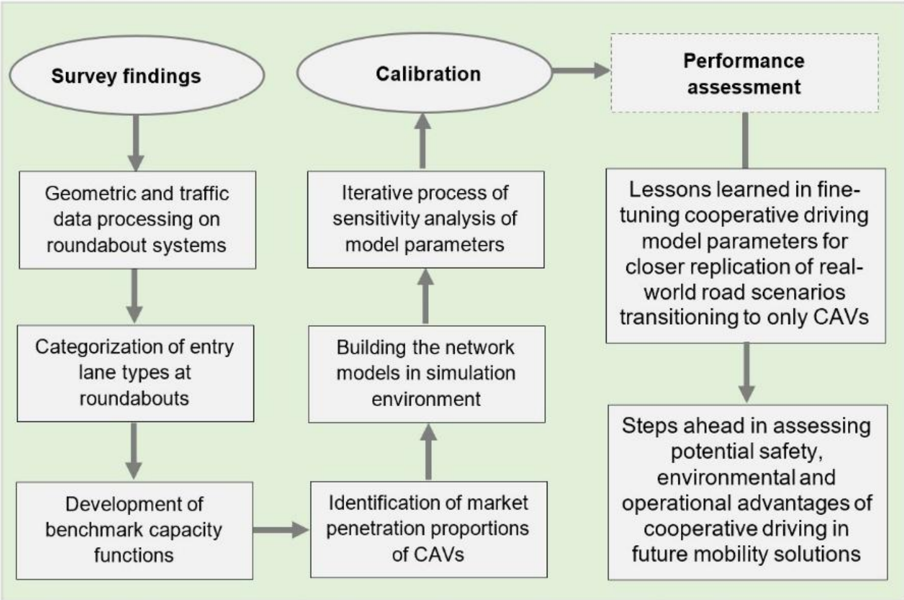


Fig. 1. Logical flowchart of the methodological approach for microsimulation-based performance assessment on roundabouts

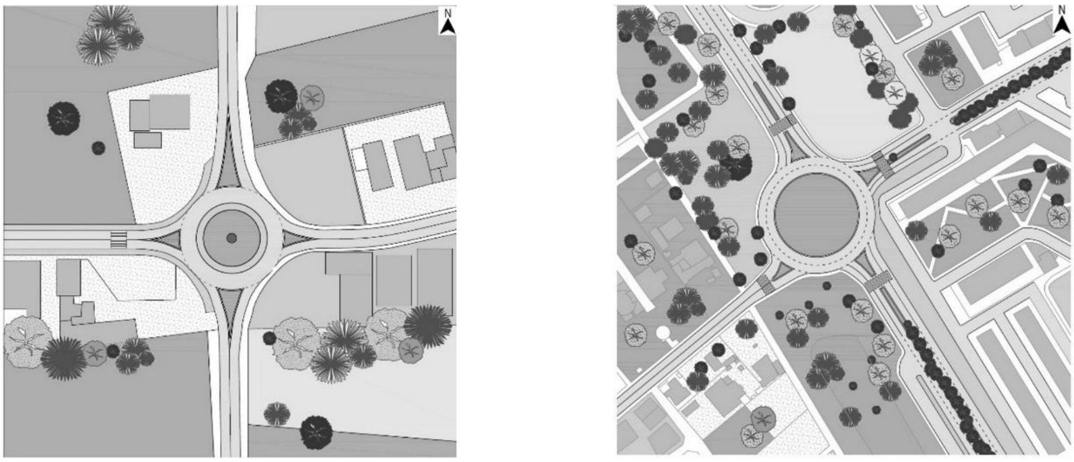
2. RESEARCH METHOD

2.1. Geometric Features and Traffic Survey

Two roundabouts were identified for designing corresponding geometric and traffic systems in Aimsun [19]. Both roundabouts are located in the road networks of two different Sicilian cities in Italy.

Figure 2 illustrates the roundabout schematics, adhering to Italian standards [20]. Their flat topography facilitates smooth traffic, aiding drivers in detecting potential conflicts. The geometric arrangement ensures easy entry, circulation, and exit while maintaining consistent visibility. Priority rules govern vehicle manoeuvring at conflict points, facilitating merging toward desired exits.

Cameras monitored traffic volumes and turning movements, supplemented by manual counts. Data collection at Roundabout 1 occurred during peak hours (7:30 to 9:00 a.m. and 7:00 to 8:30 p.m.) on weekdays from March to April 2023. At Roundabout 2, traffic surveys were conducted during peak hours (7:00 to 8:30 a.m. and 6:30 to 8:00 p.m.) from Tuesday to Thursday in November 2023. Uniformly distributed traffic from the entry approaches was observed, with minimal pedestrian presence at both sites due to the suburban feature of the installation contexts. Afternoon peak data were used for the subsequent microsimulation due to their extended duration. Table 1 shows some geometric and traffic details, and Figure 3 displays the traffic composition collected during the surveys.



(a) (b)

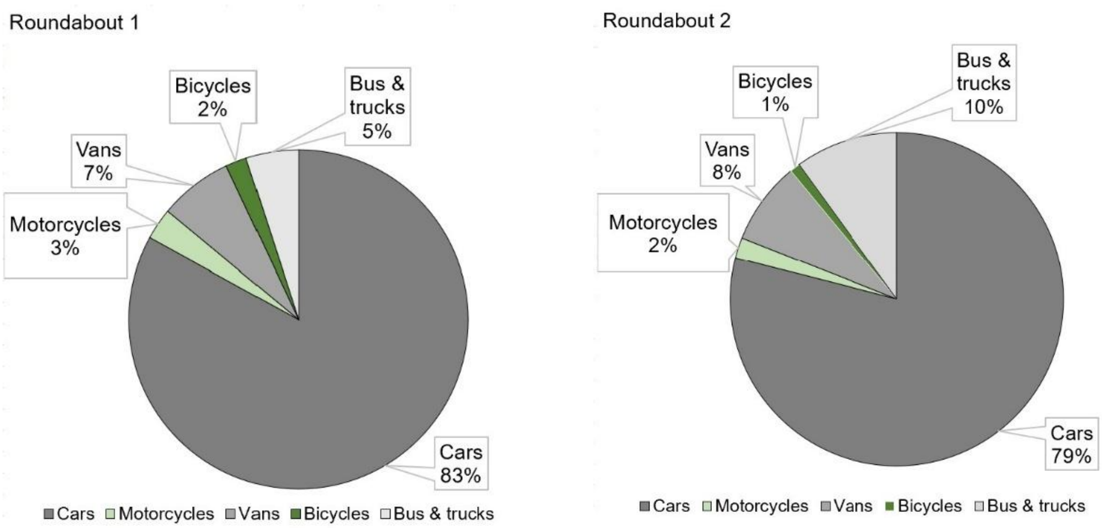
Fig. 2. The examined roundabouts:
(a). Roundabout 1 (latitude 37.660290, longitude 12.609872),
(b). Roundabout 2 (latitude 38.177443, longitude 13.309095)

Tab. 7

Geometric and traffic details at roundabouts

Roundabout	Outer diameter [m]	Circulatory lane width [m]	Entry (exit) lane width [m]	Entry traffic [veh/h]
1	39	7	4.5*	1356
2	71	8	4.5	3420

* 4 m in the minor direction (East-West)



(a) (b)

Fig. 3. Traffic composition in percentages: (a) Roundabout 1; (b) Roundabout 2

2.2. Categorization of Entry Lane Types and Benchmark Capacity Functions

Roundabout rules necessitate yielding to counterclockwise traffic, influencing interactions and gap acceptance. The priority rules manage merging, reducing the conflicts among entering and circulating vehicles. However, two-lane roundabouts face more conflicts than single-lane roundabouts due to the higher number of circulating lanes and no dividers among them [3]. Traffic surveys on the real-life layouts in Figure 2 allowed for observing driving behaviour, aiding understanding of drivers' decisions and interactions affecting entry capacity. Three types of entry lanes explained right-of-way negotiations at both roundabouts. Roundabout 1 in Figure 2a has a single-entry lane conflicting with one traffic stream circulating around the central island. Roundabout 2 in Figure 2b involves the left lane (L) or the right lane (R) of a two-lane entry conflicting with two traffic streams circulating around the central island.

Benchmark capacity functions were adjusted for cooperative adaptive cruise control vehicles using the factors from [18], the entry capacities by lane were calculated:

$$C = a \cdot A \cdot e^{-b \cdot B \cdot Q} \quad (1)$$

where:
C represents the entry lane capacity (pc/h), Q denotes the conflicting traffic flow rate (pc/h), parameters A (Roundabout 1: 1,380, Roundabout 2 (L): 1,350; Roundabout 2 (R): 1,420) and B (Roundabout 1: 0.00102; Roundabout 2(L): 0.00092; Roundabout 2 (R): 0.00085) control the intercept and slope of each capacity curve, respectively. Factors a and b from Exhibit 33-13, Chapter 33 [18] allowed for accommodating CAVs and adjusting the entry capacities; they were equal to 1 for the base functions (MPP: 0% CAVs).

Figure 4 illustrates the surface functions of the entry capacity under varying proportions of CAVs (Roundabout 1– One–lane entry conflicted by one circulating lane).

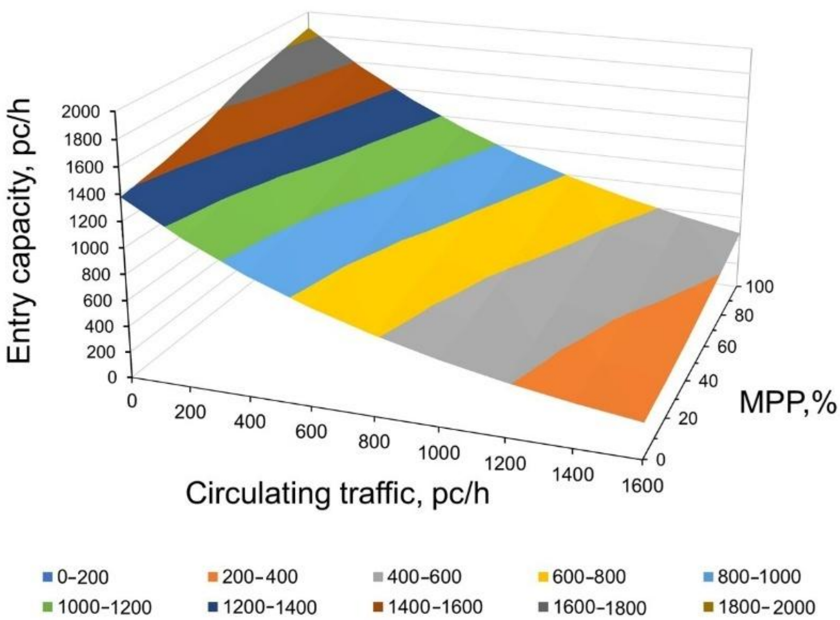


Fig. 4. Surface functions of entry capacity for different proportions of CAVs in Roundabout 1

2.3. Aimsun model setup

In this section, we outline the procedure for setting up the Aimsun model, which is important for simulating and analysing traffic scenarios. The setup process involves several steps to ensure the model is accurate and reflective of real-world conditions. After defining the study area for each roundabout and creating the roundabout network models in Aimsun, traffic demand was replicated by setting up an origin-destination matrix for each roundabout in Figure 2.

The starting time for relevant traffic demand was set at 6:15 pm. To assess the ability to replicate field traffic, 10 simulation runs were conducted in Aimsun. Each run comprised a 15-minute initialization, a 60-minute simulation, and a 15-minute completion to reset the system without affecting simulation quality. Simulated traffic matched field data within an 11% margin of error. The overall traffic matrix was partitioned into two OD matrices: one for vehicles driven by humans and one for CAVs, adhering to market penetration percentages (MPPs) of CAVs: MPP 0: 0%, MPP 1: 20%, MPP 2: 40%, MPP 3: 60%, MPP 4: 80%, and MPP 5: 100%. Thus, each MPP comprised a percentage p of CAVs and a percentage (1-p) of HVs. Seven OD matrices for Roundabout 1 and nine for Roundabout 2 were sequentially generated and assigned to the subject entry (the entry lane in Roundabout 1; the left-entry lane and right-entry lane in Roundabout 2) to simulate traffic until saturation. Circulating flow rose from 0 to 1,200 pc/h at Roundabout 1 (south entry in Figure 2a) and from 0 to 1,800 veh/h at Roundabout 2 (west entry, by lane in Figure 2b), increasing by 200.

Aimsun simulated diverse vehicle fleets at various CAV MPPs. Car-following, lane-changing, and gap-acceptance regulated longitudinal and lateral movement, as well as yielding, optimizing vehicle interactions and dynamics [19]. Cooperative adaptive cruise control facilitated data sharing, aiding driving decisions [18]. Lane changes were confined to Roundabout 2, enabling lane switches [3].

Calibrating the model parameters ensured benchmark capacity and simulated data alignment. Effective calibration of microscopic models required selecting the minimal necessary parameters, calibrated based on outcome impact. Literature [17] advises initial sensitivity analysis and manual calibration per parameter, iteratively adjusted until outputs closely match the targets, enhancing accuracy and reliability. By way of example, Table 2 displays calibrated parameters for vehicle fleets lacking CAVs; see [19] for details about the Aimsun parameters here used. The sensitivity analysis facilitated the understanding of the interactions among different vehicles and evaluated the CAV skills in mixed traffic across MPPs to calibrate the CAV parameters. Vehicle size remained uniform across the classes, but the behavioural framework for CAVs in Aimsun diverged from vehicles driven by humans, drawing from adaptive cruise control and cooperative adaptive cruise control trials. Shorter gaps occurred exclusively between CAVs. However, the optimal model parameters were identified to ensure the reproducibility of capacity targets. In turn, Table 3 shows the calibrated parameters for vehicular fleets with CAVs; see again [19] for details about the parameters here used.

Tab. 2

Calibrated parameters for traffic fleets without CAVs

Roundabout	Type of entry lane at Roundabout 1 or 2			
	Default	1	2(Left lane)	2 (Right lane)
Reaction time [s]	0.80	0.86	0.95	0.94
Speed acceptance	1.10	1.00	0.97	0.95
Gap [s]	0.00	1.58	1.33	1.00

Tab. 3

Calibrated parameters for vehicular fleets with CAVs

Roundabout	Type of entry lane at Roundabout 1 or 2			
	Default	1	2 (Left lane)	2 (Right lane)
Maximum acceleration [m/s²]	3.00	4.00	4.00	3.50
Safety margin factor	1.00	0.50	0.50	0.40
Sensitivity factor	1.00	1.00	0.50	0.50
Reaction time [s]	0.80	0.63	0.67	0.70

The calibrated parameters for traffic with CAVs included a higher maximum acceleration than the default, enhancing the performance of vehicles. The safety margin factor was reduced compared to the default value, indicating assertive CAV-driving at priority junctions. The sensitivity factor allowed the follower to estimate leader deceleration more assertively at Roundabout 2, ensuring smoother mixed traffic. The calibration also considered the reaction time (s) used by CAVs to adjust their speed to the speed variation of the next vehicle, similarly to vehicles driven by humans. The reaction time is the time of a CAV to respond to speed changes in the vehicle ahead [19]. Shorter reaction times can increase the capacity at entries, enabling the drivers to safely accept smaller gaps before entering the roundabout. CAVs demonstrated shorter reaction times than HVs, enhancing traffic efficiency. Aimsun's car-following parameter can be set uniformly for both CAVs and HVs, matching the simulation timestep [19]. Hence, a weighted average of the reaction times was computed for each user class, with the weights determined by the proportions of CAVs or HVs represented by each MPP. The cooperative gap parameter, ranging from 0.00 to high aggressiveness (1.00), was set to 0.50 to allow vehicle collaboration in creating lane-change gaps only at the two-lane roundabout, however, in line with roundabout speed limits. The sensitivity analysis considered additional parameters, but they were found to have minimal impact on the longitudinal and lateral behaviour of vehicles. By way of examples, Table 4 and Table 5 illustrate the results of the scatterplot analysis between pairs of benchmark capacity data and simulated capacities across various MPPs at Roundabout 2. The regression lines of the benchmark versus simulated capacity data were employed as a predictive tool to evaluate the model's fit to the data [17]. Each R-squared coefficient close to 1 indicated that the predictor variable could explain the response variable, confirming a strong positive correlation between the two sets of variables under examination. The GEH and RMSNE validated the model's acceptability, showing less than 5% deviation in the simulated capacities from the benchmarks for 90% of cases, confirming accurate error magnitudes [17]. Table 4 also shows the p-values from the two-sample t-test ($N=54$, $\alpha=0.05$) validating no significant difference between the benchmark and simulated capacities for each MPP. Table 5 provides similar validation for the calibrated model at Roundabout 2 (R), confirming accurate simulation of the mixed traffic across MPPs.

The safety analysis coupled the SSAM [11] with Aimsun to assess mixed traffic safety. Mean parameter values for HVs and CAVs were derived from ten simulation trajectory files per entry lane. The number of replications was determined through a sensitivity analysis to balance both computational cost and desired precision. Additionally, we ensured that the model did not exhibit significant stochastic behaviour that would necessitate multiple replications to capture adequately. Testing validated this assumption; it was found that no further simulations provided higher benefits. Specifically, the total conflicts and conflicts by type counted were the mean values from the ten trajectory files elaborated by the SSAM for every roundabout.

The sensitivity analysis revealed significant impacts of time-to-collision (TTC) and post-encroachment time (PET), where smaller values increased the conflict probability. TTC threshold was set at 1.5 s, with PET thresholds at 2.5 s for Roundabout 1 and 1.9 s for Roundabout 2. The conflict angles categorized conflicts into rear-end (<30°), crossing (>85°), and lane-changing (otherwise).

Tab. 4

Indicators of goodness-of-fit used to assess the calibrated model at Roundabout 2 (Left lane)

MPP*	Regression line	R^2	GEH (%)	RMNSE	*p*-value
0	$y = 0.85\,x + 152.00$	0.997	91.00	0.13	0.63
1	$y = 0.\ 844\,x + 145.5$	0.993	100.00	0.09	0.93
2	$y = 0.85\,x + 107.00$	0.998	100.00	0.07	0.88
3	$y = 0.86\,x + 120.00$	0.984	97.00	0.07	0.95
4	$y = 0.856\,x + 123.10$	0.987	94.00	0.06	0.84
5	$y = 0.903\,x + 185.00$	0.996	92.00	0.07	0.73

* MPP stands for market penetration percentages of CAVs

Tab. 5

Indicators of goodness-of-fit used to assess the calibrated model at Roundabout 2 (Right lane)

MPP*	Regression line	R^2	GEH (%)	RMNSE	*p*-value
0	$y = 0.85\,x + 77.00$	0.998	100	0.09	0.60
1	$y = 0.86\,x + 144.00$	0.996	100	0.07	0.56
2	$y = 0.91\,x + 22.51$	0.996	100	0.08	0.46
3	$y = 0.90\,x + 84.53$	0.995	100	0.05	0.71
4	$y = 0.92\,x + 91.61$	0.995	100	0.03	0.96
5	$y = 0.89\,x + 150.0$	0.994	100	0.05	0.90

* MPP stands for market penetration percentages of CAVs

3. ANALYSIS OF THE RESULTS

To assess the impact of CAVs on roundabout performance, various parameters were analysed, including entry capacity, delay time, and travel time. Entry capacity, pc/h, denotes the maximum number of vehicles entering the roundabout while maintaining acceptable service levels [3]. Delay time signifies the additional time vehicles spend within the roundabout due to congestion, calculated by comparing actual travel time to free-flow conditions [3]. Travel time represents the duration for a vehicle to navigate from entry to exit, influenced by the traffic volumes, geometric configuration, and operational characteristics [3]. The operational analysis involved calculating the percentage differences in parameter values for each MPP of CAVs compared to a base condition with solely HVs. Figure 5 depicts the bar charts illustrating capacity trends from MPP 0 to MPP 5.

The simulations illustrated that higher market penetration proportions of CAVs in traffic resulted in improved efficiency, thus influencing the approach capacities. Higher MPPs enabled the acceptance of shorter gaps, thereby enhancing the entry capacity and showcasing the impact of CAVs on traffic dynamics and efficiency. At Roundabout 1 when a single-lane entry approached capacity, capacity increased by 23.32% (MPP 3) and by 27.92% (MPP 5) compared to the base case featuring solely HVs. Similar trends were observed at Roundabout 2 compared to the base case: with 80% CAVs (MPP 4), capacity increased by 26.10% in the left entry lane and 19.01% in the right entry lane (see Fig. 5). These findings underscore the positive impact of CAV integration on entry capacities, emphasizing the potential for enhanced traffic flow and efficiency with increasing CAV presence. When only CAVs operated on Roundabout 2 (MPR 5), the percentage differences in entry capacity increased to 28.71% (left entry lane) and 24.73% (right entry lane) as shown in Figure 5.

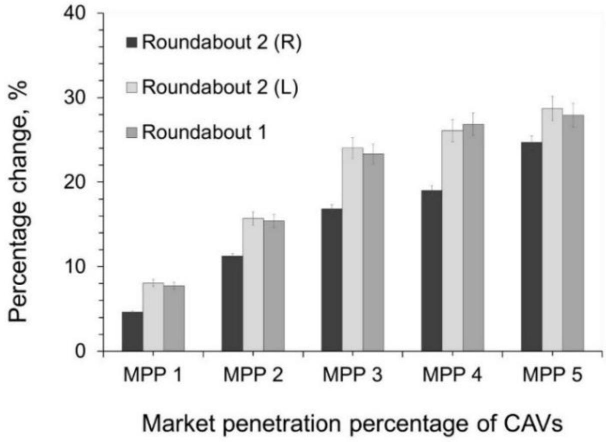


Fig. 5. Percentage variation in capacity values at the sampled roundabouts. Note that L and R stand for left entry lane and right entry lane, respectively, at Roundabout 2 in Figure 2b

Consistent with previous studies on the impact of autonomous driving [1, 12], higher percentages of CAVs in traffic improved their ability to navigate through narrower gaps, thereby enhancing entry capacity and reducing delays and travel times. Figure 6 illustrates the percentage changes in delay and travel times across MPPs. At Roundabout 1 and MPP 3 (60% CAVs), delays and travel times decreased by approximately 13.45% and 10.95%, respectively (see Figure 6a). However, when only CAVs were operating at Roundabout 1, the percentage differences in delay and travel times tended to stabilize compared to MPP 4. Delays and travel times decreased gradually at Roundabout 2. At MPR 3, delays in the left entry lane decreased by around 11.96%, while travel times decreased by approximately 16.48% (Figure 6b). In the right entry lane, delays decreased by about 11.49%, and travel times by approximately 11.42% (Figure 6c). Despite delay times stabilizing at higher MPPs due to the reduction or absence of competition with HVs, travel times notably decreased for the left entry lane in comparison to the right lane (see Figure 6b and Figure 6c). These disparities primarily stem from the assumptions of assertive behaviour, prompting CAVs to utilize the left lane, accept smaller gaps in the circulatory roadway, and adopt more efficient driving styles.

Assertive behaviour assumptions affected safety performance in both roundabout layouts (see Figure 7 and Figure 8). The total conflicts were averaged values based on the trajectory files analysed using the SSAM for both sites. The safety analysis was conducted with an approach saturation degree of 0.7 at each entry. The conflict points at each sampled roundabout are depicted in Figure 7a and Figure 8a. These figures also illustrate the total conflict percentages per entry-lane out of the total simulated conflicts at each roundabout. The conflict rates increased with higher MPPs due to intensified competition among CAVs for gap utilization (see Figure 7b, Figure 8b to Figure 8c). The simulation revealed a notable number of rear-end collisions. Roundabout 2 also showed a significant percentage of lane change conflicts (approximately 25% at each MPP), attributed to the circular roadway's size and potential lane changes.

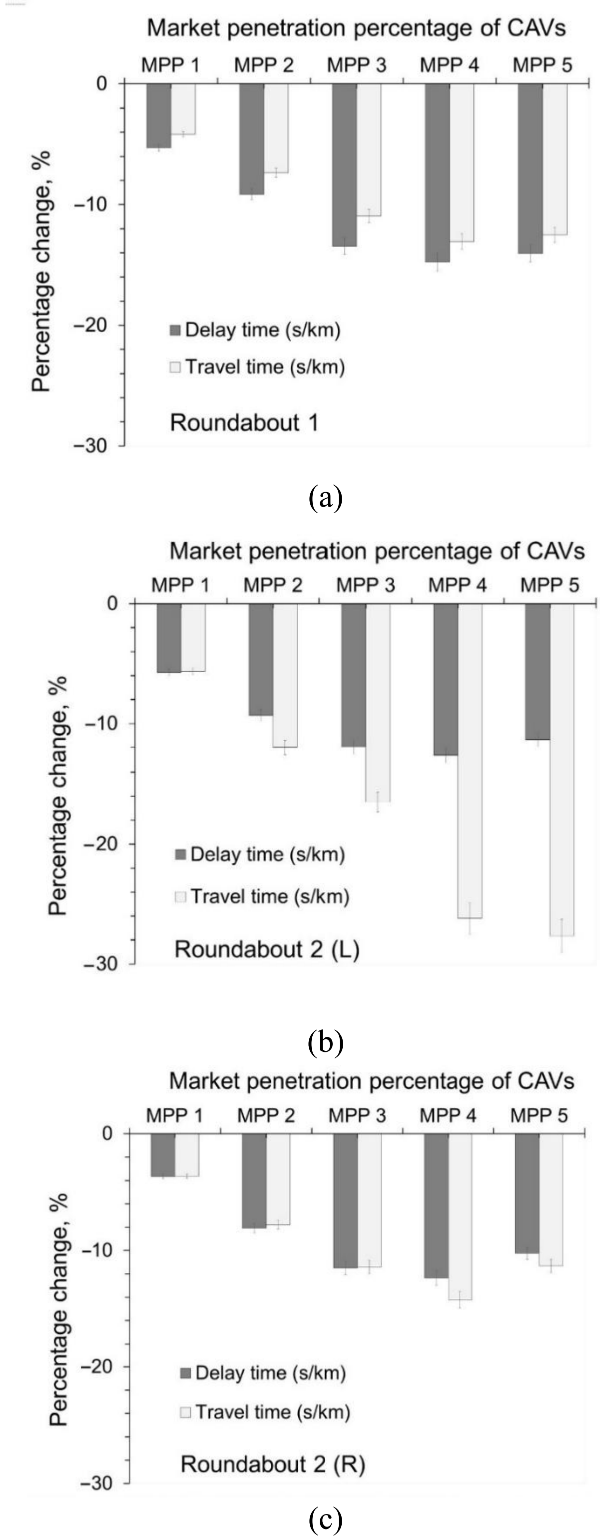
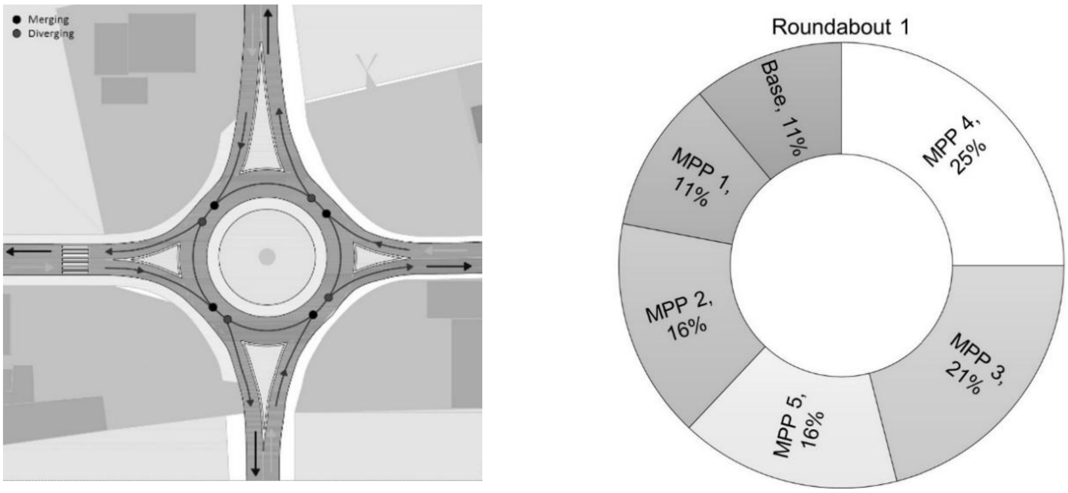


Fig. 6. Percentage variation in: (a). delays and travel times at Roundabout 1, (b). delays and travel times at Roundabout 2 (L: left entry lane), (c). delays and travel times at Roundabout 2 (R: right entry lane)

The analysis focuses on roundabouts as isolated nodes, favouring operational efficiency but raising the safety concerns for Roundabout 2. Proposed solutions include dedicated CAV lanes based on turbo roundabout design and cautious CAV behaviour simulations to address safety and adaptability issues in mixed traffic [1, 12]. While transitioning to a fully CAV fleet offers benefits, simulations serve as illustrative scenarios for guiding CAV traffic management.

Further research on diverse traffic patterns, road infrastructure and roundabout layouts is crucial for evaluating roundabout geometry's suitability for gradual CAV integration and enhancing traffic efficiency and safety [21, 22].



(a) (b)

Fig. 7. Safety analysis findings at the single-lane roundabout:
(a). conflict points, (b). percentage variation in total conflicts

4. CONCLUSIONS

Modern roundabouts are favoured in traffic engineering for their layout and traffic-calming effects. As driving technologies advance, road design standards are expected to evolve. This study addresses current challenges and emerging needs in roundabout evaluation, particularly considering automotive advancements and vehicle-to-vehicle communication. Microscopic traffic simulation evaluates safety and efficiency, shaping research and determining roundabouts' function in the advancement of cooperative, connected, and automated driving. Section 3 introduced the proposed methodological approach for estimating operational and safety performance at roundabouts with CAVs.

This study, utilizing microscopic traffic simulation, explored the impact of CAVs equipped with cooperative adaptive cruise control. Innovations in the latest Highway Capacity Manual enabled forecasting capacity enhancements with varying CAV proportions. The sensitivity analysis in Aimsun validated the model's ability to replicate benchmark capacity functions across different scenarios, emphasizing the importance of adjusting the model parameters to capture CAV behavioural tendencies. However, it is crucial to acknowledge the inherent limitations in the study's assumptions. Simulation results revealed capacity enhancement and reduced delays, yet significant differences in travel times emerged, particularly with only connected and automated vehicles.

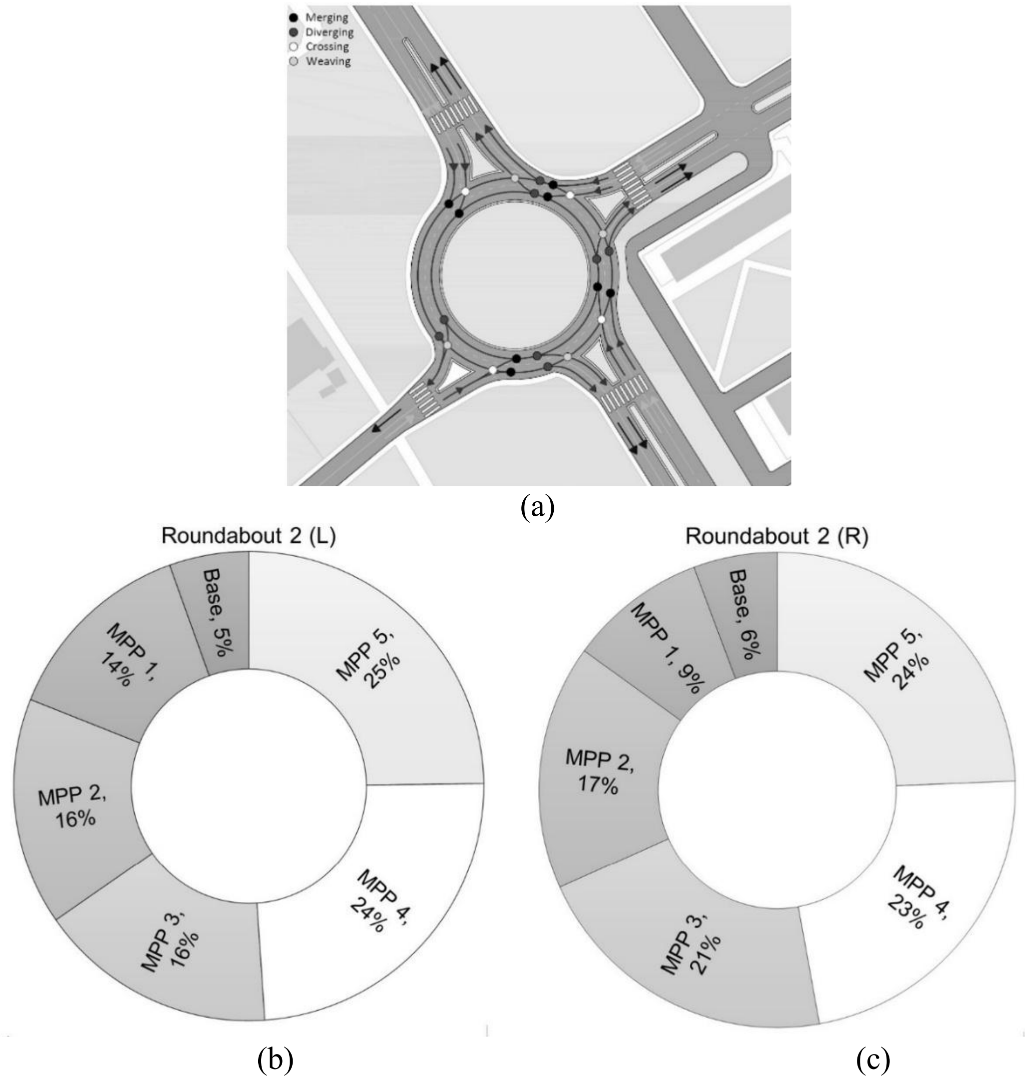


Fig. 9. Safety analysis findings at the two-lane roundabout: (a). conflict points, (b). percentage variation in total conflicts at Roundabout 2 (L: left entry lane), (c). percentage variation in total conflicts at Roundabout 2 (R: right entry lane)

These disparities highlight the interplay between site features and behavioural assumptions, such as the assertive driving of CAVs. While operational advantages are clear, safety concerns, especially in two-lane roundabouts, must be addressed. Dedicated lanes for connected and automated vehicles show promise in implementing vehicle-to-everything functionalities.

Future research should rigorously test assumptions about vehicle behaviour to determine suitable trade-offs, especially in mixed traffic environments, ensuring the safe and efficient integration of connected and automated vehicles into existing road infrastructure.

Aimsun simulations offer informative scenarios for CAV-informed traffic management but require cautious interpretation. While not definitive, these case studies provide insights into evaluating roundabouts amid the transition to fully autonomous vehicle fleets. As cooperative driving evolves, the study anticipates several research challenges in roundabout design and evaluation. Also, future developments of the research in this field should include further case studies to compare the outputs with independent traffic data that are not used in the calibration process. This step will confirm the model's predictive accuracy. New standards must address the interaction between cooperative and traditional vehicles, optimizing the lane configurations, entry/exit designs, and traffic control.Assessing safety implications, particularly with pedestrians and cyclists, is vital. At last, accurately modelling cooperative driving behaviours may require sophisticated simulation models. These efforts converge to enhance roundabout traffic management, maximizing safety and capacity amidst evolving vehicle technologies. Interdisciplinary collaboration among transportation engineers, computer scientists, and policymakers is essential to address these challenges. This collaboration ensures that the evolution toward smarter cities becomes a tangible reality, shaped by innovative research and cooperation. Ultimately, it guarantees the seamless integration of cooperative driving technologies into road design and evaluation practices.

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