TRANSPORT PROBLEMS 2024 Volume 19 Issue 2
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2023.19.2.10

Keywords: roundabout; cooperative driving; microscopic simulation; capacity; road safety; Aimsun

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SAFETY AND OPERATIONAL ASSESSMENT OF COOPERATIVE DRIVING SYSTEMS ON ROUNDABOUTS

Summary. This paper presents a simulation-driven method for assessing the safety and efficiency of traffic at roundabouts incorporating connected and automated vehicle (CAV) technology. Utilizing the newly proposed CAV-based factors specified by the Highway Capacity Manual (HCM) provided a practical framework for analyzing capacity dynamics across various traffic scenarios. Using microscopic traffic simulation on a roundabout model replicating real-world geometry and traffic attributes facilitated the identification of crucial behavioral parameters. This simulation spanned from smooth traffic scenarios to operational saturation, aiding in the study of mixed traffic scenarios during the transition to increasing CAV presence. Additionally, the study assessed the safety and traffic impact of a dedicated CAV lane using surrogate safety metrics. Aimsun software aided in model parameter calibration, which, combined with the Surrogate Safety Assessment Model (SSAM), supported safety analysis. Despite observed enhancements in roundabout performance with CAV integration, the benefits of a designated CAV lane highlighted the potential to reduce conflicts among vehicles. In conclusion, the paper emphasizes the overall performance enhancement achieved with CAVs at roundabouts while also providing insights for evaluating the potential of CAV technologies in future mobility management strategies.

1. INTRODUCTION

Growing interest in advanced road transportation technologies such as cars, trucks, and buses developed for all relevant application scenarios of CAV driving, is motivated by the expectation they will provide affordable, shared, and green mobility options in the near future [1]. Also, technological innovation in intelligent transportation systems will allow people to tackle growing road safety, energy saving, and congestion problems facing cities [2]. The extent of safety benefits and efficiency from vehicle-road connectivity remains a research area on which there is still much to discover [3]. In this regard, it is not yet known to what extent the CAV driving may require the redesign of road infrastructures or changes to their modes of use to accommodate CAVs, particularly in situations where the curved nature of roads affects drivers' trajectories during travel or turning movements [3].

Understanding how CAVs share data, such as geometry and weather, to enhance road safety and traffic efficiency necessitates a comprehensive analysis that includes both vehicles and road

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infrastructure. Additionally, it highlights the prevailing focus in the existing literature on optimizing CAV trajectories for improved mobility and implementing speed strategies to minimize delay times [4, 5]. In this regard, Wu et al. [5] proposed a distributed cooperation strategy to optimize trajectories, prevent collisions, and enhance the throughput and average speed of CAVs at roundabouts. Additionally, authors in [6] developed a comprehensive coordination system for CAVs at roundabouts, improving traffic flow and average speed as well as reducing traffic density, ensuring smooth crossings.

Enhancing roundabout safety requires integrating advanced vehicle communication, real-time monitoring, and control systems to detect hazards, optimize traffic flow, and issue alerts [1, 5]. Concerns about the reliability of smart systems highlight the necessity for practical assessments to measure effectiveness [7].

Transport engineers must strike a balance between innovation and practicality, especially when integrating new smart technologies to enhance safety at crossroads and roundabouts. Research should prioritize smart software, driver behavior, and redundancy as ongoing areas of study while also proposing advanced warning systems and vehicle-to-infrastructure communication for crash prevention and safety enhancement, especially at complex road sections and roundabouts [8]. In their study, authors in [9] explored the influence of design parameters on roundabout safety, refining safe design parameters and enhancing road safety using crash and conflict data. However, autonomous vehicles encounter challenges in assessing safety while negotiating corners at roundabouts [10]. Moreover, the safety advantages of cooperative driving may diminish in roundabouts solely occupied by CAVs [9, 11, 12]. Uncertainties persist regarding conclusions on CAV conflicts in mixed traffic due to analytical limitations. Further research is crucial for effective conflict management. The integration of smart technologies is imperative to bolster safety for both motorized and non-motorized traffic, necessitating infrastructure enhancements and objective evaluation of driving skills [13].

Decision-makers and transportation engineers bear a social responsibility to understand multiple facets of road performance in traffic scenarios involving both CAVs and human-driven vehicles (HDVs). This responsibility encompasses policies, regulations, infrastructure design, land-use planning, and evaluation of operational and safety performances [14]. Traffic microsimulation models serve as valuable tools for traffic analysts, facilitating assessments of road and corridor performances amid increasing CAV–rates and enhancing efficiency and safety [15, 16]. Moreover, there is a growing research focus on employing surrogate measures to evaluate road safety, utilizing traffic microsimulation models to anticipate traffic scenarios and evaluate the viability of roundabout solutions for smart urban environments [17, 18]. Calibration is crucial to align simulated safety metrics with traffic conditions [19]. The SSAM estimates traffic conflicts from microsimulation model trajectories, facilitating comparison of intersection types and aiding performance evaluation under diverse conditions [20].

This paper presents a simulation-based method to assess the effects of interactions between CAVs and vehicles driven by humans on roundabouts. Using a large roundabout in Palermo, Italy, as a case study, it accounts for CAV requirements on curved trajectories. Drivers navigate anticlockwise around the central island, granting right of way to entering vehicles [21]. Modeling in Aimsun [22] enabled an exploration of the entire operational spectrum, approaching entry capacity at different CAV market penetration levels in traffic. Adjustments were made to capacity curves because of the absence of advanced automation in traffic systems [23]. These adjustments were based on factors derived from [3]. The capacity curves represented the target curves for varying market penetration of CAVs. The alignment of the target capacity curves with Aimsun's simulated data was utilized for model calibration. Subsequently, the operational and safety performance of a designated lane for CAVs was assessed. The findings indicate a notable enhancement in traffic dynamics with the integration of CAVs, shedding light on the advantages of automated and connected driving technologies in transitioning to a fully CAV fleet.

This research contributes significantly to both scientific understanding and societal advancement. By accurately replicating real-world roundabout conditions, it identifies crucial cooperative driving parameters. Further, by exploring the implications of design and behavioral changes on safety and efficiency, especially with CAV prevalence, it aims to enhance traffic systems. Moreover, it underscores improved roundabout performance with CAVs compared to solely human-driven scenarios, offering valuable insights into the anticipated safety and operational benefits of CAV driving, crucial for future mobility challenges.

2. MATERIALS AND METHODS

2.1. Dataset

In assessing the impact of CAVs on traffic throughput and safety, a large-diameter roundabout in Palermo, Italy, underwent geometry analysis via field measurements. Surveys included traffic flow and speed data collection, acknowledging the influence of geometric features and traffic volumes on operational efficiency. This holistic approach sought to comprehend the effects of CAV integration on roundabout performance, vital for improving traffic flow and safety measures. Fig. 1 depicts the roundabout with a speed limit of 50 km/h situated in a suburban area linking the city center to a nearby beach area.

The roundabout has an outer diameter of 71.0 m, with entry and exit lanes that are each 4.00 m wide. The central island's positioning allows for all movements with anticlockwise circulation. The 8-m-wide circulatory roadway accommodates two circulating lanes, with the apron's outer edge raised around 10 cm above the circulatory roadway surface to deter vehicle usage. The design and dimensions of the roundabout promote efficient deflection, ensuring smooth circulation and reduced speeds at the intersection. Entry angles above approximately 42° enhance deflection and curvature at entry inner edges. Despite its size, the intersection maintains low vehicle speeds. Consistency in speeds among various vehicle movements minimizes speed differentials between conflicting traffic streams, with maximum values ranging from approximately 15 to 23 km/h. Fig. 2 illustrates the characteristics of the roundabouts. Specifically, Fig. 2a displays a standard speed-travel time profile derived from field data collected during morning rush hour traffic surveys, reflecting road users' experiences at the intersection. Additional information on recurring speed profiles in the studied context and survey methodology is available in [24]. In Fig. 2b, the typical conflict points are illustrated at a two-lane roundabout entry approach.

Alongside geometry assessments, traffic 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.) in March 2023. The roundabout operates as an isolated intersection due to enough spacing from the other roundabouts located along the corridor where it is installed. The traffic flows on the suburban corridor are typically characterized by low densities, occupancies, and rare breakdowns, so there is an infrequent possibility of approaching capacity.

The roundabout exhibits stable flow and balanced traffic volumes, with major street movements experiencing minimal delays despite equal priority. Intersection activities—through, left, and right turns—were observed for each vehicle entering, sampled every five minutes over hourly intervals, totaling 3,423 vehicles/h. As pedestrian flows were negligible due to the suburban setting, traffic flow rates were solely used as input data for Aimsun (refer to Section 2.2). While traffic data were collected, two typical capacity mechanisms were observed at entries for movements from opposite sides of the intersection. Both right and left entry lanes encountered two circulating vehicular streams in the roundabout.

In the absence of substantial CAV presence in traffic, target capacity curves were derived from the HCM capacity formula and adjusted with factors from [3]. The HCM [3] offers alternative capacity target values in cases for which field measurements are impractical [25]. The target capacity for the baseline model was based on the meta-analytical estimates of behavioral parameters as referred by [26] and traffic data collection. Equation (1) expresses the roundabout capacity model used:

$$C_{e,CAVs} = f_a \cdot a \cdot e^{-f_b \cdot b \cdot Q_c} \tag{1}$$

with $C_{e,CAVs}$ expressing the capacity adjusted with CAV-related parameters from [3] in pc/h, Q_c means the circulating flow in pc/h; a is the intercept parameter equal to 1,350 (or 1,420) for the left (or right) entry lane type; and b is the slope parameter equal to 0.92×10^{-3} (or 0.85×10^{-3}) for the left (or right) entry lane type. The adjustment factors f_a and f_b are summarized in [3].

Fig. 1. The roundabout case study: a) a drawing of the geometric layout, b) view of the south entry (latitude: 38.177494, longitude: 13.309234), c) view of the north exit (latitude: 38.178097, longitude: 13.308459), and d) view of the west entry with a temporary construction site for resurfacing the lateral sidewalks (latitude: 38.177317, longitude: 13.308365) Source: designs and photos were generated by the authors

Fig. 3 shows the roundabout capacity curves distinguished by entry lane type and percentages of CAVs. The figure also shows the base model for 100% of the vehicles driven by humans (i.e., without CAVs) for the mechanisms of capacity observed in the field.

Traffic data recorded during surveys were used in the subsequent calibration process of Aimsun's model parameters, as detailed in Section 2.2. The initial sensitivity analysis and model calibration aimed to determine the optimal values for behavioral parameters, ensuring that the model accurately represents traffic settings in real-world scenarios. This procedure began with fine-tuning specific individual model parameters, followed by a global calibration of the roundabout network model.

2.2. Microscopic modeling with Aimsun

To evaluate the influence of CAVs on roundabouts, Aimsun simulated traffic scenarios with CAV percentages ranging from 0% to 100% in 20% steps. The calibration procedure outlined by [16] was used to simulate traffic conditions until capacity was reached for the entry mechanisms identified in Section 2.1.

a)

b)

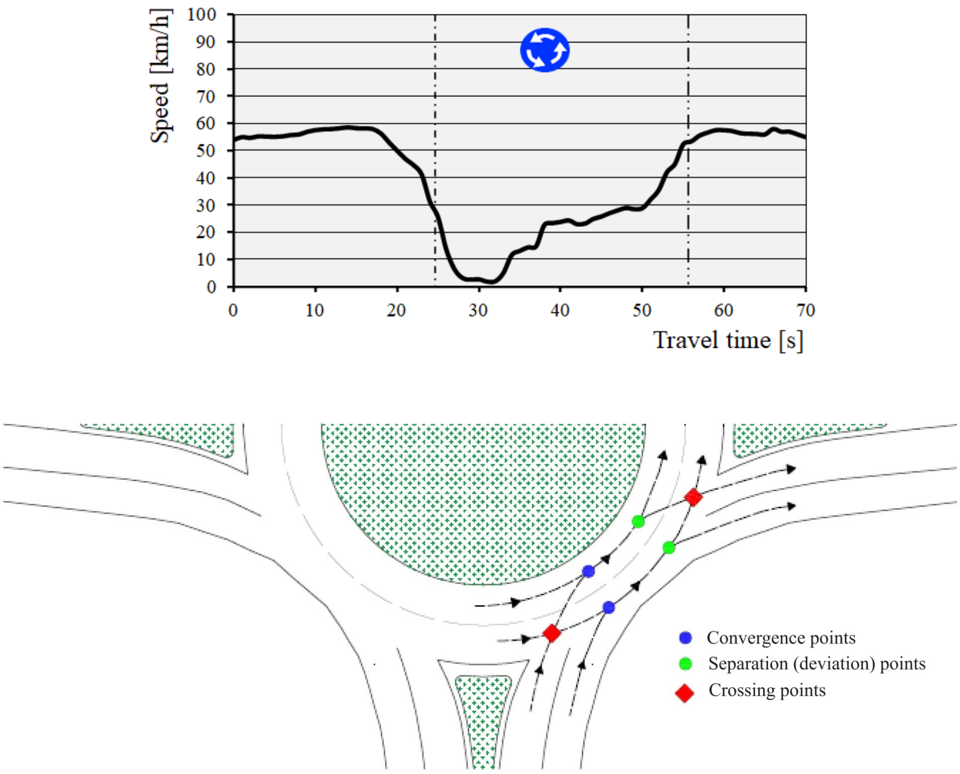

Fig. 2. Characteristics of two-lane roundabouts: a) speed-travel time profile along the influence area (250 m long) in the north-south direction and b) the number of conflict points at a two-lane roundabout entry approach

The roundabout's network model was configured to initiate dynamic scenario simulations using Aimsun software [22]. In two-lane roundabouts, entering vehicles interact with opposing vehicle streams on both inner and outer lanes of the circulatory roadway (e.g., [21, 27]). However, compared to single-lane roundabouts, two-lane ones eliminate the most severe crossing conflicts, though less severe merging conflicts may still arise. Conflicts in two-lane roundabouts usually entail low-speed side-swipes or rear-end collisions, which are of minimal severity. While more conflicts may arise compared to single-lane setups, their overall severity and frequency might be lower than in other intersection types. This is due to the traffic-calming effect of the roundabouts' curved layout, contrasting with the linear design of conventional intersections [21]. For the simulation in Aimsun, the roundabout driving rules dictated that entering vehicles select the appropriate lane before entering the model, contingent upon a wide enough gap between two consecutive circulating vehicles [22].

To simulate CAVs' driving behavior as if fully operational, we assumed 100% activation of cooperative adaptive cruise control. Meanwhile, 30% of vehicles, simulating HDVs, were operated solely with adaptive cruise control [3]. Various mixed traffic situations (MTSs) were conceptualized by increasing CAV percentages from 0% to 100% in 20% steps: base MTS (0% CAVs), MTS 1 (20% CAVs), MTS 2 (40% CAVs), MTS 3 (60% CAVs), MTS 4 (80% CAVs), and MTS 5 (100% CAVs).

Nine origin-destination matrices were incrementally assigned to each entry lane to simulate traffic until capacity was reached. This approach resulted in saturation in each entry lane, with circulating flows gradually increasing from 0 to 1,600 vehicles/h. Demand data for each MTS were divided into two matrices: one with a percentage (p) of CAVs and the other with the remaining (1-p) HDVs. Simulations ensured the number of vehicles approached the entry capacity, recorded by detectors in the roundabout model in Aimsun. Vehicle length and width were assumed equal for HDVs and CAVs. The model parameters were calibrated, aligning the target capacity curves with simulated data by MTS. Based on a sensitivity analysis, the subsequent calibration of HDVs included the following parameters:

- The speed limit acceptance by the drivers [22] was set to 0.97 for the left lane and 0.95 for the right lane at entries, compared to the default value of 1.10. This reflects typical driving behavior at roundabouts, aligning with the speed limit experienced by drivers.
- The time gaps between subsequent vehicles' rear and front bumpers were adjusted. For the left entry lane, it was set to 1.33 s, and for the right entry lane, it was set to 1.00 s instead of the default value of 0.00 s. These wider time headways account for traffic stream characteristics. These parameters influence the follower vehicle's deceleration relative to the leader vehicle's kinematics based on road entity geometry and traffic patterns.

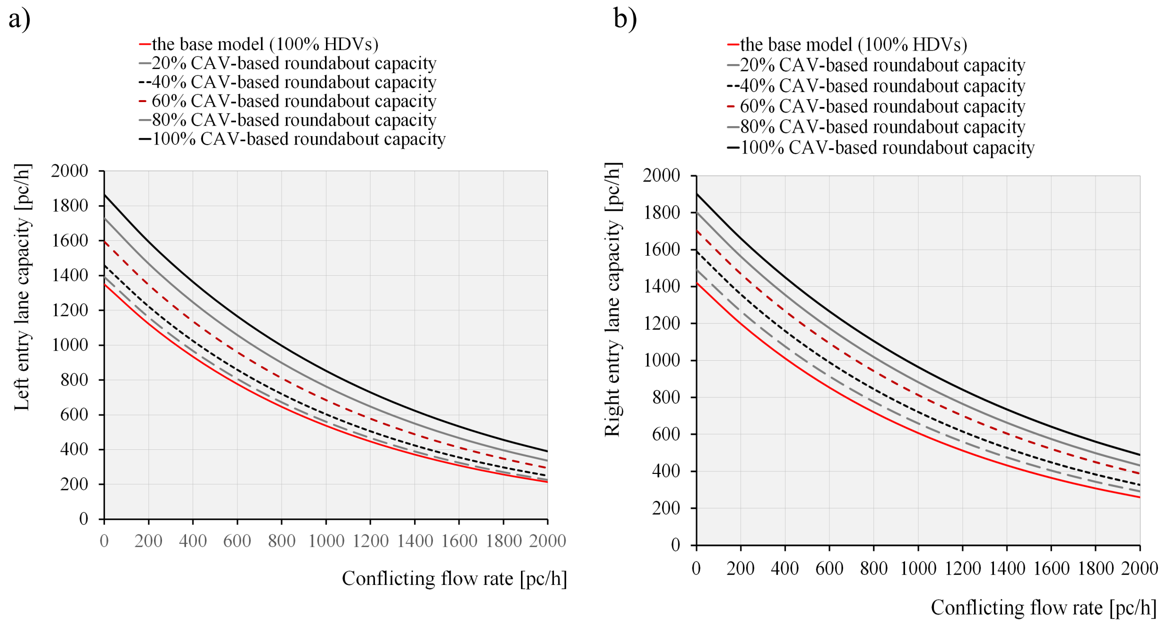

Fig. 3. The roundabout capacity curves for a) the left entry lane of the two-lane entry facing two circulating lanes and b) the right entry lane of the two-lane entry conflicted by two circulating lanes. Source: the authors' research based on data presented in [3]

The calibration of HDV driving behavior entailed aligning the driver's reaction time, a car-following parameter, across all vehicles within the same class (i.e., HDVs or CAVs) to match the simulation time step [22]. Acknowledging CAVs' quicker reaction times, mixed traffic scenarios utilized weighted average reaction times for each vehicle class, determined by CAV and HDV proportions. Thus, reaction times were adjusted from the default of 0.80 s as necessary:

- For the left entry lane, the reaction time values were set to 0.95 s in the base MTS (0% CAVs; 100% HDVs), 0.89 s in the MTS1 (20% CAVs; 80% HDVs), 0.84 s in the MTS2 (40% CAVs; 60% HDVs), 0.78 s in the MTS3 (60% CAVs; 40% HDVs), 0.73 s in the MTS4 (80% CAVs; 20% HDVs), and 0.67 s in the MTS5 (100% CAVs; 0% HDVs).
- For the right entry lane, the reaction time values were set to 0.94 s in the base MTS (0% CAVs; 100% HDVs), 0.78 s in the MTS1 (20% CAVs; 80% HDVs), 0.76 s in the MTS2 (40% CAVs; 60% HDVs), 0.74 s in the MTS3 (60% CAVs; 40% HDVs), 0.72 s in the MTS 4 (80% CAVs; 20% HDVs), and 0.70 s in the MTS 5 (100% CAVs; 0% HDVs).

Consistent with field observations, distinct reaction times were observed for the two entry capacity mechanisms. Maneuvers from the left lane were more challenging, leading to varying reaction times. Vehicles from the left typically waited longer for suitable gaps between circulating vehicles compared to those from the right. However, during the simulation, left-lane entries displayed more assertive behavior, influenced by turn geometry and kinematics. Therefore, CAVs could enhance capacity by safely accepting smaller gaps, potentially exceeding capacities with solely human-driven vehicles [3][22]. The calibration of CAVs also included the following parameters:

- The maximum acceleration for each vehicle was adjusted to 4.00 m/s² for the left lane and 3.50 m/s² for the right lane, deviating from the default of 3.00 m/s² [22][28].

- The safety margin factor, crucial for negotiating the roundabout, was adjusted. For the left lane, it was set to 0.50, and for the right lane, it was set to 0.40, deviating from the default of 1.00. These values reflect assertive driving behavior tailored to each entry lane's characteristics. Furthermore, these adjustments align with Aimsun's guidance on how roundabout geometry influences entry behavior, among other factors [22].
- The sensitivity factor concerning the follower vehicle and its capability to estimate the deceleration of the leader vehicle. The fine-tuned value of 0.50 instead of the default value of 1.00 matched the assertive driving behavior in roundabouts and denoted a balanced solution to simulate and assess cooperative driving in mixed traffic.

Also, the cooperation in creating a gap was activated so that vehicles could cooperate in accepting gaps where lane-changing on the two-lane roundabout occurred. The moderate aggressiveness level was set to 0.50 instead of 1.00 to account for the speed limit of 50 km/h. Per [25], certain parameters of Aimsun were excluded, as neither sensitivity analysis nor manual calibration showed added benefits of aligning target capacity values with simulated data. Calibration quality relied on the goodness of fit between simulated data and CAV-based capacity curves, which varied for each entry mechanism and CAV percentage. Fig. 4 compares the target capacity data with simulation output for the MTS4 scenario, featuring 80% CAVs and 20% HDVs, with a particular focus on the scatterplot for the right lane. Per [12], with increased CAV penetration rates, there was a greater chance of accepting shorter gaps. Cooperative driving allows vehicles to utilize gaps more efficiently than HDVs, thereby enhancing entry capacity (refer to Fig. 4). Table 1 showcases the results of the Geoffrey E. Havers (GEH) statistic for various CAV percentages in traffic, validating the model's acceptance. Readers seeking further details on the GEH index can refer to [25].

The t-test assessed the null hypothesis by testing the mean equality between two data groups for entry mechanisms. At $\alpha = 0.05$, it determined whether the observed differences were likely chance occurrences. The $p(\alpha)$-values, indicating the probability of observing t-values equal to or greater than target data under the null hypothesis, were as follows:

- For the left entry lane, 0.62 in the base MTS (0% CAVs; 100% HDVs), 0.93 in the MTS1 (20%CAVs; 80% HDVs), 0.88 in the MTS2 (40% CAVs; 60% HDVs), 0.94 in the MTS3 (60% CAVs; 40%; HDVs), 0.83 in the MTS4 (80% CAVs; 20% HDVs), and 0.73 in the MTS5 (100% CAVs; 0% HDVs).
- For the right entry lane, 0.60 in the base MTS (0% CAVs; 100% HDVs), 0.80 in the MTS1 (20% CAVs; 80% HDVs), 0.50 in the MTS2 (40% CAVs; 60% HDVs); 0.70 in the MTS3 (60% CAVs; 40% HDVs), 0.97 in the MTS 4 (80% CAVs; 20% HDVs), and 0.90 in the MTS 5 (100% CAVs; 0% HDVs).

Further exploration of additional capacity entry mechanisms across various roundabout layouts is essential to generate simulation data capable of reliably substituting on-field measurements. The calibration of model parameters facilitated the balancing of different characteristics of CAVs, averting unforeseen decreases (or increases) in roundabout capacity. Subsequently, we assessed the safety and performance efficiency implications of introducing a dedicated lane for CAVs, a topic previously explored in the context of turbo-roundabouts [29].

2.3. Assessing safety and efficiency with the SSAM combined with Aimsun

The SSAM [20] enabled the assessment of operational and safety effects stemming from a dedicated CAV lane in contrast to a configuration featuring shared lanes on the examined roundabout.

Integrating this method with Aimsun allowed for automated conflict analysis across different mixed traffic scenarios on previously introduced roundabout layouts. Parameters calibrated for the right lane were allocated to the dedicated CAV lane, while those for the left lane were used for vehicles driven by humans. Parameters calibrated for both vehicle categories were averaged and applied to the shared lanes. Ten simulation replications were performed for each layout using a balanced traffic matrix.

The number of replications was determined through a sensitivity analysis, balancing computational cost with desired precision. It was ensured that the model did not exhibit significant stochastic behavior, as verified through trials, indicating additional simulations did not yield substantial benefits. Aimsun generated replications in trajectory files (TRJ.files), processed with the SSAM. The SSAM analyzed conflicts in computing surrogate safety measures like minimum time-to-collision (TTC) and minimum post-encroachment time (PET), as depicted in Fig. 5.

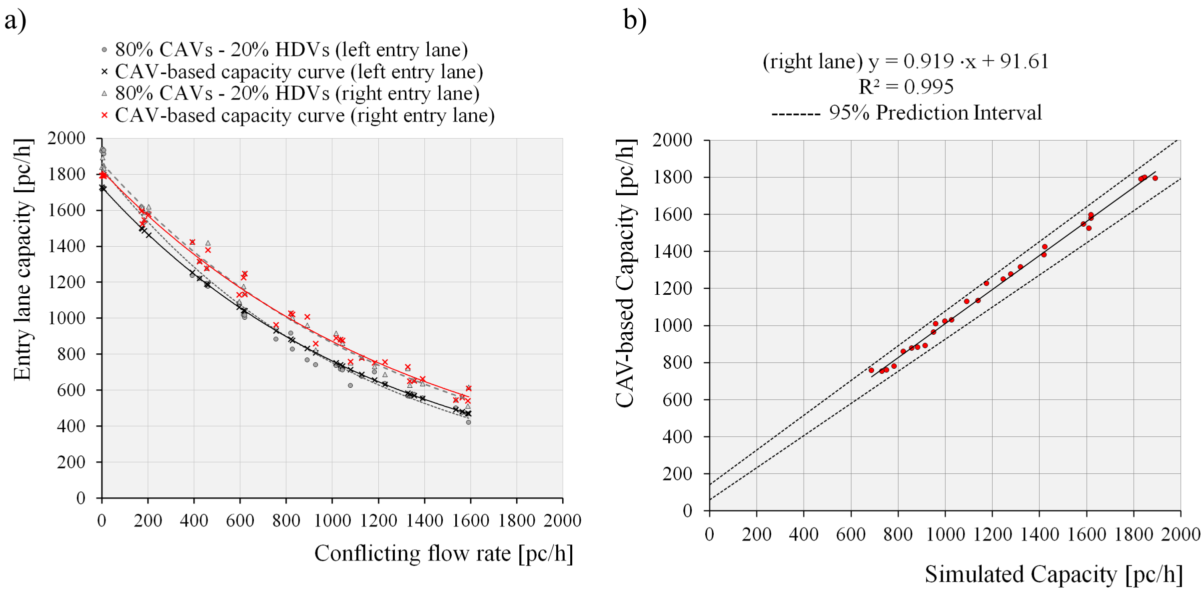

Fig. 4. The examined roundabout: a) the match between target capacity data and simulation outputs and b) a scatterplot depicting the right lane along with the 95% prediction interval

Table 1

The GEH index by entry mechanism as the CAV percentages varied

Entry mechanism	CAV percentage [%]					
	0	20	40	60	80	100
Left entry lane	90.63 (58.33 [1])	100	100	97.22	94.44	91.67
Right entry lane	100 (60.40 [1])	100	100	100	100	100

[1] GEH calculated for the uncalibrated scenario with 100% HDVs

The SSAM software utilized data from TRJ.files to extract conflict information. Initially, the default values for the maximum time-to-collision (TTC) of 1.50 s and the maximum post-encroachment time (PET) of 5.00 s were retained. Consequently, the conflict folder of the tool cataloged conflicts and surrogate safety measures. Modifications were made to the SSAM filters to identify conflicts involving CAVs in traffic. Per [19], these filters were configured to process each event and provide output data independent of the micro-simulator used. Another filter was applied to capture conflicts within 30 m of the roundabout, excluding those occurring far from the entry lines.

According to the sensitivity analysis, the key parameters influencing the system included the TTC and PET, as illustrated in Fig. 5 (e.g., [18]). Given that lower values for TTC and PET during a conflict heighten the risk of collision, the PET values are typically greater than the TTC values [20].

The maximum TTC threshold was set to 1.50 s. Specifically, the default value of TTC was retained, as any deviation below 1.50 s resulted in reduced overlap for conflicting vehicle pairs, establishing a new maximum threshold for TTC (e.g., [19]). Consequently, the maximum threshold for PET, which signifies the time difference between when the leading vehicle occupies a location and when the subsequent vehicle arrives (refer to Fig. 5), was adjusted to 2.50 s for the dedicated CAV lane (and 1.9 s for the shared lane), deviating from the default value of 5.00 s. During a conflict, the SSAM assigned a PET value to each time step, concluding the event when the final PET value was recorded and the TTC value remained below its critical threshold. Minimum thresholds for TTC and PET were set at 0.10 s, as zero values suggested processing errors [18].

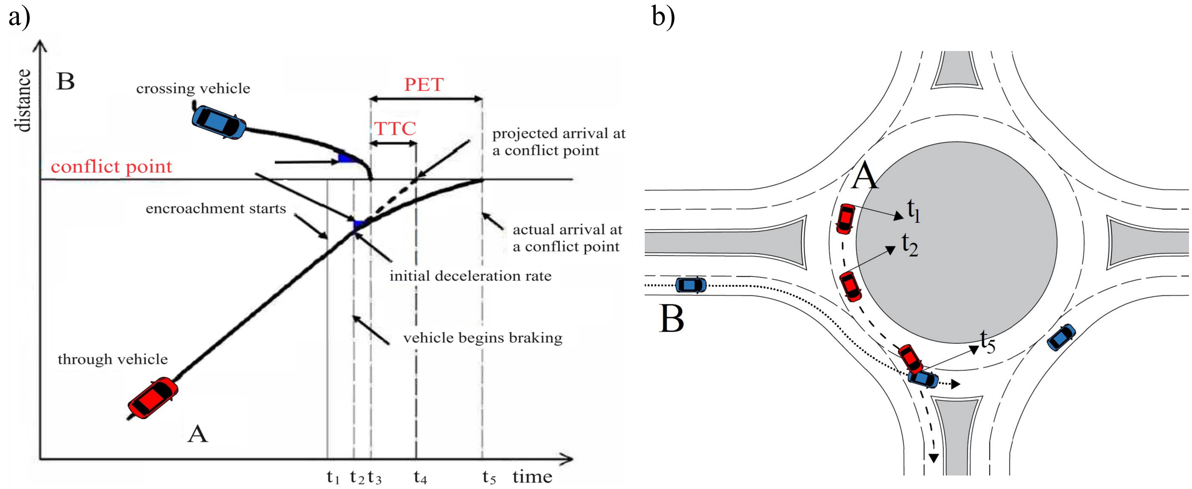

Fig. 5. Surrogate safety measures: a) the conflict point diagram and b) the trajectories of potential conflict on roundabouts

The SSAM also recorded the maximum speed of vehicles during conflicts; however, the trajectory files consistently returned values aligned with the speed limit of 50 km/h set for the roundabout in Aimsun. Additionally, the conflict angle, representing the potential collision angle between the directions from which vehicles approached the conflict point, ranged from 0° (indicating a rear approach of the subsequent vehicle) to around -135° (indicating an approach of the subsequent vehicle from the left). The conflict type parameter facilitated the classification of collisions as either rear-end or lane-change. Conflicts in traffic can be categorized as either rear-end (or crossing) if the conflict angle is within 30° or beyond 85°, or as lane-changing. If vehicles maintain their position within the same lane throughout, it is classified as a rear-end; if they change lanes during the interaction, a lane-changing conflict may happen. The classification system aids in analyzing and addressing various traffic crashes based on vehicle movements and angles, assisting in safety measures and infrastructure planning. During lane changes at intersections or roundabouts, conflicts are labeled as rear-end or lane-change depending on the conflict angle and road geometry. Throughout the simulation, the inability to change lanes due to unavailable or excessively narrow gaps resulted in the need to wait while in motion, leading to deceleration and an increased likelihood of rear-end collisions.

After sensitivity analysis, other surrogate measures were kept at their default values since they did not impact the simulation output. Figs. 6 and 7 present the outcomes of travel times (s/km) and conflict counts, respectively, for various MTSs at both roundabout layouts. The total and categorized conflict counts represent the mean values extracted from ten trajectory files analyzed by the SSAM for each layout.

3. DISCUSSION

After outlining the methodological approach, this section delves into the results concerning the potential of transitioning to fully CAV traffic. The findings demonstrate that a higher ratio of CAVs in traffic can actualize anticipated connectivity benefits. Notably, CAVs equipped with cooperative adaptive cruise control technology can safely accept shorter gaps compared to vehicles driven by humans. For instance, Fig. 4a illustrates the decrease in entry capacity as circulating traffic rises, aligning target capacity curves with the simulated data for MTS4 (80% CAVs, 20% HDVs) post-calibration. The results further demonstrate the successful calibration of the model parameters, allowing Aimsun to generate simulated capacity data closely matching target values (Fig. 4b).

Roundabout size and geometry enabled a dedicated CAV lane design. The urban environment's layout facilitated smooth CAV navigation through the roundabouts, highlighting the adaptability of CAV technology to various urban settings. Following calibration, Aimsun integrated with the SSAM evaluated the safety of the examined roundabout. The results indicate reduced vehicle travel times as CAV penetration increased in both roundabout designs (Fig. 6). Notably, with a low penetration of 20% CAVs, the travel time was reduced by approximately 3% in comparison to 100% HDV scenarios. The benefits of the dedicated lane were most pronounced for CAV percentages ranging from 60% to 100%, showing travel time reductions exceeding 10% in comparison to 100% HDV scenarios.

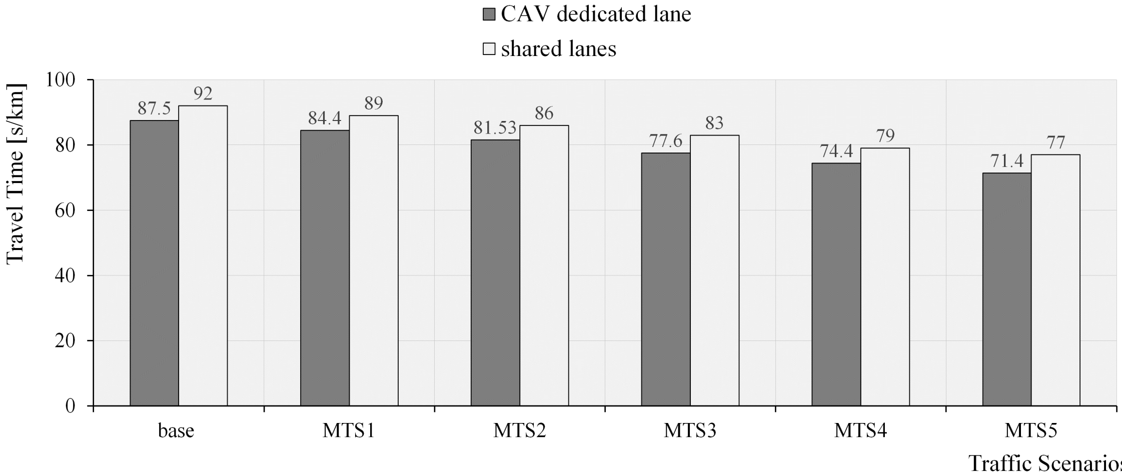

Fig. 6. Travel times for roundabouts with or without a dedicated lane for CAVs. Note: base stands for in the base scenario (0% CAVs), MTS1 stands for scenario (20% CAVs), MTS2 stands for the scenario (40% CAVs), MTS3 stands for the scenario (60% CAVs), MTS4 stands the scenario (80% CAVs), and MTS5 stands for the scenario (100% CAVs)

In the roundabout featuring a dedicated CAV lane, the travel times decreased by 18% in the fully CAV scenario compared to 100% HDV usage. However, in scenarios where lanes were shared, particularly at traffic variation extremes (100% CAVs vs. 100% HDVs), the reduction was 16.30%. These findings lack universal applicability until validated against real-world data, which are currently unavailable due to the slow pace of traditional vehicle replacement with cooperative ones despite rapid technological advancements. This highlights the need for further research and the integration of empirical data to bolster the reliability of such findings in practical urban settings.

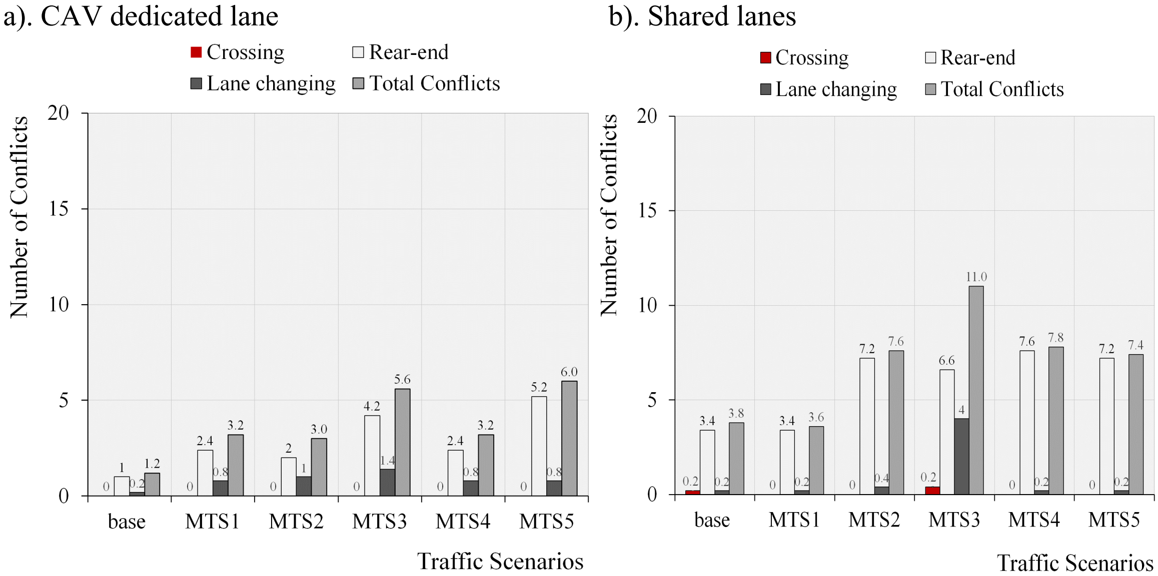

Fig. 7. Total conflicts and conflicts by type: a) a roundabout with a dedicated CAV lane and b) a roundabout where all vehicle types share the lanes. Note: base stands for the base scenario (0% CAVs), MTS1 stands for the scenario (20% CAVs), MTS2 stands for the scenario (40% CAVs), MTS3 stands for the scenario (60% CAVs), MTS4 stands for the scenario (80% CAVs), and MTS5 stands for the scenario (100% CAVs)

Fig. 7 further elucidates the validation of the SSAM analysis for the two roundabout designs. Utilizing trajectory files from Aimsun, the SSAM assessed the surrogate measures, namely TTC and PET, to gauge the probability of total conflicts [20]. The filters were set to return output data independent of the micro-simulator model [19]. It is important to mention that the installation of lane dividers was envisioned for both the entry and exit approaches, as well as the circulatory roadway of the roundabout, with a designated CAV lane. According to Aimsun's logic, this configuration ensures that lane changes occur exclusively within the approach areas where vehicles enter and exit the roundabout, contingent upon the availability of gaps where vehicles travel alongside each other [21, 27].

The roundabout with a dedicated CAV lane exhibited a significant reduction in total conflicts of about 50% compared to the shared-lane layout. This reduction persisted across traffic scenarios from 40% to 80% CAVs (Figs. 7a and 7b). However, the percentage difference diminished with 100% CAVs due to increased rear-end conflicts, reaching around 85% in the layout with the dedicated CAV lane and 95% in the other layout. Interestingly, Aimsun simulations revealed that entering vehicles, whether turning left or proceeding straight, tended to preselect the left entry lane, while those turning right preferred the right lane heedless of the lane dividers, contrary to real-world observations. Simulations highlighted that the inability to change lanes due to limited gaps resulted in vehicles moving while waiting, thus decreasing their speed and raising rear-end collision risks. These factors are crucial for road administration practitioners when assessing urban intersection improvements and roundabout lifecycle performance. Dedicated CAV lanes showed superior operational and safety performance compared to mixed lanes, aligning with literature on other road types [30, 31]. By removing HDV-CAV interactions, dedicated lanes facilitated platooning, reducing travel times and conflicts. However, when traffic consists entirely of CAVs, safety benefits can be affected by the reduced headways between vehicles, which might increase rear-end conflicts. This underscores the significance of well-designed lanes and effective traffic management strategies to balance safety and efficiency in urban traffic environments.

4. CONCLUSIONS

This paper presents a framework for assessing the impact of CAVs on roundabout performance. A large roundabout in Palermo, Italy, was modeled using Aimsun, and its geometry and traffic were analyzed. This allowed us to simulate mixed traffic scenarios with increasing CAV presence. The roundabout's size accommodated a dedicated CAV lane, and its urban environment facilitated CAV navigation. Aimsun calibrated the model parameters and, the SSAM was integrated for the safety analysis. While acknowledging the impact of assumptions on results, the study advocates for microscopic traffic simulation.

The research conceptualizes road entities with dedicated CAV lanes, evaluating their safety and operational performances. Dedicated lanes are advantageous because they separate vehicles driven by humans from CAVs, thereby reducing potential conflicts. Roundabouts, assuming assertive behavior, excel operationally but raise safety concerns, particularly in two-lane configurations with shared lanes. Implementing dedicated CAV lanes with spiral layouts and curb separation would enhance the integration of vehicle-to-vehicle capabilities. However, attributing conflicts solely to CAVs and assessing severity in shared traffic situations remain challenging when using currently available tools. Further research is needed to address methodological limitations in CAV analysis so that conflict characteristics can be more effectively integrated into decision support tools and the long-term effects of automation and connectivity on road traffic systems can be anticipated.

Demonstrating the safety and efficiency of CAVs across diverse scenarios amid growing market penetration rates could establish a vital framework. These findings may inform decision-makers and promote sustainability and innovation in urban and suburban travel management. However, comprehensive studies across different intersections and traffic conditions are essential to grasping CAVs' impacts at the corridor or network level, thus enhancing public trust amid increasing demands for smart mobility testing and deployment.

Acknowledgment

This work was supported by the Sustainable Mobility Center (Centro Nazionale per la Mobilità Sostenibile—CNMS) under Grant CN00000023 CUP B73C22000760001.

References

1. Matin, A. & Dia, H. Impacts of Connected and Automated Vehicles on Road Safety and Efficiency: A Systematic Literature Review. *IEEE Transactions on Intelligent Transportation Systems*. 2023. Vol. 24. No. 3. P. 2705-2736.
2. Parekh, D. & Poddar, N. & Rajpurkar, A. & Chahal, M. & Kumar, N. & Joshi, G.P. & Cho, W. A review on autonomous vehicles: Progress, methods and challenges. *Electronics*. 2022. Vol. 11. P. 2162. DOI: 10.3390/electronics11142162.
3. National Academies of Sciences, Engineering, and Medicine. *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*. Washington: The National Academies Press. 2022.
4. Ma, C. & Yu, C. & Yang, X. Trajectory planning for connected and automated vehicles at isolated signalized intersections under mixed traffic environment. *Transportation Research Part C: Emerging Technologies.* 2021. Vol. 130. 103309. DOI: 10.1016/j.trc.2021.103309.
5. Wu, R. & Jia, H. & Yang, L. & Miao, H. & Lin, Y. & Zhang, Y. A distributed trajectory control strategy for the connected automated vehicle in an isolated roundabout. *IET Intelligent Transport Systems*. 2022. Vol. 16. No. 2. P. 232-251.
6. Jalil, K. & Xia, Y. & Zahid, M.N. & Manzoor, T. A Speed Optimization Strategy for Smooth Merging of Connected and Automated Vehicles at T-Shape Roundabout. *IEEE Access*. 2022. Vol. 10. P. 76953-76965.
7. Lee, W.K. How reliable is smartness? And how smart is reliability? *IET International Conference on Smart and Sustainable City 2013*. Shanghai. 2013. P. 381-384.
8. Pompigna, A. & Mauro, R. Smart roads: A state of the art of highways innovations in the Smart Age. *Engineering Science and Technology, an International Journal*. 2022. Vol. 25. No. 100986. P. 1-5.
9. Tibljas, D. & Giuffre, T. & Surdonja, S. & Trubia, S. Introduction of Autonomous Vehicles: Roundabouts Design and Safety Performance Evaluation. *Sustainability*. 2018. Vol. 10. No. 1060.
10. Shetty, A. & Yu, M. & Kurzhanskiy, A. & Grembek, O. & Tavafoghi, H. & Varaiya, P. Safety challenges for autonomous vehicles in the absence of connectivity. *Transportation Research Part C: Emerging Technologies*. 2021. Vol. 128. No. 103133.
11. Tumminello, M.L. & Macioszek, E. & Granà, A. & Giuffrè, T. A methodological framework to assess road infrastructure safety and performance efficiency in the transition toward cooperative driving. *Sustainability.* 2023. Vol. 15. P. 9345.
12. Anagnostopoulos, A. & Kehagia, F. CAVs and roundabouts: Research on traffic impacts and design elements. *Transportation Research Procedia*. 2020. Vol. 49. P. 83-94.
13. Lindov, O. & Omerhodžić, A. Implementation of smart road technologies in the function of road traffic safety management. In: Karabegovic, I. & Kovačević, A. & Mandzuka, S. (eds). New Technologies, Development and Application VI. NT 2023. *Lecture Notes in Networks and Systems*. Springer, Cham. 2023. Vol. 687. P. 621-627.
14. Raju, N. & Farah, H. Evolution of Traffic Microsimulation and Its Use for Modeling Connected and Automated Vehicles. *Journal of Advanced Transportation.* 2021. Art. ID 2444363. P. 1-29.
15. Martin-Gasulla, M. & Elefteriadou, L. Traffic management with autonomous and connected vehicles at single-lane roundabouts. *Transportation Research Part C: emerging technologies*. 2021. Vol. 125. P. 1-22.
16. Tumminello, M.L. & Macioszek, E. & Granà, A. & Giuffrè, T. Simulation-based analysis of "What-If" Scenarios with connected and automated vehicles navigating roundabouts. *Sensors*. 2022. Vol. 22. No. 17. P. 1-30.

17. Tarko, A.P. *Measuring Road Safety with Surrogate Events*. 1st Edition. Elsevier. 2019. P. 304.
18. Saleem, T. & Persaud, B. & Shalaby, A.S. & Ariza, A. Can Microsimulation be used to Estimate Intersection Safety? *Transportation Research Record*. 2018. Vol. 2432. No. 1. P. 142-148.
19. Giuffrè, O. & Granà, A. & Tumminello, M.L. & Giuffrè, T. & Trubia, S. Surrogate measures of safety at roundabouts in AIMSUN and VISSIM environment. In: *Roundabouts as Safe and Modern Solutions in Transport Networks and Systems. Lecture Notes in Network and Systems*. Springer. Cham. 2019. Vol. 52. P. 53-64.
20. *SSAM. Surrogate safety assessment model and validation: Final Report*. Available at: https://www.fhwa.dot.gov/publications/research/safety/08051/index.cfm.
21. National Academies of Sciences, Engineering, and Medicine. *Roundabouts: An Informational Guide.* 2nd ed. Washington: The National Academies Press. 2010. 393 p.
22. TSS-Transport Simulation Systems. *Aimsun Next. 2020. Version 20 Dynamic Simulator User Manual*. Barcelona: TSS-Transport Simulation Systems. 2020.
23. The Society of Automotive Engineers International. *SAE J3016_202104. Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems*. Warrendale: The Society of Automotive Engineers International. 2014.
24. Giuffrè, O. & Granà, A. & Giuffrè, T. & Acuto, F. & Tumminello, M.L. Estimating pollutant emissions based on speed profiles at urban roundabouts: A pilot study. In: *Smart and Green Solutions for Transport Systems*. *Advances in Intelligent Systems and Computing*. Springer Cham. 2019. Vol. 1091. P. 184-200.
25. Barceló, J. *Fundamentals of Traffic Simulation*. London: Springer. 2010.
26. Giuffrè, O. & Granà, A. & Tumminello, M.L. & Sferlazza. A. Capacity-based calculation of passenger car equivalents using traffic simulation at double-lane roundabouts. *Simulation Modelling Practice and Theory.* 2018. Vol. 81. P. 11-30.
27. Macioszek, E. & Kang, N. Assessment of psychotechnical parameters of vehicle drivers on the roundabout at Hitachi Taga (Japan). *Scientific Journal of Silesian University of Technology. Series Transport*. 2019. Vol. 93. P. 11-22.
28. Gipps, P.G. Behavioural Car-Following Model for Computer Simulation. *Transportation Research Part B: Methodological*. 1981. Vol. 15. No. 2. P. 105-111.
29. Giuffrè, T. & Granà, A. & Trubia, S. Safety evaluation of turbo-roundabouts with and without internal traffic separations considering autonomous vehicles operation. *Sustainability*. 2021. Vol. 13. No. 16. P. 1-14.
30. Guerrieri, M. A theoretical model for evaluating the impact of connected and autonomous vehicles on the operational performance of turbo roundabouts. *International Journal of Transportation Science and Technology.* 2023. DOI: 10.1016/j.ijtst.2023.05.001.
31. Granà, A. & Curto, S. & Petralia, A. & Giuffrè, T. Connected Automated and Human-Driven Vehicle Mixed Traffic in Urban Freeway Interchanges: Safety Analysis and Design Assumptions. Vehicles. 2024. Vol. 6. P. 693-710. DOI: 10.3390/vehicles6020032.

Received 10.12.2022; accepted in revised form 11.06.2024