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# SIMULATING VEHICLE-TO-VEHICLE COMMUNICATION AT ROUNDABOUTS

**Summary.** Smart roads integrate advanced technology to enhance safety, effectiveness, and eco-friendliness, revolutionizing transportation systems. Within this framework, connectivity and automation work together to improve road mobility and energy efficiency. However, there are still uncertainties regarding their effect on road safety and traffic operations, as well as assessment methods, especially for intersections and roundabouts. Navigating roundabouts involves complex decision-making influenced by cooperative and competitive interactions between human-driven vehicles and connected and autonomous driving vehicles (CADVs), affecting gap-acceptance patterns. This research employs Aimsun Next software to simulate the rising market penetration percentages of CADVs by examining assumption-based behavior on single-lane roundabouts. It integrates CADV-based capacity modification factors from the Highway Capacity Manual 2022 and compares adapted capacity curves for CADVs, with simulated capacities for model calibration. Critical model parameters affecting CADVs' ability to enhance roundabout safety and throughput are identified, with a focus on the transition towards cooperative driving in the context of smart roads.

## 1. INTRODUCTION

Smart roads represent a significant advancement in transportation infrastructure, offering improved safety and efficiency compared to traditional roads [1]. However, their feasibility and effectiveness still require validation through pilot projects and real-world deployment. By integrating high technologies among other sensors, adaptive traffic signals, and real-time analysis of data, smart roads are equipped to detect and react to changeable traffic situations, improve traffic flow, decrease congestion, and sharpen the operational performance of roads and intersections overall.

Connectivity and automation, when integrated, hold significant potential for improving road safety, saving energy, and improving the throughput of pre-existent roads by providing real-time information to drivers and automated systems. The human-automation interaction details the breakdown of tasks between drivers and automated systems based on levels of driving automatization, spanning from the absence of automation to complete dynamic navigation without human intervention [2]. While connectivity levels lack a standardized definition, they encompass different types of communication between vehicles, between vehicles and road infrastructures, between vehicles and pedestrians, and so on. The combined impact of these technologies on long-term benefits will depend on the integration of different automation and connectivity levels [1].

In this context, the safety and efficiency of smart roundabouts remain an open question, particularly regarding whether self-driving vehicles exhibit hesitation or effectively maneuver roundabouts. Connected and autonomous driving vehicles (CADVs) are equipped with technologies that enable them to make decisions and take actions autonomously without direct human input. Additionally, CADVs

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combine digital technologies with automated systems to interact with their surroundings, using sensors, cameras, internet connectivity, GPSs, and telecommunications networks. On-board equipment with cooperative adaptive cruise control (CACC) systems permits CADVs to take advantage of briefer gaps compared to human-driven vehicles (HVs) solely utilizing adaptive cruise control (ACC) [3].

Compared to other types of intersections, roundabouts enhance traffic performance and promote safe and seamless operation, particularly by enabling equilibrated traffic flows from all paths. [3]. Thus, driving in roundabouts, especially for higher automation levels involving completely dynamic driving sans human intervention, may engender complex driving scenarios due to maneuvering mechanisms at circular intersections. Despite the ongoing development of smart intersection technologies to optimize traffic flows and facilitate CADVs on dedicated lanes or amid inhomogeneous traffic, knowledge gaps persist regarding road infrastructure requirements and the management of CADVs' movement in roundabouts. Moreover, decision-making for CADVs can require a greater workload than for human drivers when deciphering the intentions of other users regarding curvilinear trajectories, entries, exits, turns, lane changes, and so on.

Some studies have utilized information extracted from big data with automatic procedures. That is, machine learning techniques have been used to explore the impact of curved paths on automated vehicles (AVs) [4]. However, these methods often involve a long-running process, requiring reward actions to penalize incorrect actions until a high success rate is achieved. During the transitional phase of CADVs' integration, it can be crucial to examine operational challenges when CADVs and HVs coexist. However, with the present small market entry percentage (MPPs) of CADVs, research applied on the network level or at particular road entities like intersections or roundabouts remains experimental. Thus, assumptions are necessary when estimating CADV capacity enhancements at roundabouts [3]. In this respect, traffic micro-simulation is useful for assessing changes in traffic safety and vehicle operations under varying CADV-based MPPs, informing new road management measures and evaluation tools [5].

Several studies have utilized traffic micro-simulation modeling to evaluate whether CADVs negotiate roundabouts similarly to human drivers or contribute to throughput improvements in traffic as anticipated [5-12]. Although driving simulation modeling can incorporate CADV logic, predictions of future traffic conditions involve assessing potential scenarios rather than providing definitive outcomes for widespread CADV deployment [5]. The summary in Table 1 encompasses research primarily centered on applications utilizing microscopic traffic simulation models [13,14] commonly used in urban roundabout design. The papers in Table 1 will be briefly discussed in the following section.

In order to explore the potential advantages of CADV integration into the road network, this study aims to investigate the effect of CADVs on operative and safety conditions at a single-lane roundabout using Aimsun [14]. This paper modeled scenarios with CADVs in traffic; these were executed in Aimsun [14] to analyze the effect of AVs equipped with CACC in a roundabout case study across various CADV-based MPPs.

The study is inspired by the readiness of CADV-based capacity modification factors supplied by the Highway Capacity Manual [3] (HCM) for roundabouts. The 7th Edition of the HCM [3] introduced some factors for adapting the entry capacity for CADVs in different types of road infrastructures and intersections to gauge their operational effectiveness and influence on calculated capacity. The capacity modification factors for CADVs blended in traffic with conventional vehicles were derived from micro-simulation experiments, assuming reliable communication technologies.

The impact of CADVs on roundabouts was modeled by adjusting the behavioral parameters that directly influence the entry capacity [3]. Increased market penetration percentages of CADVs are expected to enhance capacity by enabling vehicles to leverage brief gaps more efficiently. Since the observed vehicular fleets were not directly observable, the HCM provided an alternative source for benchmark capacity values. This information was utilized to examine assumption-based CADV behavior and explore hypotheses regarding the transition toward an all-CADV traffic fleet.

This paper aims to answer the following research questions: Can adjustments to Aimsun model parameters enhance the alignment between CADV-based capacity modification factors and simulated data? What implications arise in traffic if there is a reasonable alignment between these capacity data sets? Can a greater percentage of CADVs in traffic leverage connectedness advantages by safely accepting briefer gaps?

Table 1
Overview of prior studies utilizing microsimulation-based approaches for evaluating roundabout performance

| Reference | Tool | Subject |
|---|---|---|
| [5] | Aimsun | A structured approach for evaluating connected and autonomous vehicle (CAV) safety and efficiency in roundabouts |
| [6] | Vissim | Assessment of how geometry influences emissions in traffic with emission-free vehicles in turbo-roundabouts and signalized intersections |
| [7] | Vissim | Multi-criteria evaluation for comparing different roundabout layouts, as well as signalized intersections |
| [8] | Vissim | Evaluate the effect of AVs on the capacity of single-lane roundabouts |
| [9] | Aimsun | Incorporating the vehicle-specific power model in a simulated environment to assess real-time vehicular emissions in two-lane roundabouts |
| [10] | Vissim | Analyzing the safety and operational aspects of transforming priority intersections in roundabouts |
| [11] | Vissim | Simulation of a signalized roundabout to evaluate capacity and operations |
| [12] | Aimsun | Efficiency assessment aimed at prioritizing public transport at roundabouts |

In order to compare simulated data with the capacity functions and to assess safety and operational performances across different CADV MPPs, this study focused on a real-world example of a single-lane roundabout. Also, this paper highlights the importance of calibrating the micro-simulation model to consider CADVs in traffic. This is linked to the current physiological rate of market penetration of the new vehicles replacing the old ones and the resulting lack of empirical evidence to validate the assumptions about cooperative driving.

From a scientific point of view, this research analyzes how model parameters influence single-lane roundabout capacity and assesses the impact of changes in driving behavior under different CADV-based MPPs, providing insights into traffic management. While certain performance metrics were selected to elucidate operational impacts, the authors acknowledge that any appraisal of traffic conditions offers insights into the potential outcomes of CADVs rather than definitive conclusions about their future status on the road network. Societal contributions include understanding the potential advantages of CADVs' employment for road users.

This paper comprises four sections. After this introduction, Section 2 describes the research area and outlines the related research. Section 3 delves into how CADVs affect roundabout environmental, operational, and safety performance using Aimsun modeling. Section 4 concludes the paper and discusses potential future advancements.

## 2. RELATED RESEARCH

The prospect of the widespread use of cooperative driving is making road infrastructures smarter [1]. Given the curvilinear nature of roundabout geometry, the safety and efficiency of roundabouts in the smart era remain an open research question. Despite the proliferation of CADVs, the road infrastructure is not yet fully prepared. Hence, evaluations regarding the effectiveness of smart roundabouts should solely rely on simulating predictive scenarios using suitable methods and models. Microsimulation modeling has gained prominence in various fields for its ability to simulate individual-level behaviors and interactions within the users' community [9, 13, 14]. In transportation, microsimulation models offer valuable insights into complex systems and policy impacts [5]. Microsimulation has also revolutionized transportation planning by allowing detailed analyses of traffic flows, congestion, and infrastructure investments [7]. Research by Osei et al. [11] demonstrated the effectiveness of microsimulation in predicting the impact of new road designs on traffic patterns, operations, and safety.

Additionally, Zakeri et al. [12] employed microsimulation to optimize public transportation routes and schedules for urban areas. Studies by Tumminello et al. [5] have highlighted the utility of microsimulation in predicting traffic flows, assessing the performance of an intersection or a roundabout, and determining the impacts of infrastructure changes.

Microsimulation modeling combined with cooperative driving technologies represents a promising approach to enhancing transportation efficiency, safety, and sustainability [6][10]. Cooperative driving technologies, such as vehicle-to-vehicle and vehicle-to-infrastructure communication, facilitate real-time data sharing among vehicles and infrastructure elements. The integration of microsimulation modeling with cooperative driving technologies also offers new opportunities for transportation planning and management. Studies by Tumminello et al. [5] and Boualam et al. [8] explored how microsimulation models can incorporate novel driving behaviors to assess the potential impacts of CADVs on traffic flow, safety, and travel time reliability.

While microsimulation modeling offers powerful tools for policy analysis, it is not without challenges [3]. Calibrating behavioral parameters is crucial in accurately modeling cooperative driving behavior [5]. This involves vehicles' communication with each other and infrastructure to streamline traffic, increase safety conditions, and improve efficiency in roundabouts. Model complexity, data limitations, and uncertainty in parameter estimation remain significant concerns in the smart age [1].

Despite numerous applications for roundabouts (see Table 1), challenges remain in implementing microsimulation-based cooperative driving systems and assessing their potential benefits. Issues such as interoperability, cybersecurity, and public acceptance also require careful consideration [1, 5]. Future research should focus on refining microsimulation models to accurately capture the dynamics of cooperative driving behaviors and evaluate the scalability and robustness of cooperative systems in real-world settings. From this standpoint, the concrete example of the one-lane roundabout under consideration in this study contributes to the research area by proposing a method to evaluate safety conditions and operational effectiveness in a mixed flow of CADVs and HVs.

## 3. CHARACTERISTICS OF THE CONDUCTED RESEARCH

The roundabout under study is located at the crossroads of Salemi Street, leading eastward to Mazara del Vallo, Italy, city center, the SP 50 provincial highway westward, and the highway 115 in a north-south and south-north direction, approximately 400 meters from highway E90. Its placement benefits from ample space in the transition from rural to urban areas and a level of topography.

The concerned roundabout has an outer diameter of 39.00 meters and a circulatory roadway width of 7.00 meters. Approaches 1 and 3 (see Fig. 1a) have single-entry and exit lanes that are 4.50 meters wide, whereas approaches 2 and 4 (see Fig. 1a) have single-entry and exit lanes with a width of 4.00 meters. Also, each approach has raised splitter islands and deflection angles exceeding 45 degrees. The layout promotes slow-speed traffic with adequate sight distances to ensure safe maneuvering. Fig. 1 depicts a sketch of the roundabout under study and a view of the northbound entry.

The traffic counts were carried out during peak morning and afternoon times (from 7:30 to 8:30 a.m. and from 6:30 to 7:30 p.m.) on three weekdays (Tuesday to Thursday) in March 2024. Traffic data were recorded using two cameras placed at the southern and northern branches (see Fig. 1a) and were supplemented with manually collected data. Only data from the morning peak hours were utilized to initialize Aimsun for the subsequent analysis, as it spanned a longer duration than the afternoon peak. Surveys revealed entering traffic flows of 1287 vehicles per hour during the morning peak. Traffic mainly comprised cars (83%), along with motorcycles (4%), vans (7%), bikes (2%), and buses/trucks (4%).

The roundabout experienced balanced traffic flows across all legs, with minimal pedestrian activity due to its distance from residential areas. The circulatory lane size precludes lane changing, and the speed limit is 30 km/h. Consistent with the literature, 85th percentile speeds were approximately 25 km/h upon entry, 20 km/h while circulating, and around 28 to 30 km/h when exiting [9]. Table 2 presents the trip matrix in the form of origin and destination of average traffic volume percentages measured in 15-

minute intervals during morning peak hours, obtained from on-site surveys. Notably, simulations considered only one entry for capacity estimation.

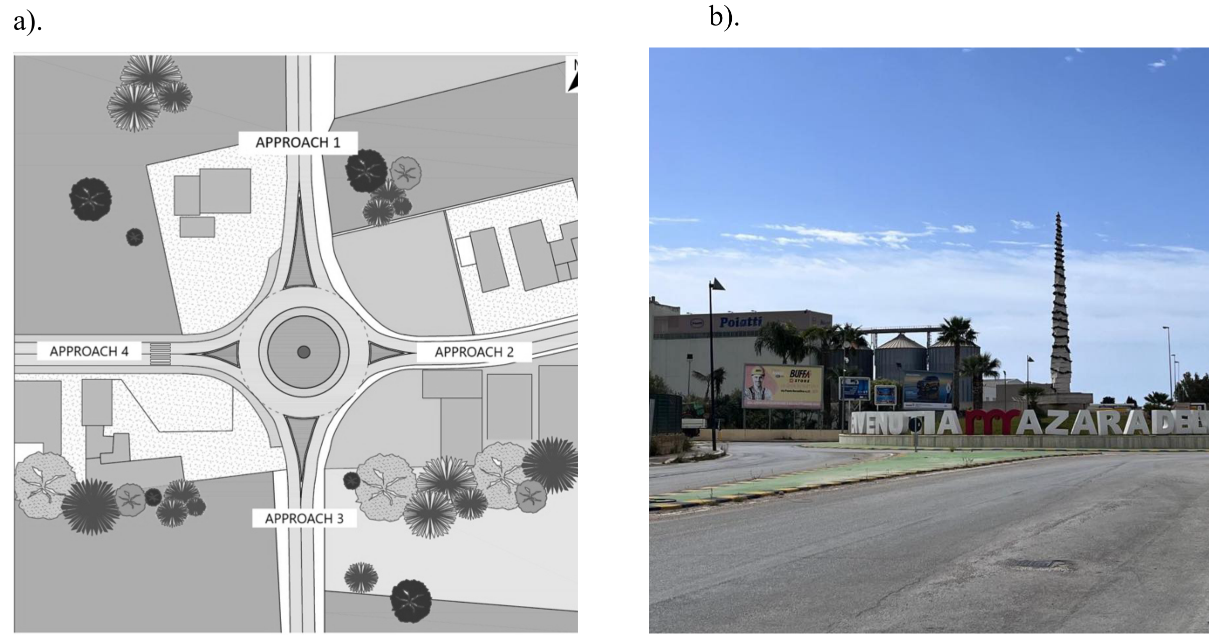


Fig. 1. Case Study: a) the roundabout located in Mazara del Vallo, Sicily (Italy) and b) a view of the northbound entry

Table 2

Matrix of traffic percentages for the single-lane roundabout in Italy

| Entry | | | | |
|---|---|---|---|---|
| (%) | Southbound | Northbound | Eastbound | Westbound |
| Southbound | 0.00 | 7.90 | 3.95 | 3.95 |
| Northbound | 6.91 | 0.00 | 11.85 | 10.86 |
| Eastbound | 2.96 | 8.89 | 0.00 | 19.75 |
| Westbound | 6.91 | 6.91 | 9.14 | 0.00 |

## 4. MICRO-SIMULATION MODELING

Initial modeling in Aimsun [14] involved constructing the roundabout model based on field-collected geometry. Each roundabout approach was constructed by inserting road sections ruled by a give-way signal, while the curved sections around the central island were joined by prioritized-featured links. The shape of the network model built in the simulated environment was then perfected based on a field survey. Detectors were strategically placed to monitor traffic parameters' evolution during simulation runs, ensuring alignment with the study context.

Various scenarios were defined to simulate the effect of connected and autonomous driving vehicles (CADVs) on roundabout performance, considering different MPPs, increasing in steps of 20%, starting from 0% CADVs and 100% human-driven vehicles (HVs) to 100% CADVs and 0% HVs. Capacity functions were calculated according to the paper's objectives and used as benchmark curves to compare simulated data across MPPs [3][15]. The capacity model of each benchmark curve underwent calibration using the critical headway and follow-up headway, relying on meta-analytic estimates from literature (refer to [16]). The capacity formula takes the general form:

$$C = a \cdot 1{,}380 \cdot e^{-\,b\cdot 0{,}00102\cdot Q_c} \tag{1}$$

where:

$C$ – the entry lane capacity (pc/h),

$Q_c$ – the conflicting flow rate (pc/h),

$a$ – CADV-based capacity modification factors for the intercept from Exhibit 33-13 [3] equal to 1,380,

$b$ – CADV-based capacity modification factors for the slope parameter from Exhibit 33-13 [3] equal to $1.02\times10^{-3}$.

Equation (1) represents the entry capacity model designed to account for CADVs. The modification factors, denoted as *a* and *b*, were set according to the values from Exhibit 33-13 by [3] for different CADV-based MPPs.

Aimsun [14] was utilized to replicate traffic patterns on the study roundabout. Initially, traffic demand between origin and destination centroids was defined to represent trips within the roundabout network model. This demand was structured as an origin-destination matrix that captured traffic flows from each origin to every destination to simulate all turning maneuvers. The simulation began at 7:00 p.m., with 10 simulation runs conducted. For ensuring realistic traffic reproduction, each run comprised a pre-loading phase of the network lasting 15 min, followed by an actual simulation phase of 60 min and one closing stage of 15 min for unloading the network. The results indicate consistent simulation outcomes with field-detected traffic data at roundabout entries during each 15-minute period in the morning peak hour. The trip matrix containing the total traffic was divided into two matrices (one containing the HV trips and another containing the CADVs trips) according to each CADV-based MPP to develop in the simulated environment a specific traffic condition, where a proportion of traffic represents CADV trips, while the remainder consists of HV trips. Each scenario progressed from uncongested to congested conditions, and seven consecutive origin-destination matrices were established. Traffic entering from the west approach (Fig. 1a) encountered an increasing circulating flow ranging from 0 to 1200 pc/h. Upon reaching congestion, vehicles entering the roundabout denoted entry capacity.

Benchmark capacity curves were calculated using Eq. (1) and modified using factors *a* and *b* based on CADV and HV percentages [4]; a and b were set to 1.00 for the MPP of 0% CADV. The benchmark curves were an alternative source of data due to the lack of levels of automation 4 to 5 in traffic.

Aimsun simulated CADVs across all MPPs, assuming reliable communication elements during the transition to a fully CADV traffic fleet as suggested by [3]. In this regard, connected and autonomous driving vehicles were assumed to be able to communicate with each other, enhancing detection capabilities and enabling cooperative maneuvers. The CADV internal system implements communication by CACC activated in CADV-to-CADV communication or by adaptive cruise control (ACC) activated in the CADV-to-HV interaction. This allows CADVs to safely accept briefer gaps compared to those used by HVs.

Model parameter calibration was made to match benchmark capacity values from Eq. (1) with simulated data. It is widely known that the traffic simulation performed with microscopic models elucidates vehicle interactions through car-following, lane-changing, and gap-acceptance rules. [14]. Car-following models dictate the lengthwise driving behavior based on leading vehicles, while lane-changing models govern the lateral movement and driving styles during lane changes. Gap-acceptance rules regulate yielding at entry lines [14].

Given the mixed fleets in each MPP, differences in CADV and HV behaviors at entries were considered. CADVs activate CACC upon encountering another CADV, gathering data for gap acceptance. When faced with HVs, CADVs rely solely on adaptive cruise control (ACC) [3,14]. Microscopic models necessitate calibration, but identifying key parameters can be challenging [15]. Thus, a stepwise approach involving sensitivity analysis and parameter tuning is recommended [15]. A sensitivity analysis was carried out to identify the behavioral parameters of Aimsun [15] for closely aligning simulated data with capacity benchmarks.

For the scenario without CADVs (100% HVs), model parameters of Aimsun calibrated by [16] and focused solely on human-driven vehicles at single-lane roundabouts were employed. Thus, for the traffic condition with 0% CADVs and 100% HVs, the calibrated parameters were the driver reaction time, set to 0.86 s (default 0.80 s); the speed limit acceptance, set to 1.00 (default 1.10); and the gap, increased to 1.58 s (default 0.00 s) [16]. Fine-tuning was necessary for the parameters governing CADV gap-acceptance behavior in heterogeneous traffic. Sensitivity analysis determined optimal parameter values for reproducing capacity benchmarks and calibrating scenarios.

The behavioral parameter of Aimsun for CADVs, derived from ACC and CACC-equipped vehicle experiments [14], were modified to simulate CADV capabilities under mixed traffic conditions; these model parameters included the maximum acceleration (4.00 m/s$^2$ instead of 3.00 m/s$^2$), the safety margin factor (0.50 instead of 1.00), and the driver reaction time (0.63 s instead of 0.80 s).

It is important to note that driver reaction time influences capacity, with lower times indicating higher capacity, as drivers can follow closer and find gaps more readily [3, 14]. In Aimsun, this parameter remains constant for all vehicles inside the same vehicular class (e.g., HVs or CADVs) throughout a simulation run. However, it must be consistent for all vehicles inside a vehicular class and equal to the simulation time step to ensure immediate reaction to speed changes [14]. When simulating the scenarios with varying CADV-based MPPs, a weighted average of reaction times for each user class was employed, reflecting the proportions of each vehicle class in the scenario's traffic composition. For human-driven vehicles, the selected model parameters also included the speed limit acceptance, adjustable to indicate the degree of adherence to the speed limits. A setting above 1 permits speeds exceeding the limit; otherwise, speeds are restricted. Additionally, the gap parameter was adjusted to regulate the time gap between vehicles. These adjustments ensured that the car-following model accurately replicated limitations imposed by the preceding vehicles on the desired speeds.

In addition to the reaction time, we regulated the maximum acceleration and safety margin factor among the CACC-equipped vehicle parameters in Aimsun. The maximum acceleration signifies the vehicle's peak performance, with values above default indicating better performance. The safety margin factor determines priority junction maneuvering, with values above 1 indicating cautious driving and values below 1 reflecting assertive driving. The sensitivity factor was also adjusted to moderate levels around 1.00 and to balance headway, thus avoiding extremes that could impact the entry capacity. Cooperation activation and aggressiveness were set moderately, considering their impact on gap creation and lane changes, but they were irrelevant for this single-lane roundabout. Other parameters were excluded, as they were deemed unsuitable for the study case. The refined parameters accounted for a compromise to realistically model varied driving behaviors and vehicle interactions in mixed traffic based on our assumptions.

The upshot of the parameter modification process involved comparing the benchmark capacity curves (i.e., the adapted capacity functions for CADVs) with simulated outputs, varying the MPPs of CADVs in traffic. In this context, for example, Figure 2a compares the benchmark capacity with simulated data for MPP 5—100% CADVs (and 0% HVs)—at the eastbound entry depicted in Figure 1a. Across all scenarios, a decrease in capacity was observed with an increase in circulating flow, while capacity notably increased with a higher CADV penetration percentage. In turn, Figure 2b shows an example of scattergram analysis for the MPP 3 (60% CADVs) with the regression line plotted alongside the 95% prediction interval. Additionally, Table 2 illustrates the results of the scattergram analysis used to depict the relationships between pairs of benchmark capacity and simulated capacities across various MPPs, specifically, MPP 0 (0% CADVs), MPP 1 (20% CADVs), MPP 2 (40% CADVs), MPP 3 (60% CADVs), MPP 4 (80% CADVs), and MPP 5 (100% CADVs). According to [15], the regression lines of benchmark versus simulated capacity data were employed as a predictive tool to evaluate the model's fit to the data. Specifically, each R-squared coefficient ($R^2$) close to 1 indicates that the predictor variable can explain the response variable, confirming a strong positive correlation between the two sets of variables under examination.

Another approach to validating transport-planning models, especially when only aggregated data is available (such as flow counts aggregated to hourly intervals at detection points), involves employing a comprehensive metric like the Geoffrey E. Havers' statistic (GEH) as referred to by [15]. The GEH was also utilized to compare the benchmark capacities and simulated data across MPPs. The GEH was applied to a single pair of benchmark-simulated measurements such that a GEH of less than 5 indicates a good fit. Thus, the model's acceptability was confirmed, as the deviation of simulated capacities from the benchmark counterparts was less than 5 in at least 85% for all MPPs (see Table 2).

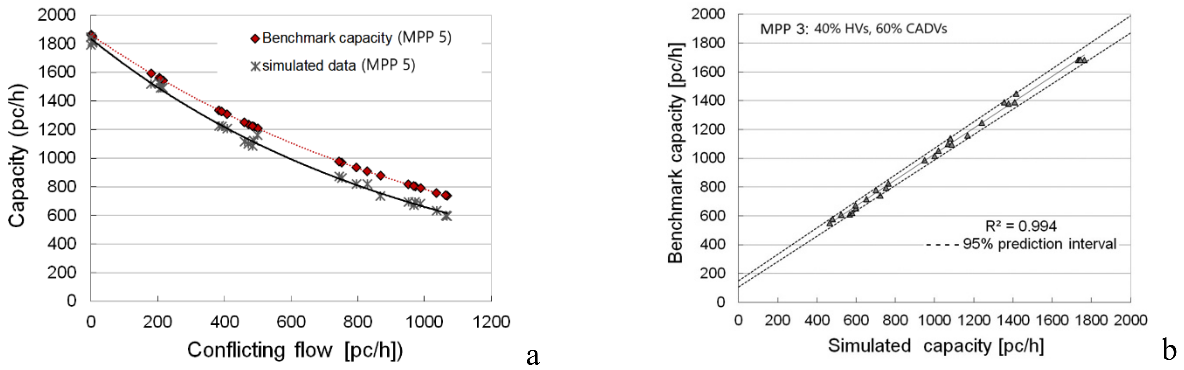


Fig. 2. An example of the upshot of the calibration process: a) a comparison of the benchmark capacity and simulated data for MPP 5 (100% CADVs and 0% HVs) and b) a scattergram analysis for MPP 3 (60% CADVs and 40% HVs)

Table 3

Measures of goodness-of-fit to evaluate the calibrated model

| MPP | Regression lines | $R^2$ | GEH [%] | RMNSE | p-value |
|---|---|---|---|---|---|
| 0 | $y = 0.84 x + 139.00$ | 0.992 | 91 | 0.12 | 0.63 |
| 1 | $y = 0. 83 x + 144.00$ | 0.993 | 100 | 0.11 | 0.93 |
| 2 | $y = 0.85 x + 132.53$ | 0.997 | 100 | 0.08 | 0.88 |
| 3 | $y = 0.90 x + 128.47$ | 0.994 | 97 | 0.07 | 0.95 |
| 4 | $y = 0.91 x + 164.42$ | 0.996 | 94 | 0.09 | 0.84 |
| 5 | $y = 0.93 x + 178.80$ | 0.997 | 92 | 0.10 | 0.73 |

The aforementioned considerations were confirmed by the results of the root mean squared normalized error (RMSNE), which provides insights into the error magnitude relative to the average measurement (see Table 2). Table 2 also presents the p-values of the two-sample t-test with N = 54 degrees of freedom and a significance level of $\alpha = 0.05$, which was used to evaluate the evidence against a null hypothesis. In this regard, the two-sample t-test validated the null hypothesis that there is no significant difference between the mean values of benchmark and simulated capacities for the MPPs corresponding to a mixed fleet of p% of CADVs and (1-p)% of HVs: MPP 0 (0% CADVs), MPP 1 (20% CADVs), MPP 2 (40% CADVs), MPP 3 (60% CADVs), MPP 4 (80% CADVs), and MPP 5 (100% CADVs).

Once the calibration was completed, the impact of the cooperative driving on roundabout safety across MPPs was simulated in Aimsun, coupled with the Surrogate Safety Assessment Model (SSAM) [17]. The SSAM processed five vehicle trajectories provided by Aimsun and assessed the probability of conflict occurrence using surrogate measures. The filters were configured to process conflicts within a 30-meter radius from the entries, designating them as part of the intersection area.

Sensitivity analysis highlighted the crucial influence of time-to-collision (TTC) and post-encroachment time (PET) on conflict probability. Smaller TTC and PET values increase conflict likelihood, with a TTC of 0 denoting imminent potential accident; TTC must be shorter than PET [17].

A maximum TTC threshold of 1.5 seconds was fixed; otherwise, it defaulted, reducing the overlap for the vehicle pair, thus recalibrating the threshold [17]. The SSAM dynamically adjusts TTC, triggering a conflict if it surpasses the threshold. The PET threshold, indicating the gap between exiting and entering vehicles in the conflict zone, was fixed at 1.90 seconds, defaulting to 5.00 seconds [17]. Processing errors were managed with minimum TTC and PET values set at 0.10 seconds. The SSAM also logs maximum vehicle speeds during conflicts.

The conflict angle, ranging from 0 degrees (direct rear approach) to approximately -135 degrees (left approach), signifies the hypothetical collision direction. SSAM categorizes conflicts by angle magnitude: rear-end (<30 degrees), crossing (>85 degrees), or lane-changing (in between). Rear-end involves same-lane vehicles, and lane-changing entails lane-switching, though this is not considered in single-lane roundabouts. For roundabout entries or exits, SSAM distinguishes conflicts by angle and lane setup. Other surrogate safety measures were maintained at default settings to deter unrealistic maneuvers. The outputs of simulation experiments are elaborated upon in the next section.

## 5. RESULTS

Traffic scenarios were developed across MPPs to assess the effect of CADVs on traffic concerning the base case with only HVs. MPPs of CADVs are as follows: starting from MPP 0 (0% CADVs), to MPP 1 (20% CADVs), MPP 2 (40% CADVs), MPP 3 (60% CADVs), MPP 4 (80% CADVs) and MPP 5 (100% CADVs). As CADV penetration increases from 0% to 100%, entry capacity is expected to increase, reflecting the integration of CADVs and their potential to optimize traffic flow. Figure 3 illustrates the entry capacity values across MPPs. It should be noted that entering capacity refers to the maximum number of vehicles overstepping the entry line in the subject approach during saturated conditions.

Fig. 4 depicts the percentage changes in delay and travel times at the study roundabout operating at entry capacity. Percentages were calculated by comparing parameter values at the subject entry in each scenario with those in the base scenario (100% HVs).

Delay time represents the time vehicles lose compared to free-flowing traffic, while travel time accounts for all possible routes taken by vehicles in the roundabout, as detected by sensors. The analysis highlighted improvements from different perspectives. Specifically, the integration of CADVs showed promising changes in entry capacity, delay, and travel time. This suggests that CADVs offer potential benefits that can enhance traffic efficiency and reduce congestion compared to human-driven vehicles. It emphasizes the importance of integrating CADVs into traffic management strategies to improve overall flow and reduce travel and delay times.

Roundabouts feature fewer points of vehicular conflict compared to traditional intersections. This reduction significantly diminishes the likelihood of severe conflicts, such as right-angle and head-on collisions, particularly during left-turns. The conflict points for a single-lane roundabout are depicted in Fig. 5a. Diverging conflicts occur when traffic streams separate, such as during right turns to exit into the adjacent leg. However, varying speeds can increase the risk of rear-end collisions. Merging conflicts occur when streams join, often resulting in rear-end crashes.

Safety analysis, with a roundabout approach saturation degree of 0.7, supports a resolute driving attitude for CADVs. However, the investigated scheme's safety performance appears to be marginally compromised by the hypothesis of assertive behavior, as shown by the total conflicts in Fig. 5b. These conflicts represent the average value from five trajectory files elaborated by the SSAM. Conflicts increased up to MPP 4, indicating growing competition among vehicles for gap utilization (see Fig. 5b). A fully CADV fleet shows high safety benefits. Additionally, 100% rear-end conflicts were observed for vehicles within the traffic stream due to the roundabout's configuration. Despite the effectiveness of single-lane roundabouts in reducing conflicts, particularly for 100% CADVs due to their geometric attributes, a better balance between cautious and assertive behavior should still be analyzed.

Finally, Fig. 6 illustrates the simulation framework of the study, detailing the structure and methodology employed for conducting simulations and analyzing results.

## 6. CONCLUSIONS

Considering the initial stage of CADV implementation, the absence of real data necessitates assumptions to be made when modeling CADVs’ impact on road performance. Predictions resulting from these assumptions can vary from cautionary to resolute driving attitude, leading to the creation of numerous scenarios that challenge public transport agencies and operators in planning for a CADV-integrated future on smart roads. Assessing situation-aware driving behavior in mixed traffic still requires the investment of considerable resources, time, and effort in research endeavors. Recently, the

Highway Capacity Manual (7th edition) introduced new methodologies to evaluate capacity enhancements across different road types based on varying percentages of CADVs.

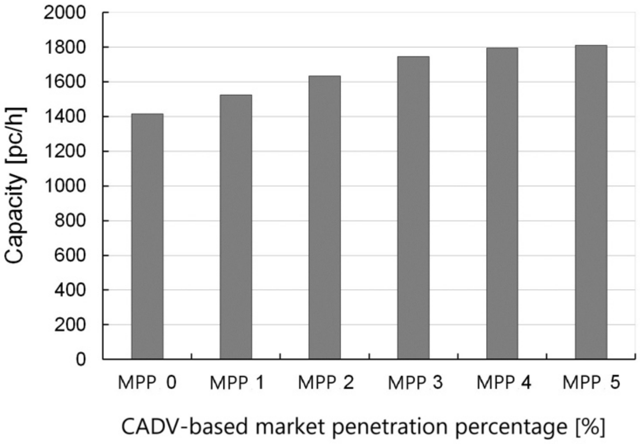


Fig. 3. The trend in entry capacity across varying market penetration percentages (MPPs) of CADVs starting from MPP 0 (0% CADVs) to MPP 5 (100% CADVs)

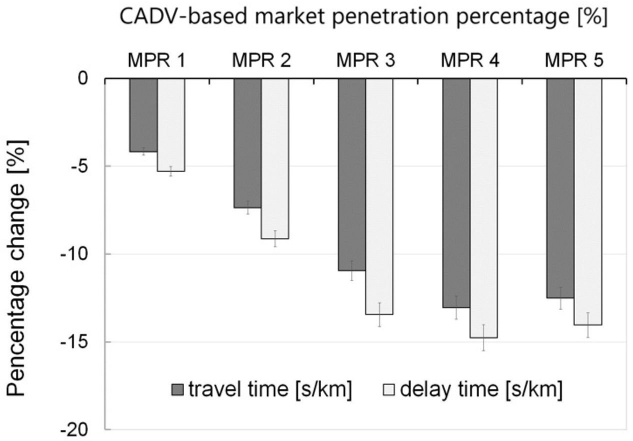


Fig. 4. The trend in the percentage change of delays and travel times at the studied roundabout for varying market penetration percentages (MPPs) of CADVs

From this perspective, this paper outlines processes for evaluating the impact of CACC-equipped CADVs on roundabout operations and safety. Geometric and traffic data from a single-lane roundabout were collected to conceptualize and model traffic scenarios in Aimsun. These scenarios were used to analyze hypothesis-based behaviors of CADVs. The study's concept was inspired by CADV-based capacity modification factors made available to by the HCM for different CADV-based MPPs in roundabouts.

Based on the analyses carried out, the following conclusions were formulated:

- This study investigated a real-world one-lane roundabout, moving toward a comparison between the capacity functions for connected and autonomous driving vehicles and simulated data, as the traffic fleet progressively switched towards all-CADVs. This study aimed to validate hypotheses regarding Aimsun model parameters, which primarily influence roundabout efficiency and safety. Due to the unobservable nature of vehicular fleets, the CADV-based capacity functions can serve as an alternative source for benchmark capacity values, as per literature [15].

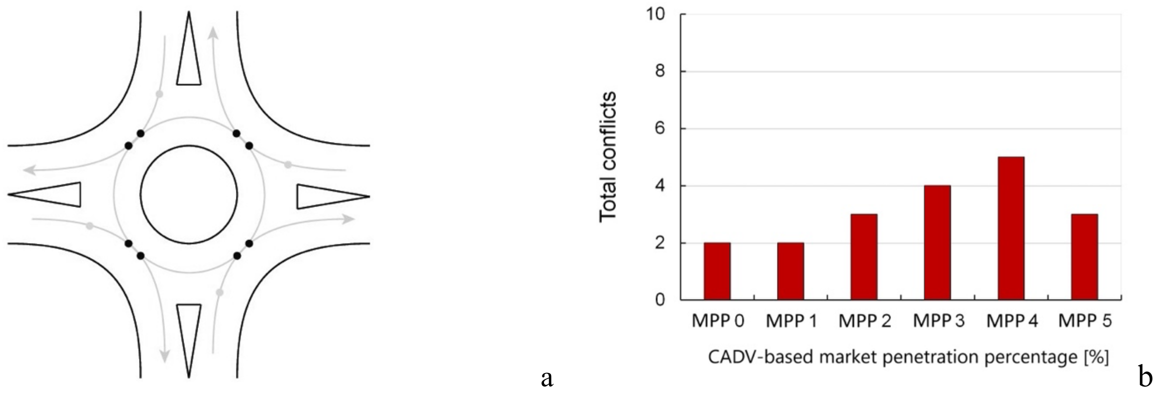
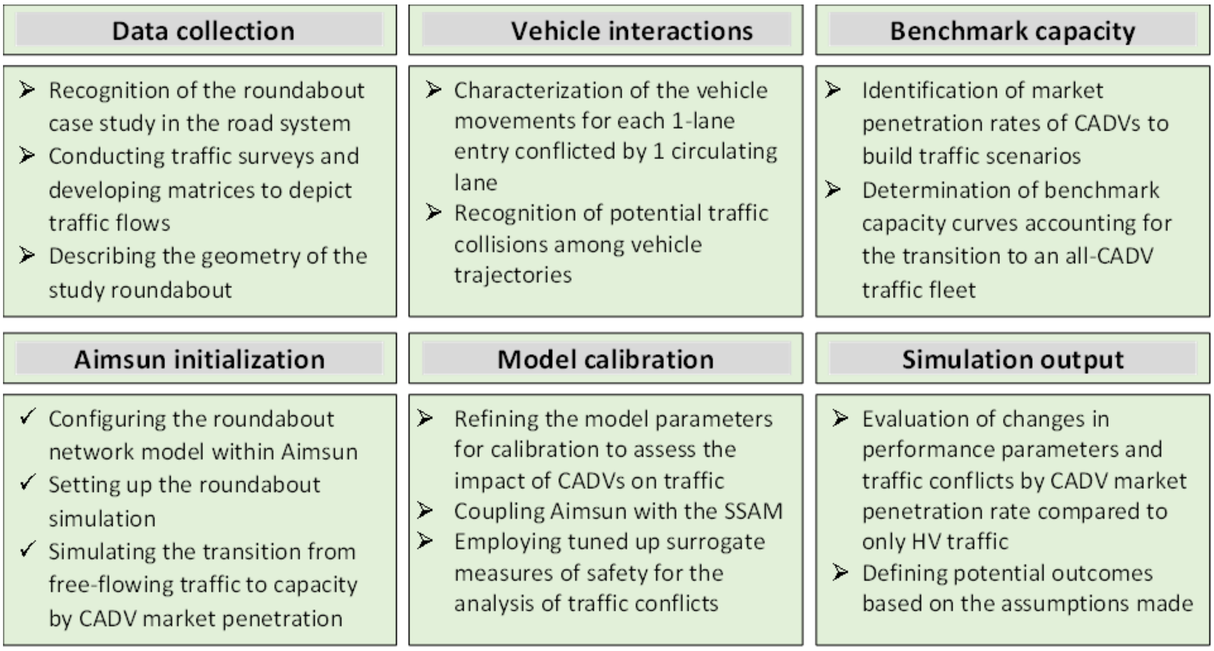


Fig. 5. Conflicts at the examined roundabout: a) merging and diverging conflict point and b) the trend of the simulated total conflicts



**Data collection**

- ➢ Recognition of the roundabout case study in the road system
- ➢ Conducting traffic surveys and developing matrices to depict traffic flows
- ➢ Describing the geometry of the study roundabout

**Vehicle interactions**

- ➢ Characterization of the vehicle movements for each 1-lane entry conflicted by 1 circulating lane
- ➢ Recognition of potential traffic collisions among vehicle trajectories

**Benchmark capacity**

- ➢ Identification of market penetration rates of CADVs to build traffic scenarios
- ➢ Determination of benchmark capacity curves accounting for the transition to an all-CADV traffic fleet

**Aimsun initialization**

- ✓ Configuring the roundabout network model within Aimsun
- ✓ Setting up the roundabout simulation
- ✓ Simulating the transition from free-flowing traffic to capacity by CADV market penetration

**Model calibration**

- ➢ Refining the model parameters for calibration to assess the impact of CADVs on traffic
- ➢ Coupling Aimsun with the SSAM
- ➢ Employing tuned up surrogate measures of safety for the analysis of traffic conflicts

**Simulation output**

- ➢ Evaluation of changes in performance parameters and traffic conflicts by CADV market penetration rate compared to only HV traffic
- ➢ Defining potential outcomes based on the assumptions made

Fig. 6. The simulation framework of the study presented in this paper

- The results underscore the efficiency of the calibration process. The model parameters were well-defined to line up the CADV-based capacity functions and simulated data across varying the considered market penetration percentages so that the impact of CADVs on traffic performance could be evaluated. Higher penetration percentages were correlated with increased capacity, which is consistent with existing research indicating that higher market penetration enables vehicles to accept reduced gaps and utilize them more efficiently [5]. For instance, with 80% CADVs in a single-lane entry nearing saturation, capacity increased by 27% compared to the base scenario of 100% human-driven vehicles (HVs). Similarly, at 80% CADV penetration, significant reductions in delays and travel times were observed, with percentage differences of approximately 15% and 11.03%, respectively. Also, single-lane roundabouts' effectiveness in mitigating conflicts through geometric characteristics has been demonstrated to outperform dependence on driver compliance with traffic control devices such as traffic lights.

- The technological shift towards CADVs demonstrates clear benefits in operational performance, progressively enhancing entry capacity, delays, and travel times in each MPP compared to HV-only conditions. However, differences in delays and travel times tended to stabilize when only CADVs were present in the roundabout. Consequently, definitive conclusions regarding the optimal penetration percentage remain elusive due to the scarcity of real-world data validating the assumptions on which this study's findings are based.
- In essence, the paper's main focus lies in the process of perfecting model parameter values and the influence of CADVs on traffic performance. Also, scenarios conducted in Aimsun using CADV logic were based on projections rather than definitive outcomes once CADVs were fully operational. Many considerations stem from coherent assumptions grounded in current knowledge, addressing the research questions. However, lacking indisputable evidence makes these assumptions neither universally acceptable nor generalizable for future smart roads. Nevertheless, traffic scenarios offer insights into CADV effects on roundabouts, despite substantial variability in multiple factors. Instead of assuming an ideal process, attention should be paid to outcome trends. Transitioning to 100% CADVs may necessitate different time and funding allocations for vehicles and infrastructure, potentially resulting in unexpected outcomes, such as maximizing connectivity benefits by safely accommodating briefer gaps.

The further exploration of diverse study cases regarding different roundabout layouts and traffic data is necessary to uncover additional opportunities presented by CADVs and possible links between roundabout layouts and CADV-influenced traffic settings.

Examining various traffic patterns and roundabout layouts will enhance the general comprehension of how design regulations for roundabouts could be refined to accommodate smart mobility technologies within the existing road network. Additionally, future research should address environmental impacts and alternative methodologies for determining the level of service as CADVs become more pervasive in the market.

**List of acronyms**

- adaptive cruise control (ACC);
- automated vehicles (AVs);
- connected and autonomous driving vehicles (CADVs);
- connected and autonomous vehicles (CAVs)
- cooperative adaptive cruise control (CACC);
- Geoffrey E. Havers' statistic (GEH);
- Highway Capacity Manual (HCM);
- human-driven vehicles (HVs);
- market penetration percentages (MPPs);
- origin-destination (OD);
- post-encroachment time (PET)
- root mean squared normalized error (RMSNE);
- Surrogate Safety Assessment Model (SSAM)
- time-to-collision (TTC);

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