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Toward smart and sustainable road intersection design embedding connected, cooperative and automated vehicles

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Abstract

In this paper the performance of Human Driven Vehicles (HDVs) mixed with Connected, Cooperative and Automated Vehicles (CCAVs) were analyzed at intersection level, considering different geometric design solutions associated with the corresponding traffic control modes. The intersection selected as case study is located in the City of Opole, Poland. Aimsun Next was used to simulate the infrastructural and traffic scenarios conceptualized by incorporating increasing market penetration rates of CCAVs. In the simulating environment CCAVs' driving parameters were well-defined according to the geometric layouts built by comparing simulated data with benchmark capacity functions (BCFs). In the transition toward fully CCAVs fleet, the methodological approach based on microsimulation, enables to endorse and analyze the assumptions underlying the appraisal of CCAVs' operational performance at the intersection level. The results provided a future insight of traffic scenarios that can occur at intersections under mixed traffic conditions of HDVs and CCAVs. The methodological comparison of different geometric layouts enables to evaluate feasibility of design strategies adequate with the CCAVs' performance expectations also useful in urban road corridor level assessments.

Keywords: *road intersection; connected, cooperative and automated vehicles; traffic microsimulation; Aimsun Next.*

1. Introduction

Recent advances in connected, cooperative, and automated vehicles (CCAVs) present new opportunities to enhance operational performance at intersections due to their high-tech communication devices (see Ni, 2020). With the transition toward smart and sustainable road intersections in mind, this research aims to analyze the interaction between the growing market penetration rates (MPRs) of CCAVs and the human driven vehicles (HDVs), across

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various intersection layouts associated to the corresponding traffic control modes. Aligned with the objectives of technological innovation for smart roads outlined by Pompigna and Mauro (2022), this paper investigates the role of microsimulation in assessing the performance of road intersections in the transition to fully CCAV fleets. The selected case study is a signalized intersection located in the city of Opole, Poland. Additionally, a two-lane roundabout was designed as an alternative intersection solution to facilitate comparison, with efficiency serving as the guiding criterion. The choice of the alternative geometrical solution stemmed from the opportunity to assess both the traffic calming effect in the specific context of the installation and the yield negotiation between cooperative vehicles. To achieve this objective, Aimsun was used to simulate infrastructural scenarios across increasing MPRs of CCAVs. Within the simulation environment, the driving parameters of CCAVs were well-defined based on the geometric and functional network models of the examined intersections, as well as their traffic settings, by comparing simulated data with benchmark capacity functions (BCFs). These BCFs, which reflect the presence of CCAVs at the intersections under examination, were derived using CCAV-based adjustment factors provided by the Highway Capacity Manual (2022). The entry capacity (pc/h), delay (km/s) and travel (km/s) times were selected as key performance metrics for assessing operational performance of CCAVs mixed with HDVs in traffic. The simulation results highlighted that as the MPRs of CCAVs increased, the improvement in capacity was higher at the signalized intersection than at the designed roundabout. However, the trends of delay and travel times, although decreasing in both intersections, showed different results based on the considered entry lane and lane group. Despite the importance of refining the model parameters of the traffic microsimulation model, it should be noted that the formulated assumptions could have affected the simulation results as referred by Tumminello et al. (2022) and Granà et. al. (2024); moreover, the research outcomes should be not understood as a deterministic interpretation of reality but rather as a reliable projection of future scenarios. From a social perspective, the paper aims to highlight the benefits associated with a CCAVs deployment targeted to offer improved, safer and environmentally friendly driving. Future insights should aim to explore vehicle-to-infrastructure communication policy for improving smart traffic control efficiency at intersections. However, the proposed microsimulation approach can guide designers and practitioners in the road field to evaluate different geometrical and functional intersection solutions incorporating CCAV functionalities and potentialities.

The paper structure is as follows: after the introduction section, in section two the characterization of the case study and Aimsun modeling assumption were presented. The section three presents and discusses the results, while section four concludes the paper.

2. Materials and Method

2.1. Characterization of the case study

The intersection selected as a case study is located in a suburban area of the city of Opole, Poland (50º 39'17" N 17º 57'16"E) southeast of the city center. The four-legged intersection is defined by a main road Jerzego i Ryszarda Kowalczyków street that leads to the city center and a minor one, Mieszka I street in the northeast direction and Jagiellonów street in the southwest direction. The vehicle paths are defined by the approach alignments for all vehicle maneuvers. Actually, the North, East, and West road approaches consist of two entry lanes, each 3.25 m wide, and one exit lane 3.50 m wide; the South approach has three entry lanes each 3.25 m wide and one exit lane 3.50 m wide. All intersection approaches have a shared through and right-turn lane, and an exclusive left-turn lane with the exception of the Northbound approach which has an exclusive lane for each type of maneuver (see Fig. 1a). Currently the traffic flows at the intersection are managed by a traffic signal operating with fixed cycle length. Fig. 1b shows the roundabout layout chosen as an alternative design solution to the signalized intersection to compare CCAVs operating conditions between them (see section 2.2). To lead the subsequent microscopic-level analysis, a field survey was carried out to count the actual traffic flows flowing at the intersection. Traffic data surveys were conducted during the peak hour on weekdays in October 2023. The extracted data returned a total volume of 2250 veh/h composed of 89% cars, 1% motorcycles and mopeds, and 10% heavy vehicles. Since the suburban nature of the context, a percentage of pedestrians and cyclists was negligible. The majority of traffic flows, approximately 37,5% concerned the crossing maneuver of the vehicles coming from the main road to minor street, i.e. the traffic movements in the west-east directions and vice versa (see Fig. 1, approaches 3 and 4); in turn, about 26% of the total traffic flow regarded the crossing maneuvers by vehicles coming from the minor street to the main road. The right- and left-turns from the main road resulted equal to 17,5% total traffic volume registered, while the turning movements of the vehicles coming from the minor street were approximately 19%. Actually, the cycle length of the traffic signal lasts for 120 seconds and it is divided into 4 phases:

- Phase 1: the green time is given to the right-turn and through movements on approaches 1 and 2 with 27 percent green time on the total cycle length;
- Phase 2: the green time is given to the left-turn on approaches 1 and 2 with 10 percent green time on the total cycle length;
- Phase 3: the green time is given to the right-turn and through movements on approaches 3 and 4 with 43 percent green time on the total cycle length;
- Phase 4: the green time is given to the left-turn on approaches 3 and 4 and to right-turn on approach 2 with 10 percent green time on the total cycle length.

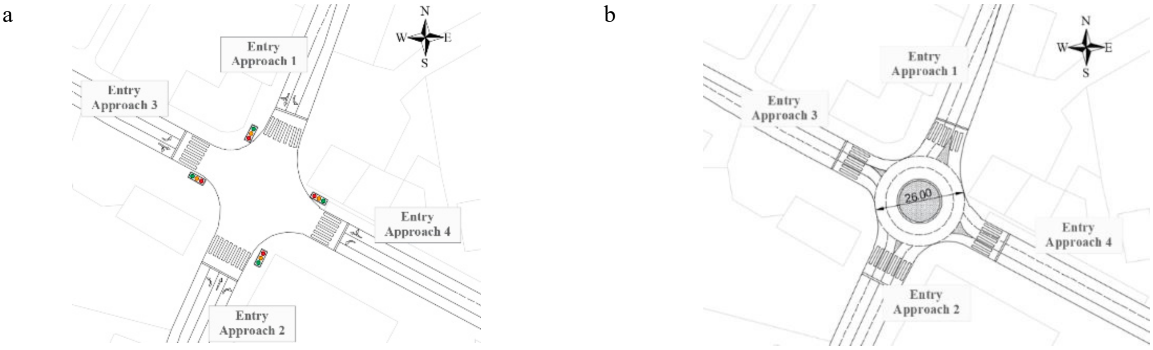

Fig. 1. (a) the sketch of signalized intersection under study with approaches indication; (b) the sketch of the designed two-lane roundabout

The movements at the regarded intersection (see Fig. 1) are organized in lane groups (see Table 1). A lane group consisted of one or more lanes accommodating all the movements entering the subject intersection approach; whereby exclusive turn lanes, such as the left-turn in this case, are represented by an individual lane group (or in other words a separate lane group); in turn, the shared movements, i.e. right-turns and through movements, are considered as a single lane group as referred by Highway Capacity Manual (2022). Table 1 shows, for each entry approach in Fig. 1(a), the numbering of the lane groups and the corresponding allowed movements.

Table 1. Characteristics of the lane groups at the signalized intersection under study.

	Entry Approach 1		Entry Approach 2			Entry Approach 3		Entry Approach 4	
Lane groups No	1	2	3	4	5	6	7	8	9
Corresponding movements	(L)	(T+R)	(L)	(T)	(R)	(L)	(T+R)	(L)	(T+R)

Note: (L) stands for left turn; (T) for through movement and (T+R) for combined through movement and right turn.

In accordance with the current traffic signal that does not include permitted left-turn movements, the entry capacity of a lane group was calculated with the following general formula:

$$C = \frac{\beta \cdot N_l \cdot S_{fr}}{C_l} \tag{1}$$

where C is the capacity expressed in veh/h; β is the effective green time (s); N_l is the number of lanes in a lane group; S_{fr} is the saturation flow rate (veh/h/ln) and finally C_l is the total cycle length (s).

The saturation flow rate for each lane group is calculated as product of a base value of the saturation flow rate and various factors to characterize particular condition on intersection approach. The saturation flow rate is computed with the following equation (Highway Capacity Manual (2022)):

$$S_{fr} = s_b \cdot \prod_{i=1}^{n} f_i \tag{2}$$

where S_{fr} is the saturation flow rate (veh/h/ln); s_b is the base saturation flow rate (veh/h/ln) multiplied by a series of adjustments factors that may reduce its value due to specific conditions of impedances on the subject approach. These factors are related to: lane width, heavy vehicles in traffic, approach grade, the presence of car parks near the subject approach, bus stops in the intersection area, the major activities in the intersection facility context, the presence of left-turning or right-turning vehicles in a lane group, and finally the presence of pedestrians turning left and pedestrians and/or cyclists turning right. The n=11 factors above can assume values at most equal to 1, which means no influence in reducing the saturation flow rate. For the intersection in Fig. 1, all the adjustment factors were considered equal to 1 except for those relating to the lane width, the presence of heavy vehicles and for the turn movements if present in the subject lane group. The presence of pedestrians and cyclists was found to be negligible based on the field survey data; as a consequence, the corresponding adjustment factors were set equal to 1.

2.2. Aimsun modeling

In order to investigate operating conditions at the signalized intersection selected as case study, a microscopic analysis was performed using Aimsun Next (2020). The first step of microscopic modeling was the reproduction of the intersection geometry consistently with the real-world counterpart by creating road sections, by defining the type of road and the number of traffic lanes, and by linking the sections through nodes. The demand data has been represented in the form of an Origin-Destination (O-D) matrix. Centroids of the built model were positioned to define the start and end points of trips, with traffic flows quantified between them. Detectors were strategically placed on road sections to record the evolving values of traffic parameters throughout the simulation. The current traffic signal was replicated in Aimsun Next, creating a signal-timing plan that aligns with the predefined signal groups and phases. To simulate traffic scenarios embedding CCAVs that interface in driving with HDVs, increasing market penetration rates (MPRs) of CCAVs in traffic were considered. Thus, different traffic scenarios starting from the current one (baseline scenario) with 100% of HDVs, toward the exclusive presence of CCAVs in traffic were simulated, considering growing MPRs of CCAVs with a 20% step. In Aimsun the CCAVs driving parameters were well-defined by comparing the entry capacity function by MPRs and simulated data. CCAVs may increase capacity thanks to their capability to safely exploit closer headways respect to HDVs. The saturation flow rate computation also took into account increasing MPRs of CCAVs in traffic. According to HCM (2022), Chapter 31 the base saturation flow rate values were assumed different depending on the MPRs of CCAVs for the through movements. For the protected left-turns, the HCM (2022) provides an adjustment factor to be included in the Eq. 2, as a function of increasing MPRs of CCAVs. For the other movements at signalized intersections the adjustments for CCAV capacities provided in the HCM (2022), Chapter 33, were considered. Before starting the simulation runs, the reliability of the micro-simulator to represent surveyed traffic was tested. The warm-up of the network model involved launching ten one-hour replications, with five minutes dedicated to initialization for loading the network and an additional five minutes for discharging it. A comparison between simulated and observed data by lane group yielded a percentage error of less than 12%. In the simulation environment, entry approach 3 at the intersection depicted in Fig. 1 reached saturation, aligning with the specified capacity value from Eq. 1. Hence, the amount of traffic flows entering the intersection approach, guarantor of saturation conditions, was assigned to the network model through the O-D matrix. According to the above MPRs, the O-D demand matrix was split into two matrices, each representing a certain percentage of CCAVs and the remaining percentage of HDVs. After defining the OD matrices, a one-hour simulation was initiated, incorporating 5 minutes for pre-loading the network using the default parameters of Aimsun. As automation levels 4 and 5 of CCAVs (SAE International, 2022) have not yet penetrated the market, field-based data reflecting mixed traffic with both CCAVs and HDVs could not be surveyed. Consequently, benchmark capacity functions (BCFs) were constructed based on Eq. 1. The cycle length was kept constant while the duration of effective green time varied by lane group, as illustrated in Fig. 2. There was a necessity to fine-tune the model parameter values to ensure that the simulated capacity curves aligned with the BCFs. To address this, a sensitivity analysis was conducted to identify which model parameters exerted the most influence on the simulation results. It was found that for HDVs, the speed limit acceptance, maximum acceleration, normal reaction time, reaction time at stop, and reaction time at traffic lights were the most sensitive parameters. The speed limit acceptance parameter signifies the extent to which road users adhere to speed limits. Values close to unity indicate strict adherence, limiting drivers from reaching the speed limit values, whereas values below unity indicate a more assertive driving behavior, with drivers traveling at speeds below the limit. The maximum acceleration refers to the highest acceleration applied in the Gipps (1981) car-following model. The normal reaction time is the time spent by the follower reacting to speed variation of the leader vehicle. The reaction time at stop is used for vehicles stationing at stop line and it represents the time it takes a vehicle to react to acceleration changes in the vehicle ahead; in turn, the reaction time at traffic light is realized in presence of traffic signal and it is the time taken by a driver stopping at a red light, to react to the departure when the traffic light turns green. In general, lower reaction time values imply higher capacity, as vehicles react more promptly to changes in speed and acceleration of the vehicle ahead, allowing them to drive closer to preceding vehicles. In addition to the above parameters identified for HDVs, the clearance, normal deceleration, distance gain, time gap leader and time gap follower resulted the most sensitive parameters for CCAVs; the last three parameters of the car-following model by Gipps (1981), characterize the connected and autonomous driving behavior. The clearance is a parameter specifies the distance between a vehicle and the preceding one when the vehicles unmoving. The normal deceleration is the maximum deceleration used in the car-following model by Gipps (1981). Cooperative vehicles used CACC gap regulation mode to control speed and position based on the vehicle ahead; thus, the distance gain, time gap leader and time gap follower are parameters to manage the relative position between the leader and follower vehicles. The values of the most sensitive parameters were well-defined by comparing the simulated capacity data with the BCFs. Fig. 2 shows the surface functions of the benchmark capacity under different proportion of CCAVs in traffic for each lane group in the subject approach. Fig. 2 shows improved capacity when the MPR percentages of CCAVs increase, as a consequence of their ability to accept smaller gaps in traffic. The percentage difference between the simulated capacity data and BCFs was employed as criteria to accept or reject the simulation model. The procedure for tuning-up the model parameters was iterative. If the percentage difference between simulated capacities and benchmark data was less than 5%, the simulation model successfully replicated the phenomenon under study. Otherwise, it was necessary to search for a new combination of model parameter values that minimized the percentage deviation between simulated capacity data and BCFs. In Table 2, the parameters modeled in Aimsun are presented. The normal reaction time and reaction time at stop and traffic lights, were uniformly set across the vehicle classes, and they were equal to the simulation step. Consequently, the weighted average of the reaction times was utilized to account for the varying abilities of vehicles to exploit traffic gaps. The weights for reaction times were assumed in accordance with the MPRs of CCAVs. The scattergram analysis was performed to compare the benchmark versus simulated capacity data for different proportions of CCAVs and HDVs. By way of example, Fig. 3 shows the scattergram for the mixed traffic with 60% CCAVs and 40% HDVs obtained by varying the effective green time from 10 s to 45 s for the lane group No 6 and from 20 s to 55 s for the lane group No 7 (see Table 1 for the characterization of the lanes groups).

To analyze CCAVs' performance on other intersection layouts, a two-lane roundabout was selected as an alternative to the current signalized intersection. The four-legged roundabout consists of two entry lanes and one-way exit lanes for all approaches except the Northbound, which has two entry and exit lanes (refer to Fig. 1b). According to Polish guidelines (2022), the designed roundabout is classified as a compact small size roundabout, featuring a non-traversable central island with an outer diameter of 26 m and two circulatory lanes, each 3.50 m wide (refer to Fig. 1b). The geometric design also incorporates raised splitter islands and deflection angles exceeding 45 degrees. The roundabout network model was constructed in Aimsun to evaluate the operational conditions of mixed traffic including CCAVs and HDVs. Additionally, the most sensitive model parameters for the roundabout case were identified for calibration purposes. Regarding capacity, the general equation for the roundabout is as follows:

$$C_{e,CCAVs} = f_{(a)} \cdot a \cdot e^{-f_{(b)} \cdot b \cdot Q_c} \tag{3}$$

where $C_{e.CCAVs}$ is the CCAVs' capacity value by entry lane according a MPR from time to time considered; a and b represent the intercept and slope parameters, respectively; the intercept values were 1,420 and 1,350 pc/h, while the slope values were 0.085 and 0.092 for the right and left entry lanes. The $f_{(a)}$ and $f_{(b)}$ express the adjustment factors for the parameters a and b, respectively. Eq. 3 was used to determine the benchmark capacity functions (BCFs), reflecting the presence of different MPRs of CCAVs at roundabouts. The intercept and slope parameters were adjusted with the lane-based factors drawn from the HCM (2022) for different proportions of CCAVs. The simulated capacity was obtained reproducing saturation condition in the network model through the O-D matrix, then split into two O-D matrices based on the CCAV-MPRs. The traffic flows entering each entry lane were simulated separately from free-flowing up to capacity, using 9 subsequent O-D matrices. The operational performance of the right and left entry lanes was separately analyzed due to differences in the entry mechanisms at roundabouts. To reach entry capacity in Aimsun, the circulating flow gradually increased from 0 to 1,800 veh/h in steps of 200 veh/h for both entry lanes. Also, for the roundabout, the model parameters were tuned up for both entry lanes displayed in Table 3.

Table 2. Results of the tuning-up parameters process for the signalized intersection under study.

Model parameters	Default value	tuned-up model parameters values			
		Lane group No 6		Lane group No 7	
		HDVs	CCAVs	HDVs	CCAVs
Speed limit acceptance	1.10	1.30	1.60	1.30	1.60
Maximum acceleration [m/s^2]	3.00	3.20	3.40	3.20	3.40
Normal deceleration [m/s^2]	4.00	4.00	3.50	4.00	3.50
Clearance [s]	1.00	1.00	0.50	1.00	0.50
Distance gain	0.45	0.45	0.60	0.45	0.60
Time gap leader	1.50	1.50	0.50	1.50	0.50
Time gap follower	1.50	1.50	0.50	1.50	0.50
Reaction time [s]	0.80	0.85 [1]	0.62 [2]	0.80 [1]	0.60 [2]
Reaction time at stop [s]	1.60	1.75 [1]	1.06 [2]	1.60 [1]	0.82 [2]
Reaction time at traffic light [s]	1.20	1.36 [1]	1.02 [2]	1.20 [1]	0.73 [2]

[1] This value corresponds to the case 0% MPR of CCAVs. [2] This value corresponds to the case 100% MPR of CCAVs.

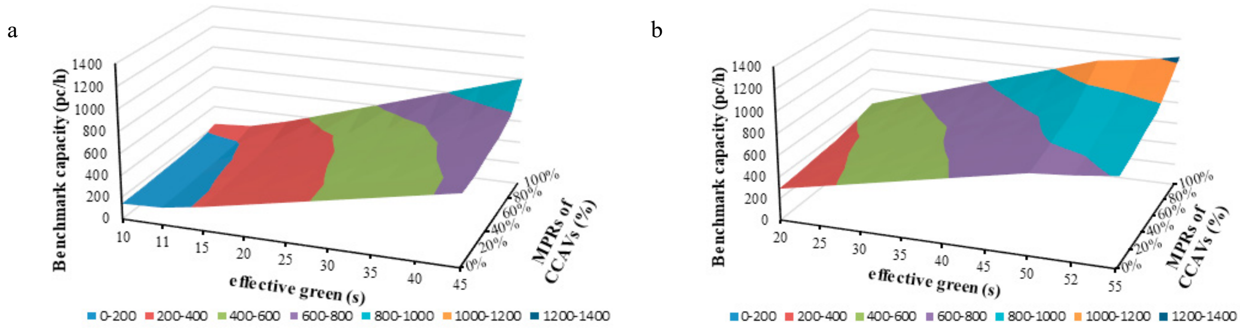

Fig. 2. Benchmark capacity surface functions for: (a) the lane groups No 6; (b) the lane groups No 7. Note: MPR means market penetration rate, while CCAV stands for connected, cooperative and automated vehicle.

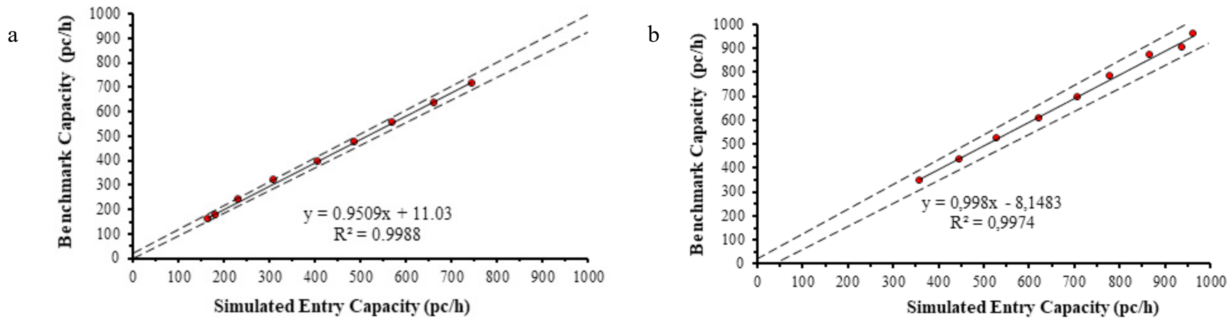

Fig. 3. Scattergram analysis for the mixed traffic with 60% CCAVs and 40% HDVs for: (a) the lane groups No 6; (b) the lane groups No 7.

In contrast to the signalized intersection, the roundabout involved additional factors: a) the gap parameter regulated vehicle spacing via car-following algorithms; b) the safety margin factor determined vehicle movement, with assertive drivers using values below default; c) the sensitivity factor aided follower vehicles in estimating leader deceleration, as referred by Tumminello et al. (2022). The reaction times were a weighted mean of values of each vehicle class (i.e. HDVs and CCAVs) as set for the signalized intersection. According to Barcelò (2010), the

GEH statistic determined model acceptance. Thus, the calibrated model was accepted if deviations between simulated and benchmark capacities were under 5 in at least 85% of cases.

Table 3. Results of the tuning-up parameters process by roundabout entry lane.

Model Parameters	Default Values	Tuned-up values			
		Left entry lane		Right entry lane	
		HDVs	CCAVs	HDVs	CCAVs
Speed acceptance	1.10	0.97	1.10	0.95	1.10
Gap [s]	0.00	1.33	0.00	1.00	0.00
Reaction Time	0.80	0.95 [1]	0.67 [2]	0.94 [1]	0.70 [2]
Max acceleration [m/s^2]	3.00	3.00	4.00	3.00	3.50
Safety margin factor	1.00	1.00	0.50	1.00	0.40
Sensitivity factor	1.00	1.00	0.50	1.00	0.50

[1] This value corresponds to the case 0% MPR of CCAVs. [2] This value corresponds to the case 100% MPR of CCAVs.

3. Results and discussion

Starting from the parameter tuning process, the operational performance of mixed HDVs and CCAVs traffic was assessed. A comparative analysis was carried out between the current signalized intersection and the proposed roundabout. Capacity (veh/h), delay (s/km), and travel time (s/km) were selected as performance indicators. Simulation outcomes indicated enhanced operational conditions with higher MPRs of CCAVs. Fig. 4 shows the impacts of the CCAVs on entry capacity for both intersections. Fig. 4a illustrates the capacity comparison between the left entry lane at the roundabout and the left turn movement (lane group No 6) at the signalized intersection, showcasing how capacity varies with increasing MPRs of CCAVs. Similarly, Fig. 4b showcases capacity variations across different MPRs for the right entry lane at the roundabout and the right-turn and through movements (lane group No 7) on the signalized intersection approach. As MPRs of CCAVs increased, the percentage increase in capacity was overall higher for the signalized intersection compared to the roundabout (refer to Fig. 4a and Fig. 4b). Specifically, Fig. 4a shows that, for MPRs from 20% to 60%, the increase in capacity for the two examined turning movements were comparable. Conversely, starting from the 60% MPR onwards, the capacity increase at signalized intersections surpassed that of the roundabout, doubling the percentage value for 100% CCAV operations. Similarly, Fig. 4b shows the increase in capacity for the signalized intersection. Meanwhile, the percentage decrease of the travel and delay times with the rise of the MPR of CCAVs, was overall higher for the exclusive left-turn in the individual lane group (lane group No 6) at the signalized intersection than the corresponding left entry at the roundabout (see Fig. 4c and Fig. 4d). In turn, higher benefits in reducing the delay and travel times, were registered for the right entry lane only conflicted by one circulating stream at the roundabout, compared to the lanes group No 7, sharing right-turn and through movements at the signalized intersection (see Fig. 4c and Fig. 4d).

4. Conclusions

In the transition toward smarter and more sustainable road intersections, the operational efficiency of mixed CCAVs and HDVs traffic should be analyzed. As not all vehicles are equipped with high communication and automation levels (SAE International, 2022), micro-simulation provides a valuable tool to simulate future scenarios incorporating varying market penetration rates of CCAVs. To assess the impact of increasing MPRs of CCAVs, Aimsun has been applied to compare different intersection layouts from the performance efficiency perspective. A two-lane roundabout was designed as an alternative solution to the current signalized intersection, which served as a case study. The geometric and functional network models for each intersection were constructed in Aimsun; the model parameter tuning ensured simulation reliability. The simulation results show, as the MPRs of CCAVs increased, a considerable increase in capacity for the signalized intersection compared to the roundabout counterpart. In turn, the trend recorded for the delay and travel times depended on the entry lane or the lane group. These results are supported by the CCAVs ability to react promptly to the green signal or the kinematic changes of the vehicle ahead considering their high-tech devices of communications onboard (Yu et al., 2023). The CCAVs driving behaviour resulted assertive also in case in which the typical roundabout negotiation and traffic calming effect missed. The methodological approach based on microsimulation, proposed in this research, enables to endorse and analyse the assumptions behind the valuation of CCAVs' operational efficiency at the intersection level. However, the outcomes of this study rely on the assumptions made and should not be understood as a deterministic interpretation of reality but rather as a reliable projection of future infrastructural scenarios. A future hypothesis to be investigated could be the assessment of signal intersection operations with CCAVs when the cycle length is depending by the traffic flow rates. Also, various intersection design solutions can meet pre-established planning goals. Further research is also needed to enhance vehicle-to-infrastructure communication. At last, the methodology set out in this paper has been shaped to support road designers and practitioners in the feasibility assessment for alternative designs solutions aligned with CCAVs' performance expectations, also for urban road corridor level.

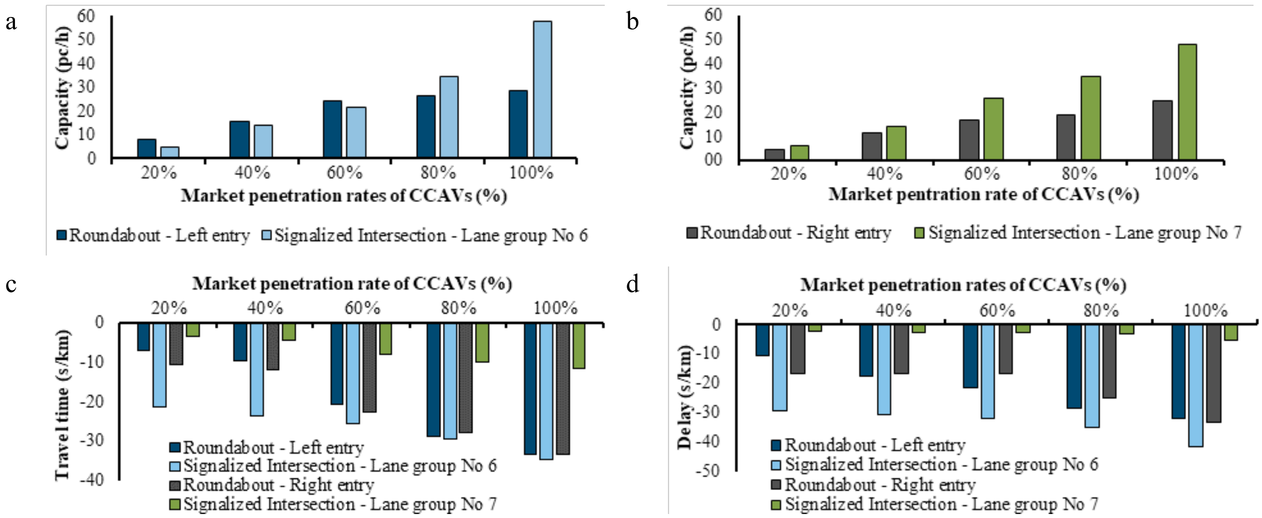

Fig. 4. Percentage differences for traffic scenarios with increased MPRs of CCAVs: (a) roundabout left entry vs lane group No 6 capacity; (b) roundabout right entry vs lane group No 7 capacity (c) roundabout vs intersection approach travel time; (d) roundabout vs intersection approach delay.

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