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PERFORMANCE RATING OF COOPERATIVE DRIVING ON URBAN ROADS INCORPORATING TRAFFIC-CALMING SOLUTIONS

Summary. Over the last decade, traffic calming measures have been increasingly used to meet the needs of modern cities in improving the quality of road spaces and the efficiency of urban mobility. In the era of cities in transition, cooperative driving vehicles (CDVs) allow for new prospects in smart mobility development, but they also leave many open issues. This paper explores the performance of CDVs employed as a smart public transport system, paired with traffic calming solutions (TCSs), using a microsimulation-based approach. The TCSs, including the rearrangement of the roadway, the installation of two single-lane roundabouts, and the planning of a restricted-traffic area, were designed for a section of the coastal road network of a small city in southern Italy selected as a case study. In Aimsun Next, the coordinated solution comprising the TCSs and CDVs was compared with the existing roadway configuration assumed as the baseline road layout. Model parameters were calibrated by matching the simulated data with purpose-built reference capacity functions as the market presence percentages of CDVs varied. The simulation results reveal that the synergy of TCSs and CDVs can improve overall traffic conditions compared to the current scenario. The approach proposed in this study can guide road planners and decision-makers in evaluating various road design alternatives and traffic management solutions covering the combined application of CDVs and TCSs.

1. INTRODUCTION

The development of smart cities, alongside intelligent transport systems, requires designers and policymakers to create eco-friendly, cost-effective solutions to efficiently manage traffic flows, improve road safety, and enhance the livability of urban spaces. In alignment with smart city goals, smooth traffic management has the potential to significantly elevate the quality of road spaces and urban mobility. In this context, traffic calming solutions (TCSs) are essential for significantly enhancing the quality of road spaces and urban mobility through non-invasive devices aimed to reduce adverse effects of motorized traffic, protect the most vulnerable road users, and make urban public spaces functional and aesthetically pleasing [1]. TCSs encompass traffic control and management, road design solutions, and physical devices for regulating access to specific urban areas and controlling vehicle speeds. Chicanes, lane shifts, road narrowings, speed humps, speed lumps, and speed tables are primarily responsible for speed control [2]; meanwhile, roundabouts smooth traffic, and restricted-traffic areas (RTAs) and pedestrian areas restrict or prevent access to motorized vehicles during certain time slots. Smoothing traffic flows and reducing speeds through TCSs can lower both the number and severity of crashes while decreasing

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pollution and environmental noise, thus enhancing the livability and safety of urban spaces for shared mobility.

In the transition to smart cities, TCSs must incorporate cooperative driving technologies as part of Intelligent Transport Systems. Cooperative driving vehicles (CDVs) can improve traffic conditions, enhance road safety, provide a high-performance driving experience, and promote the sustainable development of smart roads [3,4]. Depending on the automation level, CDVs can reduce the driver's workload and may eventually replace humans in their driving tasks [5]. CDVs use advanced technologies for real-time data exchange, allowing them to communicate with each other and with infrastructure. This enhances traffic efficiency since CDVs can adjust their speed and distance to the vehicle ahead while maintaining road safety [6]. The transition to fully automated mobility will follow a step-by-step path in which CDVs will interact with human-driven vehicles (HDVs) and need to integrate with smart road technologies. Interactions between CDVs and HDVs can vary significantly depending on the traffic scenario and the road environment. Traffic scenarios in urban areas, which involve a high degree of interaction among different road users, such as HDVs, public transport, pedestrians, cyclists, and e-scooters, could pose challenging situations for CDVs. Additionally, the type of intersection, along with the associated traffic control modes—such as signalized intersections, two-way stop-controlled intersections, or roundabouts—requires different driving behaviors. Indeed, CDVs may face demanding driving tasks when navigating roundabouts due to curved trajectories and the need to interpret HDVs' intentions in the yield negotiation process. Furthermore, the trajectory deviations imposed by some smoothing traffic measures may be difficult to interpret for CDVs.

Several studies have examined the effects of the combined application of different traffic calming measures (TCMs) on speed reduction and their impact on road safety at both the urban and neighborhood levels [7,8]. However, when planning multiple and consecutive TCMs, the relative distance among different devices should be considered if benefits are to be gained from an effective speed reduction [9,10]. Indeed, some studies have shown that TCMs' speed-reduction effect can decrease immediately after passing the purpose-designed devices and suggest a value for spacing them [9,10].

In the era of cities in transition, TCSs should integrate the digital and technological innovation of smart roads. The benefits for the urban environment and road users from the application of TCSs align with those expected from the use of cooperative driving technologies [11]. Research in this field is increasingly using micro-simulation models to assess the performance of CDVs under mixed traffic conditions with HDVs [11,12]. According to research findings, CDVs perform better than HDVs in increasing operational performance [13]. As the penetration rates of CDVs rise, the optimization-based approach of trajectories at roundabouts also demonstrates notable performance gains, especially regarding reductions of travel times [13]. Even though using machine learning techniques could be beneficial, their iterative nature commonly results in high computational costs and long processing times. In light of the current scarcity of empirical data on vehicles with the highest levels of automation, the microsimulation-based approach used to analyze CDVs' performance offers insights into potential future scenarios during the transition to fleets composed entirely of CDVs. Therefore, the simulation results should be regarded as specific to individual studies, and their generalization requires the assessment of many varied cases [13]. Although numerous studies have evaluated the advantages and potential of the deployment of CDVs and the application of TCSs separately, research on their combined effects is still lacking. To address this gap and provide new knowledge and insights on this topic, this study explores how smart mobility can be successfully integrated with TCSs.

Based on the above, this paper examines the performances and environmental impact of the interplay of traffic calming solutions (TCSs) and cooperative driving vehicles (CDVs) employed as public transport systems in urban areas by using a micro-simulation approach. In this regard, the coastal road of the urban area in Mazara del Vallo, Italy, was chosen as a case study. After the field data collection and recognition of the existing roadway configuration assumed as baseline road layout (BRL), traffic calming solutions (TCSs), including the rearrangement of the roadway, two single-lane roundabouts, and a restricted-traffic area (RTA), were designed. Moreover, considering future traffic demand developments, two mobility scenarios (MS1 and MS2) involving CDVs shaped like a mini-bus for public transport service were conceptualized. In an Aimsun Next micro-simulator [14], the planned TCSs and the corresponding mobility scenarios (MS1 and MS2) were compared with the baseline road layout and relative baseline mobility scenarios (BMS1 and BMS2). The model parameters were calibrated by matching the simulated data with purpose-built reference capacity functions (RCFs) based on corrective factors provided by the Highway Capacity Manual [15], as the market presence percentages (MPPs) of CDVs varied. Delay time and polluting emissions from mobile sources were selected as metrics to assess the operational performance and environmental advantages of the application of TCSs, including CDVs. Also, safety benefits were assessed by elaborating the simulated trajectories in the Surrogate Safety Assessment Model software [16]. Simulation findings highlighted that the combination of the TCSs and CDVs can improve operation and safety conditions, leading to some environmental benefits. Fig. 1 shows the methodological framework of the microsimulation-based approach proposed in this research.

This research proposed a microsimulation-based methodological approach to evaluate how CDVs can efficiently work in synergy with TCSs. The aim of this approach is to assist road designers and decision-makers in appraising various road design alternatives and traffic management solutions that align with the benefits of smart mobility. From a social perspective, the integration of CDVs and TCSs can enhance accessibility, improve the livability and safety of road spaces, promote eco-mobility, and support the technological advancement of smart cities while ensuring environmental sustainability.

The paper is structured as follows: after the introduction in Section 1, Section 2 presents the materials and methods applied in this research. Section 3 shows the experimental findings and the relative discussion. Finally, Section 4 presents the conclusions and directions for future research.

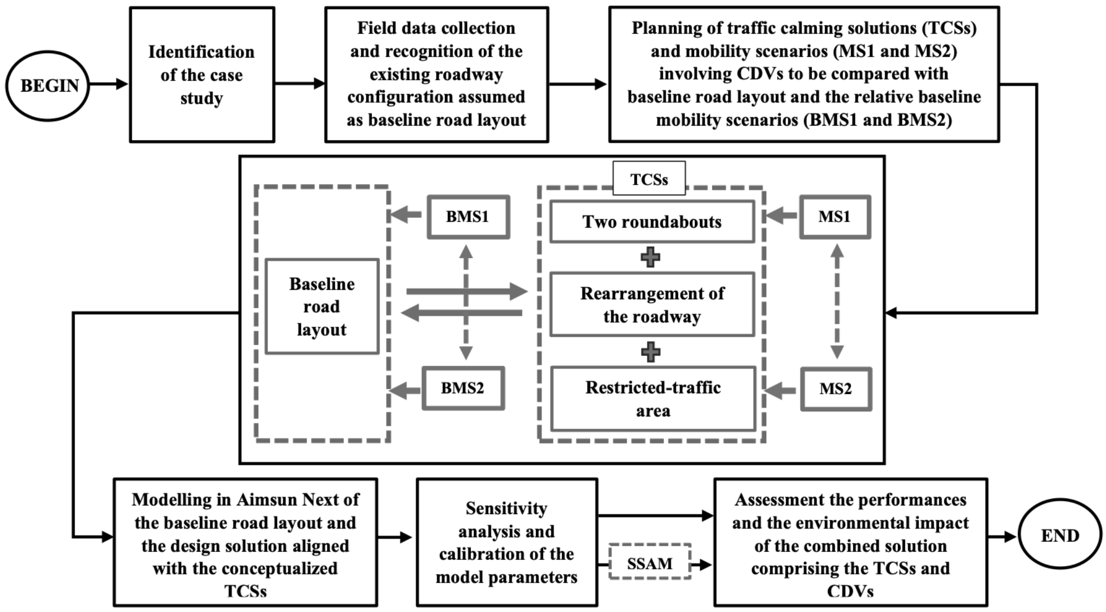

Fig. 1. Methodological framework of the simulation-based approach proposed in this research. CDVs = cooperative driving vehicles, TCSs = traffic calming solutions, MS1 and MS2 = mobility scenarios 1 and 2. respectively, BMS1 and BMS2 = baseline mobility scenarios 1 and 2, respectively

2. DATA AND METHODOLOGY

2.1. Description of the Case Study and Smoothing Traffic Strategies

The case study was identified in a stretch of the coastal road (approximately 1.9 km long) of the urban network in the city of Mazara del Vallo, Italy (from 37°39’33’’N, 12°34’12’’E to 37°39’48’’N, 12°33’09’’E). Fig. 2 displays the road network model under study, and Fig. 3 shows the roadway cross-section for the current and designed configurations. Presently, the roadway is around 9.75 m wide, and it consists of a 3.00-m-wide two-way cycle path including an insurmountable curb, a 2.75-m-wide central lane for motorized traffic, a 2.50-m-wide parallel parking and a 1.50-m-wide sidewalk (see Fig. 3a). The existing roadway configuration (Fig. 3a) was assumed as a baseline road layout (BRL) for comparison with the conceptualized design solution involving the combined application of CDVs and TCSs. Field data were collected in October 2024 during peak hours, with a volume of 715 vehicles per hour recorded. Given that the summer season had already ended by the time the survey was done, the traffic volume was mainly composed of cars, with a negligible percentage of pedestrians and motorcycles. Also, the percentage of heavy vehicles was irrelevant, given that the road overpass at the entrance to the examined network makes it possible to bypass traffic on the seafront.

The designed TCSs included the rearrangement of the roadway, the installation of two single-lane roundabouts (Rb1 and Rb2), and the planning of a restricted-traffic area (RTA). The rearrangement of the roadway involved the creation of a one-way cycle path and the removal of parallel parking to make room for a dedicated traffic lane for the transit of the smart public transport system (see Fig. 3b). It is noteworthy that the section of road under study (which runs from roundabout 1 to 2) is part of a circular route enabling cyclists, CDVs and motorized users to travel in opposite directions.

In addition, several areas along the road network suitable for parking were identified to meet the demand for parking.

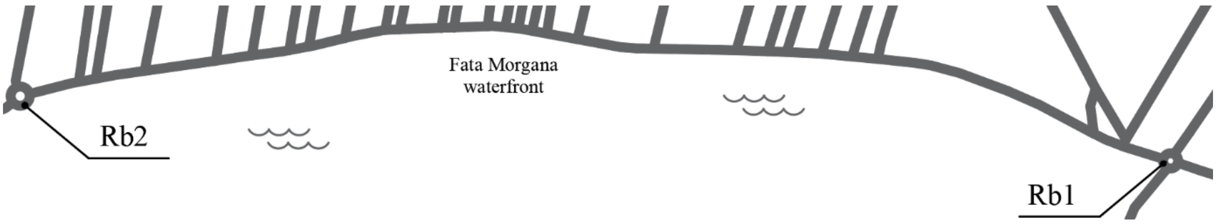

Fig. 2. The road network model under study

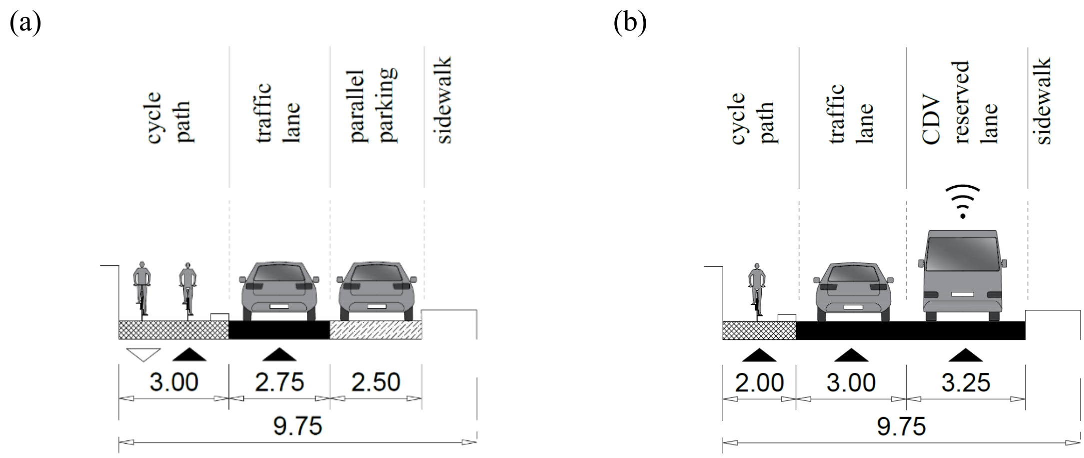

Fig. 3. The roadway cross section: (a) current configuration and (b) designed configuration. All measures are indicated in meters. CDVs = cooperative driving vehicles

According to Italian standards [17], both roundabouts are classified as mini roundabouts, with Rb1 having an outer diameter of 21 m and Rb2 having an outer diameter of 18 m. Rb1 is a four-legged roundabout, whereas Rb2 is a three-legged roundabout. Both roundabouts have one-way entry and exit lanes on each approach, a 7-m-wide circulatory roadway, a partly surmountable central island, raised splitter islands, and deflection angles satisfying the Italian standards [17]. Fig. 4 shows the intersection area where Roundabout 1 was designed, along with the layout of the four-legged single-lane Roundabout 1 (Rb1), while Fig. 5 displays a view of the current area where Roundabout 2 (Rb2) was conceptualized. The restricted-traffic area (RTA), whose development was outlined by Rb1 and Rb2 (Fig. 2), was planned in three time slots (TSs) and was active every day of the week from June to September for 10 hours per day. The smart public transport service was carried out in each time slot by fully electrically powered cooperative driving vehicles (CDVs) shaped like a mini-bus. During TS1 and TS3, access to the RTA is prohibited to all motorized traffic except CDVs, while in TS2, access to the RTA is open to all road users to meet residents' needs to return home at lunchtime, as well as other road users who need to get in and out of the area (Table 1).

(a) (b)

Fig. 4. Intersection view: (a) current area in which Roundabout 1 (Rb1) was designed and (b) the designed four-legged single-lane Roundabout 1 (Rb1)

(a) (b)

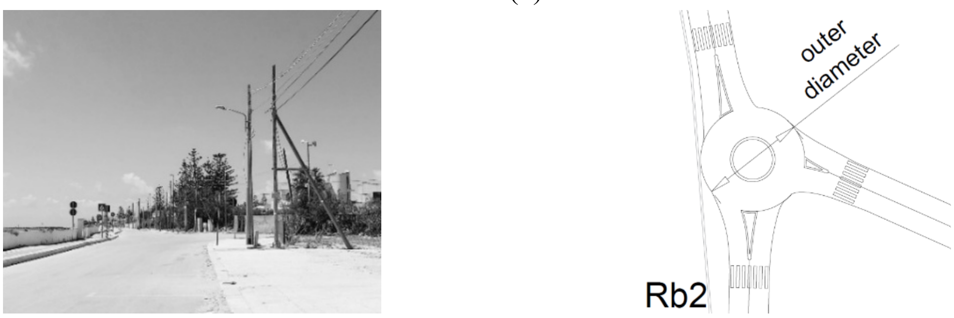

Fig. 5. Intersection view: (a) current intersection area in which Roundabout 2 (Rb2) was designed and (b) the designed three-legged single-lane Roundabout 2 (Rb2)

The existing road configuration has been designated as the baseline road layout (BRL) to effectively compare the performance of the proposed solution with the current one. Additionally, two baseline mobility scenarios (BMS 1 and BMS 2) were developed and simulated for the baseline road layout (Table 1). Thus, the planned STSs and the corresponding mobility scenarios (MS1 and MS2) were compared with the baseline road layout and the relative baseline mobility scenarios (BMS1 and BMS2).

Table 1 presents each time slot's duration, a description of the access conditions (i.e., the road users allowed to transit the RTA), and the organization of the simulation plan for each mobility scenario. For example, the performance of the designed solution simulated during TS2, considering MS1, was compared to that of the baseline road layout simulated during the same TS2, taking BMS1 into account. It is important to note that the conceptualized design solution and the baseline road layout (BRL) were compared only during TS2, as it was not applicable for other time slots (Table 1).

2.2. Aimsun modeling

The Aimsun Next micro-simulator was utilized to assess the operational effectiveness and environmental benefits of the interplay between traffic calming solutions (TCSs) and smart public transport systems. Additionally, the safety performance of the combined solution involving TCSs and cooperative driving vehicles (CDVs) was evaluated by analyzing the simulated trajectories in Surrogate Safety Assessment Model (SSAM) software [16]. Two distinct micro-simulation models were created in Aimsun Next to compare the existing road layout with the designed solution. The road network was modeled by incorporating road sections and specifying the road type and corresponding speed limits for each section. These road sections were then interconnected by nodes, where priority rules were established. The traffic demand for cyclists, pedestrians, and HDVs was defined using origin-destination (O-D) matrices, which necessitated the placement of centroids to introduce traffic flows into the network. Since the public transportation system was operated by CDVs, their paths and traffic flows were simulated using dedicated traffic lanes, equipped with user-specific stops and a planned timetable. CDVs were designed akin to mini-buses, with a length of 7 m, a width of 2.20 m, and a maximum capacity of 30 passengers. In line with the current development of eco-mobility, each CDV was electrically powered. Furthermore, high communication reliability was assumed for CDVs, as they were equipped with cooperative adaptive cruise control devices that facilitated inter-vehicle communication and information exchange. These systems reduced the distance between successive vehicles and enhanced overall traffic efficiency and safety conditions [15].

Table 1

The schedule for the LTZ and the simulation plan

	Time Slot 1 (TS1) 9:00 a.m.–1:00 p.m	**Time Slot 2 (TS2)** 1:00 p.m.–4:00 p.m	**Time Slot 3 (TS3)** 4:00 p.m. - 7:00 pm
Access condition description	Access to the RTA is prohibited for all motorized traffic except for CDVs.	Access to the RTA is open to all road users.	The access to the RTA is prohibited for all motorized traffic except CDVs.
Mobility scenario 1 (MS1) valid for the design solution	• Bike: 80/120/160/200* bike/h • CDVs frequency: 15' • Pedestrian: 200 ped/h	• Bike: 120 bike/h • CDVs frequency: 15' • HDVs: 750/600/750* veh/h • Pedestrian: 150 ped/h	• Bike: 140/160/180* bike/h • CDVs frequency: 15' • Pedestrian: 220 ped/h
Mobility scenario 2 (MS2) valid for the design solution	• Bike: 120/160/200/240* bike/h • CDVs frequency: 10' • Pedestrian: 220 ped/h	• Bike: 160 bike/h • CDVs frequency: 10' • HDVs: 1000/850/1000* veh/h • Pedestrian: 200 ped/h	• Bike: 160/180/200* bike/h • CDVs frequency: 10' • HDVs: no vehicle • Pedestrian: 220 ped/h
Baseline mobility scenario 1 (BMS1) valid for the baseline road layout (BRL)	• Not applicable	• Bike: 120 bike/h • HDVs: 750/600/750* veh/h • Pedestrian: 150 ped/h	• Not applicable
Baseline mobility scenario 2 (BMS2) valid for the baseline road layout (BRL)	• Not applicable	• Bike: 160 bike/h • HDVs: 1000/850/1000* veh/h • Pedestrian: 200 ped/h	• Not applicable

*RTA = restricted-traffic area, CDV = cooperative driving vehicles, HDVs = human-driven vehicles. * Incremental traffic volume steps in each one-hour simulation.*

Aimsun's accuracy in replicating traffic flows was tested by conducting 10 one-hour simulation runs that involved only HDVs. The simulation results highlight the need for model parameter calibration, as the percentage difference between the simulated data and field data exceeded 10%. Due to the limited availability of empirical data on highly automated vehicles, reference data needed to be sourced for comparison with the simulated results. Therefore, reference capacity functions (RCFs) with increasing market presence percentages (MPPs) of CDVs were built for calibration purposes. Indeed, in the gradual transition to a fully connected and automated mobility, various traffic scenarios with increasing levels of CDVs' MPPs were devised as follows: MPP 1 = 0% CDVs; MPP 2 = 20% CDVs; MPP 3 = 40% CDVs; MPP 4 = 60% CDVs; MPP 5 = 80% CDVs; MPP 6 = 100% CDVs. The RCFs were built using the following formula for capacity calculation at roundabouts that takes into account CDVs in traffic:

$$C_{CDVs}=f_{(a)}\cdot a\cdot e^{-f_{(b)}\cdot b\cdot Q_c} \quad (1)$$

where C_{CDVs} is the CDV's capacity (pc/h); *a* is the intercept parameter, the value of which was 1,380 pc/h; and *b* is the slope parameter, the value of which was 1.02×10^{-3} [18]. Fig. 6 shows the surface of the reference capacity function built based on Equation 1 as the CDVs' MPPs varied.

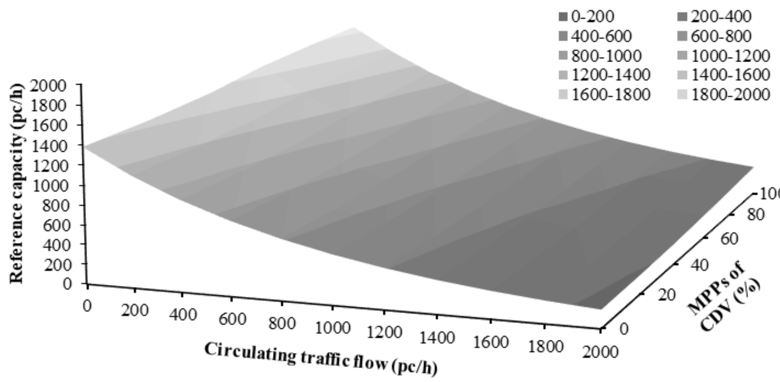

Fig. 6. Surface of reference capacity function

To compare the simulated capacity data with the RCFs, each roundabout model was gradually brought to saturation conditions by loading increasing traffic volumes into the O-D matrix, ranging from free flow to capacity. Thus, according to the MPPs of CDVs, the O-D matrix was fractionated into two parts: one with a definite percentage (x) of CDVs and another with a remaining percentage (1-x) of HDVs.

Various algorithms govern simulation runs in Aimsun [14]. The driving behavior on road sections is determined by Gipps' car-following model, which defines the relative distance between two consecutive vehicles [18]. In turn, Gipps' lane-changing model determines lane-changing behavior by appraising the available gaps among vehicles in adjacent lanes [18]. Moreover, the CDV driving behavior and the intra-vehicle communication are reproduced by using cooperative adaptive cruise control and adaptive cruise control modules [14]. During navigation, CDVs activate cooperative adaptive cruise control devices when meeting other CDVs; otherwise, when encountering HDVs, they enable the adaptive cruise control system.

The most sensitive model parameters were identified prior to calibration. Calibration involves iteratively adjusting these parameters until the simulation results closely match the observed data [19].

The most sensitive parameters for HDVs involved in the calibration process were as follows:

- The reaction time, measured in seconds, indicates the time a vehicle takes to react when the preceding vehicle changes its speed. It can be set as a fixed value—equal to the simulation step duration for all vehicle types—or as a variable across different vehicle types. In this case, it was fixed at 0.86 s (the default value is 0.80 s). This calibrated value corresponds to the 0% CDVs since the values of reaction times were calculated as the weighted mean, where each weight was the MPP of CDV considered in each scenario.
- Speed limit acceptance is a driver's respect for speed limits and, therefore, denotes a certain driving behavior. Values greater than 1 indicate the surpassing of speed limits while values below 1 suggest more cautious driving. In this case, a value of 1.00 was used instead of the default value of 1.10.
- The gap is the distance between two successive front bumpers and was assumed to be equal to 1.58 s instead of the default value of 0.00 s.

The most sensitive CDV parameters involved in the calibration process were the following:

- The reaction time, defined as above, was fixed at 0.63 s, replacing the default value of 0.80 s. This calibrated value corresponds to the 100% CDVs since the values of reaction times were calculated as the weighted mean, where each weight was the MPP of CDV considered in each scenario.
- Maximum acceleration, measured in m/s^2, indicates the highest accelerations that a vehicle can achieve while running in the network. In this case, it was assumed to be 4.00 m/s^2 instead of the default value of 3.00 m/s^2.

- The safety margin factor determines the vehicle's movement at a priority junction and was set to 0.50 instead of the default value of 1.00.

A scatter analysis was applied to determine the goodness of calibration, whereby the simulated data were compared with RCFs while considering different proportions of CDVs and HDVs in traffic [19] (Fig. 7). For example, Fig. 7a shows a scatterplot for the mixed traffic with 40% CDVs and 60% HDVs, whereas Fig.7b depicts a scatterplot considering a CDV' MPP of 80%. The prediction intervals close to 95% and R^2 values around 0.99 in both plots (Figs. 6a and 6b) indicate strong agreement between the simulated capacity data and RCFs. Thus, the calibrated model can be deemed reliable in the replication of the studied phenomenon.

Additionally, the impact of the designed solution on air quality was assessed within the microsimulation environment. Since the public transport vehicles were electrically powered, pollutant emissions from mobile sources—such as carbon dioxide (CO_2) and nitrogen oxides (NOx)—were estimated only for HDVs using the London Emissions Model in Aimsun [14].

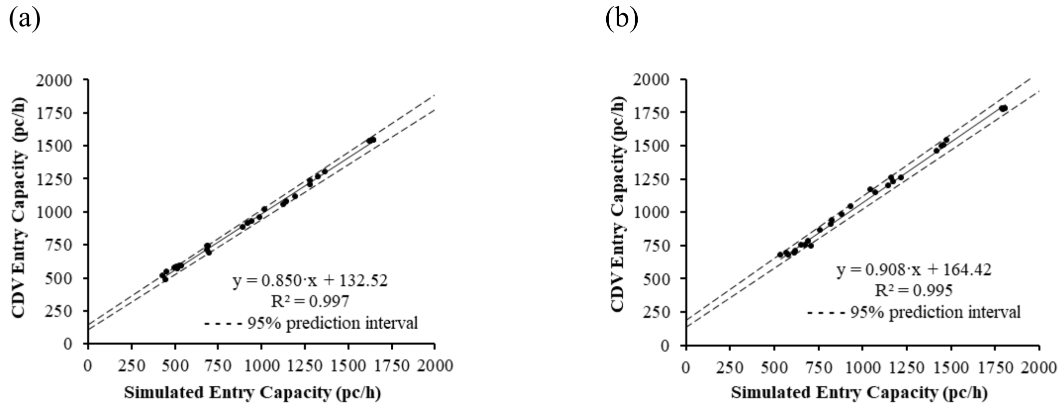

Fig. 7. Scatterplots for (a) mixed traffic with 40% CDVs and 60% HDVs and (b) mixed traffic with 80% CDVs and 20% HDVs

The simulated trajectories from Aimsun were processed using Surrogate Safety Assessment Model (SSAM) software to assess the safety performance of the interaction between traffic calming solutions and CDV deployment [16]. The SSAM enables the exploration of the safety conditions of any road entity by means of surrogate safety measures. According to a comparative study utilizing several micro-simulators, the most important SSAM parameters were identified as time to collision (TTC), expressed in seconds; post-encroachment time (PET), expressed in seconds; and maximum speed (MaxS), expressed in m/s [20]. Time to collision (TTC) indicates the likelihood of a collision and refers to the minimum time-to-collision value observed during a conflict. The upper threshold for TTC was set at 1.5 s, which aligns with the default value. The post-encroachment time (PET) is the interval between the passage of a vehicle and the following vehicle at the same point within the conflict area. The PET threshold was set at 2.5 s, replacing the default of 5.0 s. Although smaller TTC and PET values suggest a higher probability of a collision, potential conflicts were filtered by establishing minimum values for both parameters at 0.10 s, since a value of 0 indicates processing errors [21]. The MaxS indicates the highest speed of vehicles involved in a collision; a minimum threshold value of 1.00 was used. Moreover, the SSAM software classifies conflicts based on the collision path of vehicles: rear-end conflicts occur when the conflict angle is between 0° and 30°, lane-changing conflicts occur when the angle is between 30° and 85°, and crossing conflicts occur when the angle exceeds 85° [16]. Thus, the safety analysis conducted using the surrogate safety measures enabled us to estimate and classify the simulated potential conflicts.

3. RESULTS AND DISCUSSION

This paper offers a comparative analysis of a combined solution integrating traffic calming solutions (TCSs) and cooperative driving vehicles (CDVs) employed for public transport in urban areas using a micro-simulation approach. The study simulated the planned TCSs and CDV behaviors within conceptualized mobility scenarios and compared these with baseline road layout and the relative mobility settings. Because empirical data on high automation and connectivity are limited, model parameters were calibrated by aligning the simulation results with RCFs derived from adjustment factors for CDVs at roundabouts based on the Highway Capacity Manual (HCM) [15]. The results of the model parameter refinement process demonstrated a good fit between the simulated data and RCFs (Fig. 7). The microsimulation outputs were analyzed to assess the operation performance, safety benefits, and environmental impact of the designed solution involving TCSs and CDVs. In this regard, the simulated delay time and polluting emissions from mobile sources were selected as metrics for assessing the operational efficiency and the environmental benefits of the planned solution compared to the existing one. However, since CDVs are electrically powered, only emissions from HDVs were estimated. Additionally, the safety performance of the proposed solution was assessed using surrogate safety measures that provided the number of potential conflicts. Regarding the restricted-traffic area (RTA), the designed solution and the current configuration were compared during TS2, when access to the RTA is open to all road users. This comparison was not applicable for other time slots, as access to the RTA was restricted to all motorized traffic except for public transport vehicles. The percentage ratios of metrics such as delay time, pollutant emissions, and total conflicts were calculated based on their total simulated values in two mobility scenarios in order to compare the planned and current solutions (Figs. 8a and 8b). Fig. 8a displays these percentage rates for each metric relative to the total for MS1. The simulation results reveal improved overall operating conditions for the designed solution, with a delay time rate of 45%, compared to 55% for the present road configuration. From an environmental impact point of view, the designed solution improved air quality, producing about 39% of total emissions, compared to 61% generated by simulating the current configuration. The simulation results also indicate a notable improvement in road safety for the planned solution, with a percentage rate of 9% for the total conflicts (see Fig. 8a). Conversely, the MS2 scenario (Table 1), which involved higher traffic volumes circulating in the network compared to MS1, showed less advantageous results than MS1 (Fig. 8b). However, Fig. 8b shows that the designed road solution can enhance operational, safety and air quality conditions. The designed solution simulated a delay time rate of 45%, compared to 55% for the baseline road layout (Fig. 8b). The same trend as seen for delay time was registered for the polluting emissions, with a percentage ratio of about 47% for the designed solution and 53% for the actual one. Lastly, the combined solution of TCSs and CDVs simulated only 14% of the total conflicts, thus improving road safety conditions compared to the current situation (Fig. 8b).

In addition, the percentage difference between the planned and current solutions was calculated concerning the three selected metrics (Figs. 9a and 9b). Fig. 9a depicts the percentage difference in delay time, pollutant emissions, and total conflicts of the designed solution compared to the baseline road layout, which was obtained by simulating MS1 and BMS1. The results in Fig. 9a show that the designed solution can enhance overall traffic conditions, highlighting main improvements in road safety. In fact, the percentage reduction in delay time and pollutant emissions was around 18% and 37%, respectively, for the designed solution compared to the baseline; the decrease is more significant for the simulated total conflicts, as it was around 90% (Fig. 9a). Fig. 9b displays the percentage differences in delay time, polluting emissions, and total conflicts for the designed solution compared to the baseline configuration by simulating MS2 and BMS2. The simulation results show that the percentage decreases in delay time, pollutant emissions, and total conflicts were around 17%, 12%, and 83%, respectively, for the designed solution compared to the baseline layout (Fig. 8b). Therefore, the designed solution demonstrated the potential to improve overall traffic conditions and air quality, even in mobility scenarios with high traffic volumes. The analysis of the simulation trials revealed that the planned solution, comprising TCSs and CDVs, offers new opportunities to develop smart mobility and create safer road spaces and healthier urban environments.

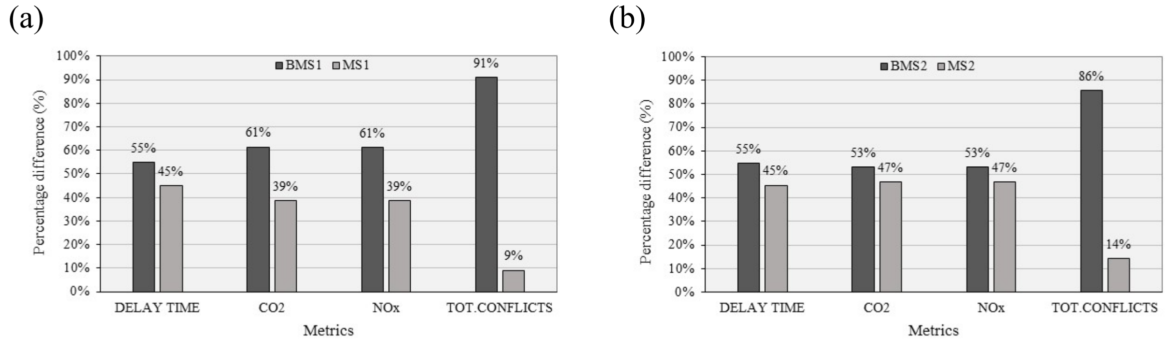

Fig. 8. Percentage ratios of delay time, pollutant emissions, and total conflicts evaluated with respect to their total simulated values considering (a) mobility scenario 1 (MS1) and baseline mobility scenario 1 (BMS1) and (b) mobility scenario 2 (MS2) and baseline mobility scenario 2 (BMS2)

By leveraging digital communications and smart sensors, zero-emission CDVs can optimize delays and travel at close range from each other while maintaining high safety standards and minimizing their environmental impact. On the other hand, TCSs promote smoother traffic flows by reducing stop-and-go driving. Additionally, by encouraging consistently low driving speeds, the planned solution offers notable benefits for road safety. These improvements are particularly evident in low-traffic-volume conditions (Figs. 8 and 9), during which vehicle interactions naturally induce lower speeds. Although the relationships between vehicle speed, acceleration, and pollutant emissions require further investigation, the results of this study indicate that the planned TCSs can improve air quality by promoting smooth driving. Additionally, the simulation findings suggest that including roundabouts as part of the TCSs provides further benefits in enhancing safety conditions.

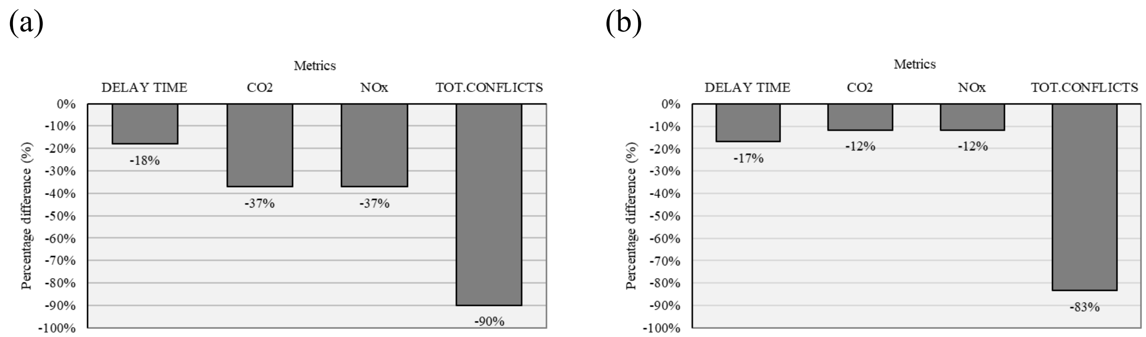

Fig. 9. Percentage difference between the designed solution and the current one, simulating (a) mobility scenario 1 (MS1) and baseline mobility scenario 1 (BMS1) and (b) mobility scenario 2 (MS2) and baseline mobility scenario 2 (BMS2)

4. CONCLUSIONS

The transition to smart cities presents new opportunities to develop road technologies that can be integrated with urban environments. Transportation planners and road engineers face the challenge of designing solutions that promote smart and eco-friendly mobility. Traffic calming strategies aim to lower vehicle speeds, thereby enhancing safety and creating more livable, healthy, and attractive urban spaces. To remain relevant in the evolution of smart cities, smart traffic solutions must incorporate digital road technologies. Cooperative driving technologies are emerging as promising advancements in the automotive industry, as they aim to manage and optimize traffic flows safely. This research evaluated the interaction between traffic calming solutions (TCSs) and cooperative driving vehicles (CDVs), focusing on operational, safety, and environmental impacts. A micro-simulation approach was used to assess the performance of a designed solution in future scenarios. The study focused on the coastal road network of Mazara del Vallo, where TCSs—including roadway rearrangements, two single-lane roundabouts, and a restricted-traffic area (RTA)—were implemented, with cooperative-driving vehicles (CDVs) serving as the public transport system. Two mobility scenarios (MS1 and MS2) were developed to address the increasing demand for mobility. The planned TCSs and corresponding mobility scenarios were compared to the baseline road layout using an Aimsun Next micro-simulator. Because empirical data on fully automated mobility are limited, reference data were arranged for model calibration, resulting in reference capacity functions (RCFs) based on corrective factors from the Highway Capacity Manual and varying market presence percentages (MPPs) of CDVs [15]. The results of the scatter analysis indicate a strong correlation between the simulated capacity data and the reference capacity functions, demonstrating that the calibrated model reliably reproduces the examined phenomenon. Three simulated metrics—delay time, pollutant emissions, and potential total conflicts—were selected to compare the designed solutions with the existing road configuration. The simulation results show that the synergy between the TCSs and CDVs can enhance operational and safety conditions, as well as air quality. By leveraging communication technologies, CDVs can reduce delays and increase capacity while maintaining high levels of road safety. Additionally, by facilitating smooth driving, the TCSs provide safe road spaces. Roundabouts, as part of the TCSs, play a significant role in overall improvements in safety and traffic conditions. Future research should investigate vehicle speed profiles to explore the relationship between speed reduction from traffic calming strategies and vehicular emissions.

The simulation outputs highlight several advantages of broadly implementing smart mobility integrated with effective traffic management, offering insights into future scenarios rather than definitive predictions. Due to the current lack of empirical data on fully automated smart mobility, assumptions regarding CDV driving behavior were necessary. Therefore, further research on the CDVs' driving behavior on various road entities is needed to achieve more generalizable results. However, since a full CDV fleet needs time to become present in the field, an intermediate scenario involving the inclusion of an electrically powered human-operated mini-bus could be simulated. In the age of cities in transition, integrated road planning solutions present new opportunities for advancing smart mobility and enhancing the quality of life in urban areas. The microsimulation-based approach proposed in this study can aid road planners and decision-makers in assessing various road design and traffic management solutions involving traffic calming solutions and smart mobility. However, the feasibility of the proposed solution, associated costs, and potential challenges must be considered. A cost-benefit analysis could support decision-making by evaluating the life-cycle costs of the design alternatives. Additionally, involving the urban community is crucial to the success of the planned solutions.

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