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Developing Highway Capacity Manual Capacity Adjustment Factors for Connected and Automated Traffic on Roundabouts

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Abstract: Connected and automated vehicles (CAVs) are expected to transform future transportation systems. Over time, these vehicles might enhance traffic efficiency and safety, especially at urban intersections. Therefore, it is essential to make adaptations to the traffic analysis models that are currently designed for human-driven vehicles only. This paper aims to assess the impact of CAVs on the entry capacity of roundabouts and develop an approach to adjust the capacity values calculated by the Highway Capacity Manual (HCM) for planning level analysis. Both single- and double-lane roundabouts are studied under various CAV market penetration rates and conflict flow rates in this paper. A specific CAV application, cooperative adaptive cruise control (CACC), is evaluated in this study because it enhances the car-following behavior at the roundabout entrance and has the best potential for improving the entry capacity. The simulation results indicate that the introduction of CAVs can substantially improve the entry capacity as the market penetration rate increases for both single- and double-lane roundabouts. The capacity improvement is more significant in the single-lane roundabout than in the double-lane roundabout. The capacities under different CAV market penetration rates and conflict flow rates are calculated and compared with the capacity results estimated from base models in the HCM to acquire the adjustment factors. Finally, a table of capacity adjustment factors is provided for the future implementation of HCM models. **DOI: 10.1061/JTEPBS.0000674.**

Author keywords: Connected and automated vehicles (CAV); Highway capacity manual (HCM); Capacity adjustment factors; Microscopic simulation; Roundabout.

Introduction

While roundabouts are a relatively new type of intersection in the US, they are becoming more common as evidence of their benefits grows (Rodegerdts 2010). These unsignalized intersections allow drivers to cross the intersection without the need for a complete stop and have been found to reduce the number of conflict points and the severity of crashes.

Thanks to the advancement of connected and automated vehicle (CAV) technologies, communications between vehicles (V2V) and between vehicles and infrastructure (V2I) provide new possibilities for traffic control. This bilateral communication reduces the number of unknown states and disturbances, increases the amount of information that can be inferred, and provides a higher capability of cooperation between vehicles and infrastructure (Peng 2016). As a result, the application of CAV has great potential in improving driving safety, comfort, and efficiency, leading to a revolution in transportation system operations. Understanding the impacts of CAV is essential for future transportation control, policymaking, and urban design.

The adaptive cruise control (ACC) system allows a vehicle to drive behind a leader at a certain distance, which improves traffic safety as well as fuel efficiency (Ghiasi et al. 2019). Enabling the connectivity between vehicles and roadside units, the ACC application could be extended to form a platoon known as cooperative ACC (CACC) (Guo et al. 2019). With the shared information between vehicles, CACC allows vehicles in a platoon to maintain smaller headways as compared to ACC (Lazar et al. 2018). For intersection coordination of CAV traffic, multiple protocols have been proposed in recent years. Using V2V and V2I technologies, vehicle gaps can be reduced, thus increasing roundabout traffic flow (Kim et al. 2014). Note that in this paper we use the term platoon to indicate a string of CACC vehicles, the operation of which is also partially informed by temporary platoon leaders. (Martin-Gasulla and Elefteriadou 2021)

Although a few researchers have studied the application of CAVs on roundabouts, most of them focused on energy consumption and travel time problems. Zhao et al. (2018) studied energy consumption and travel time at different penetration rates of CAVs.

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They developed a coordination algorithm for CAVs under different market penetration scenarios and analyzed the effects on capacity, but the study is only feasible for two-approach simple roundabouts. Virdi et al. (2019) investigated the safety performance of mixed fleets of CAV in a roundabout, but the study didn't explore the performance difference between different roundabout configurations.

For future transportation system planning and operations, agencies need to understand how road capacity would be impacted by the increasing penetration rate of CAVs (Litman 2017). Currently, the Highway Capacity Manual (HCM) is the most used source for capacity and level of service (LOS) estimation and prediction. HCM models for roundabouts are based on empirical information and models developed from actual observations of pure human-driven traffic. Given the relatively young age of roundabouts as a road facility, the HCM roundabout model is still in flux. The latest HCM 6th Edition (HCM6) (Transportation Research Board 2016) has revised the proposed capacity model, citing observations of capacities higher than the ones predicted by HCM 2010 (Transportation Research Board 2010). Although the HCM suggests local calibration of its model through gap acceptance information from similar roundabouts in the area, most users just use the default model.

The current HCM models are developed for traffic with human-driven vehicles (HDVs) only and do not consider the potential impact that CAV could have on the roundabout capacity. Therefore, it is necessary to investigate this impact under partially or fully deployed CAV scenarios, compare the results with those computed from HCM models, and develop adjustment factors based on the basic HCM capacity models. The purpose of this paper is to explore the impact of CAVs on the capacity of both the single- and double-lane roundabout and develop capacity adjustment factors (CAFs) for CAVs over various market penetration rates (MPRs) to modify the HCM capacity results.

The remainder of this paper is organized as follows: section "Methodology" provides a detailed description of the methodology to achieve the study objective. Sections "CAV Modeling" and "Results" cover the simulation experiments and results. The table that summarizes the CAFs is also included in the "Results" section. Finally, section "Conclusions and Future Research" concludes this paper and proposes future research directions.

Literature Review

CAVs can coordinate their decisions to avoid long gaps at roundabout entry points and consequently provide a unique opportunity to improve traffic operations. While there are many studies in the literature that have evaluated the effects of CAVs on traffic operations at different transportation facilities such as intersections (Mirheli et al. 2018) or freeways (Zhou et al. 2016), roundabouts have not received the same level of attention (Zhao et al. 2018). Azimi et al. (2013) developed a CAV movement control protocol based on discretizing the circular roadway of a roundabout into several cells. The protocol allowed each cell to be occupied by only one vehicle at a time. The cells could be occupied based either on a first-come-first-serve (FCFS) discipline or any predefined vehicle priority. Zhao et al. (2018) proposed an optimization program with the objective of acceleration/deceleration rate minimization. However, their trajectory optimization approach did not consider merge maneuvers at the entry approaches. Martin-Gasulla and Elefteriadou (2019) proposed a rule-based control logic that adjusted the speed of vehicles to avoid conflicts at merging locations based on an FCFS principle.

The approaches regarding integrating CAV features in roundabout improvement can be categorized into centralized and decentralized approaches (Chen and Englund 2016). In centralized approaches, at least one of the tasks is done by a centralized unit. The centralized approaches can be sorted to optimization-based and heuristic. In decentralized methods, each of the vehicles gathers local information from other vehicles within a certain range, and based on those data, they calculate the proper control policy. One of the challenges associated with decentralized approaches is the situation of deadlock because of using only local information. The decentralized approaches can also be divided into heuristic and optimization-based methods. In the approach proposed by Dresner and Stone (2004), at the high level, priorities are determined by a central controller and given to each of the vehicles, then in the low level, every vehicle is responsible for adhering to the assigned priorities by solving an optimization problem with the preceding vehicle's current and anticipated subsequent states. In Zohdy and Rakha (2016), the roundabout is demonstrated to have comparable performance as an optimized intersection control system under the CAV environment called intersection CACC (iCACC). The iCACC system ensures the collision-free principle and minimizes the intersection delay. Although the comparison results are based on simulations, the potential of roundabouts for CAV management is revealed, and theoretical analysis is worthy of study.

Methodology

Base Model Development

In this study, a set of microscopic simulations were conducted to study the impact of CAVs on the roundabout capacity. Planung Transport Verkehr (PTV) has multiresolution traffic modeling platforms that include macroscopic, mesoscopic, microscopic, and hybrid mesoscopic-microscopic modeling engines. The microscopic simulator VISSIM is the one we used for this study. As shown in Fig. 1, two roundabout models were developed in VISSIM: a single-lane roundabout and a double-lane roundabout. Both models are four-leg roundabouts. The single-lane roundabout consists of four single-lane entries conflicted by one circulating lane. The double-lane roundabout has four double-lane entries conflicted by two circulating lanes. The maximum diameters of the single-lane roundabout and the double-lane roundabout are 44.8 m (147 ft) and 56.4 m (185 ft), respectively.

The HCM provides different capacity models for different types of entry lanes in roundabouts. To investigate the impact of different CAV MPRs on the entry capacity, the models developed in this study need to be calibrated by the HCM models.

Previous studies have summarized that the settings of three elements in VISSIM have a critical impact on the operational performance of roundabout simulation models (Schroeder et al. 2012) These elements include: (1) priority rules (PR) or conflict areas (CA), which control the yielding logic; (2) reduced speed areas (RSA), which provide temporary speed control over a short roadway distance; and (3) the Wiedemann 74 car-following model, which controls the simulated car-following behavior.

In this study, the CA is adopted to control the yielding logic at the roundabout entrances. We calibrated the simulation networks by adjusting the simulation parameters in VISSIM. The capacity curves generated by the simulation results are compared with the HCM capacity curves to ensure that the calibrated simulation models have acceptable goodness of fit with the HCM models. The calibration results are given in a later section.

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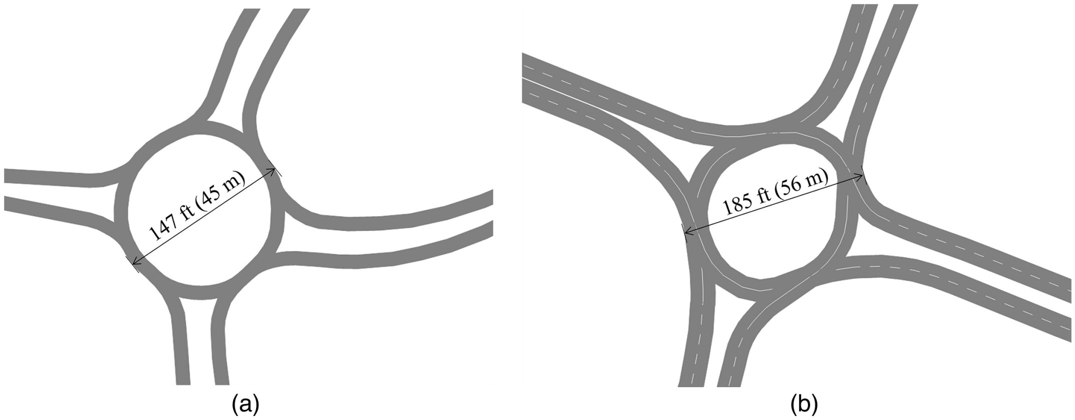

Fig. 1. Roundabout models: (a) one-lane roundabout; and (b) two-lane roundabout.

Model Calibration

Both the single- and double-lane roundabout VISSIM models are calibrated by the HCM roundabout capacity models. Specifically, the left and the right entry lane of the double-lane roundabout are calibrated separately because the HCM offers different capacity formulas for each entry lane. The simulation models are calibrated by adjusting the parameters regarding the CA, the Wiedemann 74 driving model, and the RSA. The calibration results are illustrated in Fig. 2, which shows the capacity curves derived by the HCM capacity models, the calibrated VISSIM models, and the default VISSIM models, respectively. As shown in Fig. 2, after model

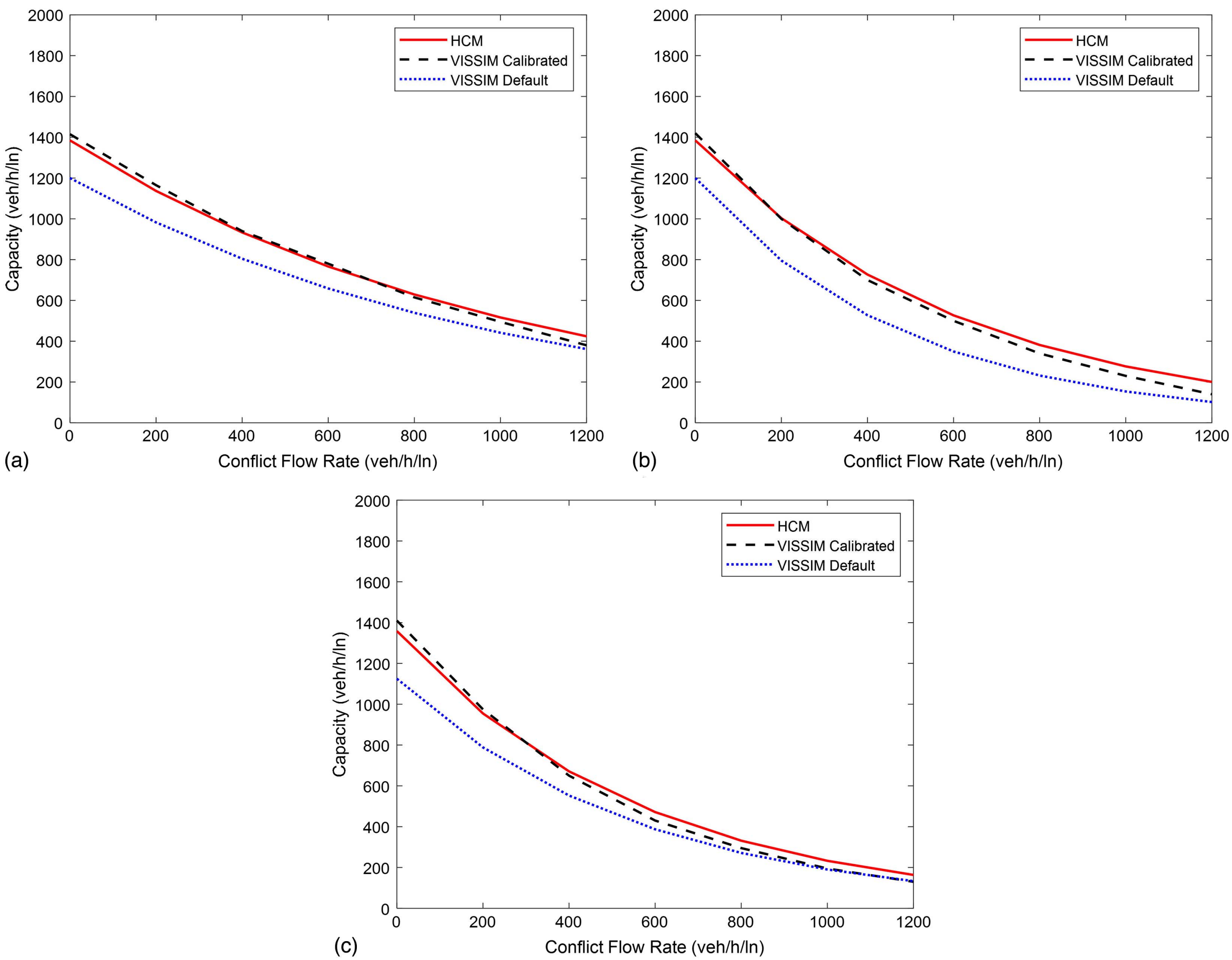

Fig. 2. Model calibration results: (a) single-lane roundabout; (b) double-lane roundabout, left entry; and (c) double-lane roundabout, right entry.

Table 1. Calibrated parameter set of conflict area in VISSIM

Model	Parameters	VISSIM default value	Calibrated value
Single-lane roundabout	FrontGapDef	0.5	0.4
	RearGapDef	0.5	0.4
	SafDistFactDef	1.5	1.3
Double-lane roundabout, left entry lane	FrontGapDef	0.5	0.3
	RearGapDef	0.5	0.3
	SafDistFactDef	1.5	1.3
Double-lane roundabout, right entry lane	FrontGapDef	0.5	0.2
	RearGapDef	0.5	0.2
	SafDistFactDef	1.5	1.2

calibration, the error between the VISSIM default capacity curves and the HCM capacity curves is much reduced.

The primary method of calibration was done by repeatedly adjusting the behavior parameters mentioned previously until a calibration goal was reached. We set the traffic demand on all analysis movements as saturated conditions. For each roundabout case, the capacity calculated by the HCM method will be compared with the simulation result collected in VISSIM when the conflicting flow rate for each lane varies from 0 to 1,200 vehicles/hour/lane (veh/h/ ln) at 100 veh/h increments of the conflict movements. According to the calibration result (as Fig. 2 shows) in the network, a comparison of VISSIM default and calibrated elements is listed in Table 1.

The three control parameters for the conflict area are defined as follows:

- Front gap default (FrontGapDef): Minimum gap time in seconds between the rear end of a vehicle in the main traffic stream and the front end of a vehicle in the minor traffic stream. Using 0.5 s as the default to adhere to the minimum gap time, the yielding vehicle slows down as it approaches the conflict area and stops in front of it, as long as the vehicle has priority in front of or in the conflict area. Once the vehicle with the right of way has left the conflict area, the yielding vehicle can enter it and no longer takes the front gap into account.
- Rear gap default (RearGapDef): Minimum gap time in seconds between the rear end of a vehicle in the minor traffic stream and the front end of a vehicle in the main traffic stream. This is the time that must be provided after a yielding vehicle has left the conflict area and before a vehicle with the right of way enters it. Vehicles are perceived within a maximum distance of up to 100 m. Default gap time is 0.5 s.
- Safety distance factor (SafDistFactDef): This factor is multiplied with the normal desired safety distance of a vehicle in the main traffic stream in order to determine the minimum distance a vehicle of the yielding traffic stream must keep when it is completely in the conflict area merging conflicts.

CAV Modeling

CACC/Platooning

The CACC car-following models developed in this study were based on a well-accepted study by Milanes and Shladover (2014), which has been previously used (Guo and Ma 2020). The lateral behaviors are modeled the same as human-driven behavior because this study focuses on the impact of the car-following behavior of CACC operations at the early stages of deployment and does not explicitly consider lane changes for platooning. Interested readers should refer to those studies for model details.

The PTV VISSIM is used in this study as the simulation platform. The VISSIM driver model dynamic link library (DLL) interface [i.e., application programming interface (API)] and component object model (COM) interface are used to realize the bundled CAV application logic. We adapted their model in VISSIM implementation to include testing various settings of intraplatoon gaps for sensitivity analysis. We also developed additional CACC protocols in VISSIM API for operations of CACC vehicles to form or leave platoons and perform lane following under various conditions.

As shown in Fig. 3, if no vehicle is in front of the subject CAV, it will apply the speed regulation mode to regulate the driving behavior. This mode keeps the subject CAV cruising with target speed to reduce unnecessary oscillations, as shown in Eq. (1) (Liu et al. 2018a)

$$a_{sv} = k_1(v_f - v_{sv}) \tag{1}$$

where k_1 = control gain of the difference between current speed v_{sv} and free-flow speed v_f; and determines the acceleration a_{sv}. The control gain k_1 is set to 0.4 s^{-1} in this study.

In the case where the front vehicle is an HDV, the subject CAV will switch to the ACC mode to regulate the driving behavior. If the subject CAV is too close to the preceding vehicle (i.e., the detected clearance distance is smaller than a given minimum following threshold), it will switch to the ACC gap regulation mode to maintain a safe following time gap, as shown in Eq. (2). Otherwise, the CAV will repeatedly implement previous control logic to ensure consistent driving behavior

$$a_{sv} = k_2(d - t_{hw}v_{sv} - L) + k_3(v_l - v_{sv}) \tag{2}$$

where $k_2 = 0.23\ \text{s}^{-2}$ and $k_3 = 0.07\ \text{s}^{-1}$ are control gains on following distance difference and speed difference, respectively. The headway d, preceding vehicle length L, and preceding vehicle speed v_l are considered in Eq. (2).

If the preceding vehicle is a CAV, the subject vehicle will switch to the CACC mode and communicate with the preceding vehicle to exchange critical information (e.g., speed, location, platoon size). If the length of the previous CACC platoon is less than the maximum allowable platoon length, the subject CAV will catch up with the preceding CACC platoon and become a platoon follower; therefore the intraplatoon gap t_2 (0.7 s in this study) is applied to tightly follow the preceding CAV. Otherwise, the subject CAV becomes a CACC platoon leader and applies the interplatoon gap t_1 (1.5 s in this study) to follow the preceding CAV. The specific regulation mode depends on the actual time gap between the subject CAV and its preceding CAV. If the time gap is larger than a given threshold (2 s in this study), the subject CAV will apply speed regulation mode, as shown in Eq. (1). Otherwise, it will apply the CACC gap regulation mode to keep a safe following distance with the determined following gap (i.e., interplatoon gap or intraplatoon gap) by implementing Eqs. (3)–(6) (Liu et al. 2018a)

$$v_{sv}(t) = v_{sv}(t - \Delta t) + k_p e_k(t) + k_d \dot{e}_k(t) \tag{3}$$

$$a_{sv}(t) = \frac{(v_{sv}(t) - v_{sv}(t - \Delta t))}{\Delta t} \tag{4}$$

$$e_k(t) = d(t - \Delta t) - t_1 v_{sv}(t - \Delta t) - L \tag{5}$$

$$\dot{e}_k(t) = v_l(t - \Delta t) - v_{sv}(t - \Delta t) - t_l v_{sv}(t - \Delta t) \tag{6}$$

where $k_p = 0.45\ s^{-1}$ and $k_d = 0.125\ s^{-1}$ are gap error control gains.

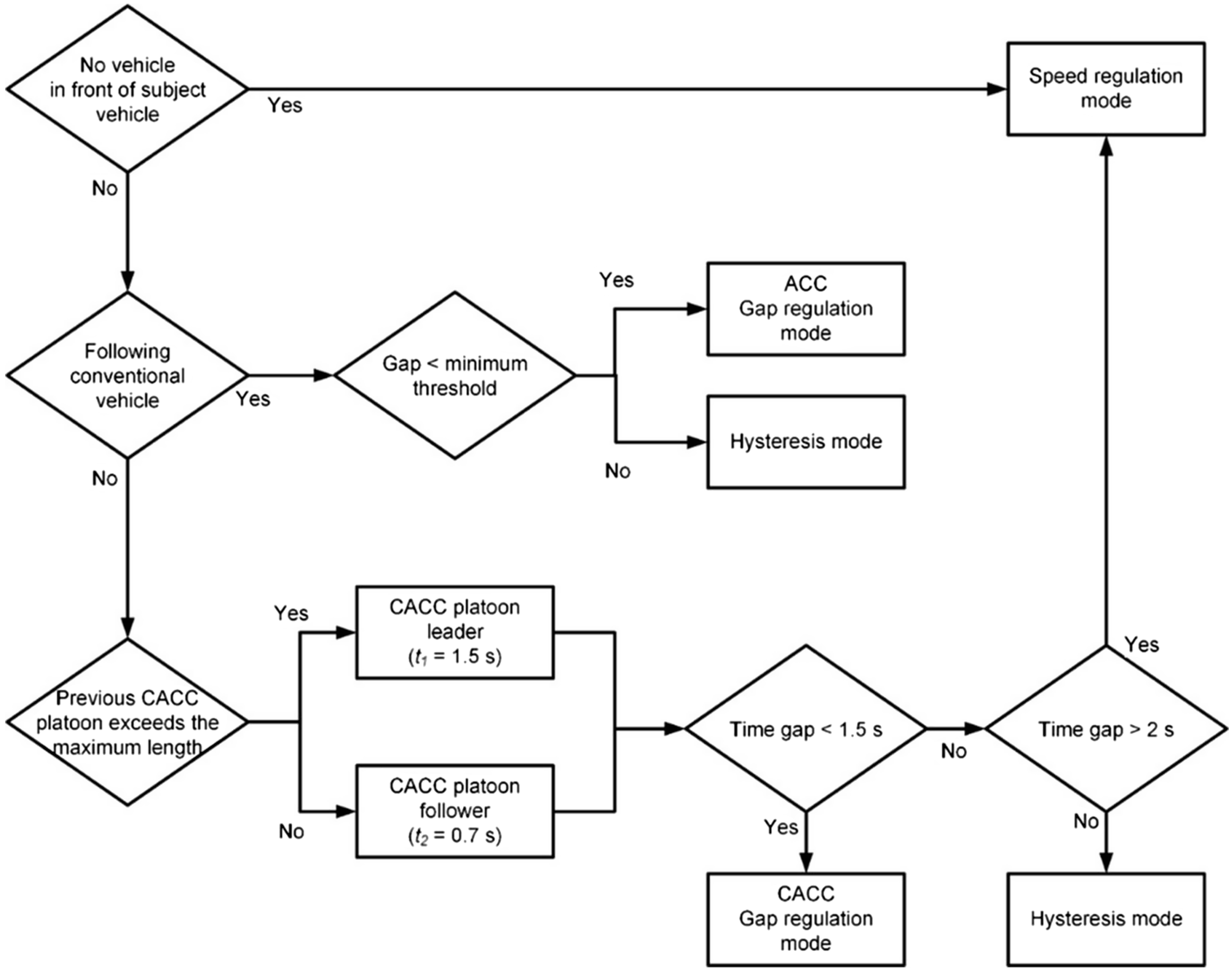

Fig. 3. CACC logic flowchart.

Due to the linearity of the aforementioned models, the vehicles cannot handle emergency braking to avoid collisions. The forward collision warning algorithm (Liu et al. 2018b) developed by the Collision Avoidance Metrics Partnership (CAMP) is included in the CACC car-following modes to determine whether the gap between the subject vehicle and the preceding vehicle is sufficient for a safe car following. If the crash warning is activated, it implies that a crash will happen if both the subject vehicle and the preceding vehicle keep their current acceleration speeds for the next few seconds.

Gap Acceptance Behavior of CAVs Near Roundabout Entrance

The major behavioral advantage of CAVs over HDVs near the roundabout entrance is the outstanding car-following behavior due to CAV platooning behavior. To ensure good platooning behavior near the roundabout entrance, we developed a CAV gap acceptance protocol in addition to the CACC control logic. This protocol allows multiple CAVs to platoon into the roundabout within the same accepted gap. The control logic is shown in Fig. 4. For a platoon of CAVs, when the CAVs are driving toward the roundabout entrance from the entry lane, the CACC protocol is combined with the gap acceptance decision to determine

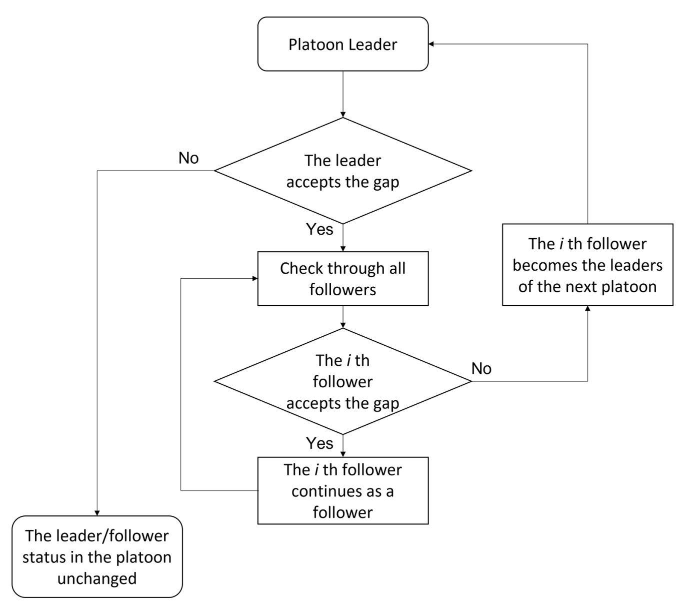

Fig. 4. CAV gap acceptance logic flowchart.

the vehicle's leader/follower status. If the leader in the platoon rejects the current gap, the platoon followers retain their status. On the other hand, if the leader accepts the current gap, then the platoon members would refresh their status sequentially as follows: (1) if the first vehicle in the remaining platoon also accepts the gap, it retains the status of a follower and keeps following the proceeding vehicle; and (2) if not, the status of the first vehicle in the remaining platoon switches to the leader and the whole determine process repeat all over again.

Gap Acceptance Data and Lane Capacity Data Extraction

Gap acceptance theory includes three basic elements: the distribution of gaps generated on the conflict flow, the utilization of these gaps, and the relative priority of the movements. More details can be found in the HCM, Chapter 20 (Transportation Research Board 2016). Critical headway and follow-up headway are considered as the reflection of the driver's behavior to the gaps generated. Critical headway is the minimum time interval in the major-street traffic stream that allows intersection entry for one minor-street vehicle (Troutbeck 2016). For the critical headway, three main statistical methods are commonly utilized in most research: the Raff method (Raff 1950), logistic regression method, and maximum-likelihood method (Kyte et al. 1996). This paper uses the Raff method as modified by Troutbeck (2016) for calculating the critical headway.

Estimation of Critical Headways and Follow-Up Headways

The Raff method is the most commonly used procedure for estimating critical headways and is a reasonable substitute with modification for the maximum likelihood method used for model development in the HCM (Troutbeck 2016). Using this graphical method, two cumulative distribution curves are drawn: one of them relates gap lengths t with the number of accepted gaps less than t and the other relates t with the number of rejected gaps greater than t. The intersection of these two curves gives the value of t for the critical gap. The estimation of the follow-up headway is a much simpler process. First, we measure the headway between consecutive queued vehicles entering the roundabout. Then the follow-up headway for each simulation run is obtained by averaging the measured follow-up headways among all the entering vehicles.

Estimation of Entry Capacity using Traffic Flow Data

The capacity of the subject entry can be directly measured by the flow data collected from the data collection points set at the end of the entering approach. To eliminate the oscillation caused by the randomness of the traffic flow, the peak 15-min flow is used to calculate the hourly rated capacity. The 2-h simulation period is divided into eight 15-min intervals and the interval with the peak flow is the maximum 15-min flow. Then the capacity is obtained by multiplying the maximum 15-min flow by four.

HCM Capacity Model Adjustment

As mentioned previously, the roundabout capacity formula in the HCM is expressed as an empirical function of the conflicting flow rate. In fact, the HCM also offers a generalized form of the formula based on the Siegloch model (Siegloch 1973) as follows:

$$C = Ae^{-B \cdot v_C} \tag{7}$$

$$A = \frac{3{,}600}{t_f} \tag{8}$$

$$B = \frac{t_c - (t_f/2)}{3{,}600} \tag{9}$$

where C = entry lane capacity (veh/h); v_c = conflicting flow (veh/h); t_c = critical headway (s); and t_f = follow-up headway (s).

The CAF is the ratio of the capacity of the evaluated scenario to that of the benchmark (CAV MPR $= 0\%$). The equation to calculate CAF can be revealed as in Eq. (10)

$$C_{\mathrm{adj}} = C \times CAF \tag{10}$$

where C_{adj} = adjusted capacity (veh/h/ln); C = base capacity (veh/h/ln); and CAF = capacity adjustment factor.

In the HCM, the base capacity is always assumed as the capacity under ideal conditions, without the impact of truck percentage, weather, or other impacts. The only variables considered in this study are conflicting flow rate (CFR) and CAV MPR. Therefore, other elements are neglected, and the base case is considered as the condition under which CAV MPR $= 0\%$ under different CFRs. Under these base cases, CAF $= 1$.

Results

Simulation Test Scenarios

In the current HCM capacity methods, the calculation of entry capacity is specified by entry lanes. The capacity of each entry lane is expressed as an empirical function of conflicting flow, i.e., the circulatory traffic flow that directly passes in front of the subject entry lane. That is to say, the single-lane roundabout, the left entry lane of the double-lane roundabout, and the right entry lane of the double-lane roundabout each own an exclusive formula to calculate the capacity.

Therefore, three basic simulation models are created for the single-lane and double-lane roundabout in this study. Because the major objective of this study is to analyze the influence of CAVs on the entry capacity, for each basic model, six variant models representing CAV MPR ranging from 0% to 100% at 20% increments are also built.

All simulation experiments performed in this research were based on simulation runs of 7,500 s (125 min) at a resolution of 10 time steps per simulation second. A 5-min warm-up period was included in each run to allow traffic to stabilize before collecting data between 300 and 7,500 s (120 min). Each run was used to obtain the entering flow under one circulating flow. A total of seven (14 for double-lane cases) conflicting flow regimes were used to generate data throughout a range of practical circulating flows, with 10 simulation runs using different random seeds per conflicting flow rate. The flow regimes start from the circulating flow of 0 veh/h. For each subsequent regime, 200 veh/h is added for both the single-lane and double-lane roundabout cases.

Effects of CAV MPR on the Entry Lane Capacities

In each of the three base case models, six CAV MPR scenarios—0%, 20%, 40%, 60%, 80%, and 100%—are tested and each generates a capacity curve. The comparison of capacity curves in different MPR scenarios are given in Fig. 5. As shown in Figs. 5(a–c), the impact of CAV on entry capacity is significant for both the single- and double-lane roundabouts. At each conflicting flow rate, the capacity of an entry lane increases remarkably with the increase of CAV MPR.

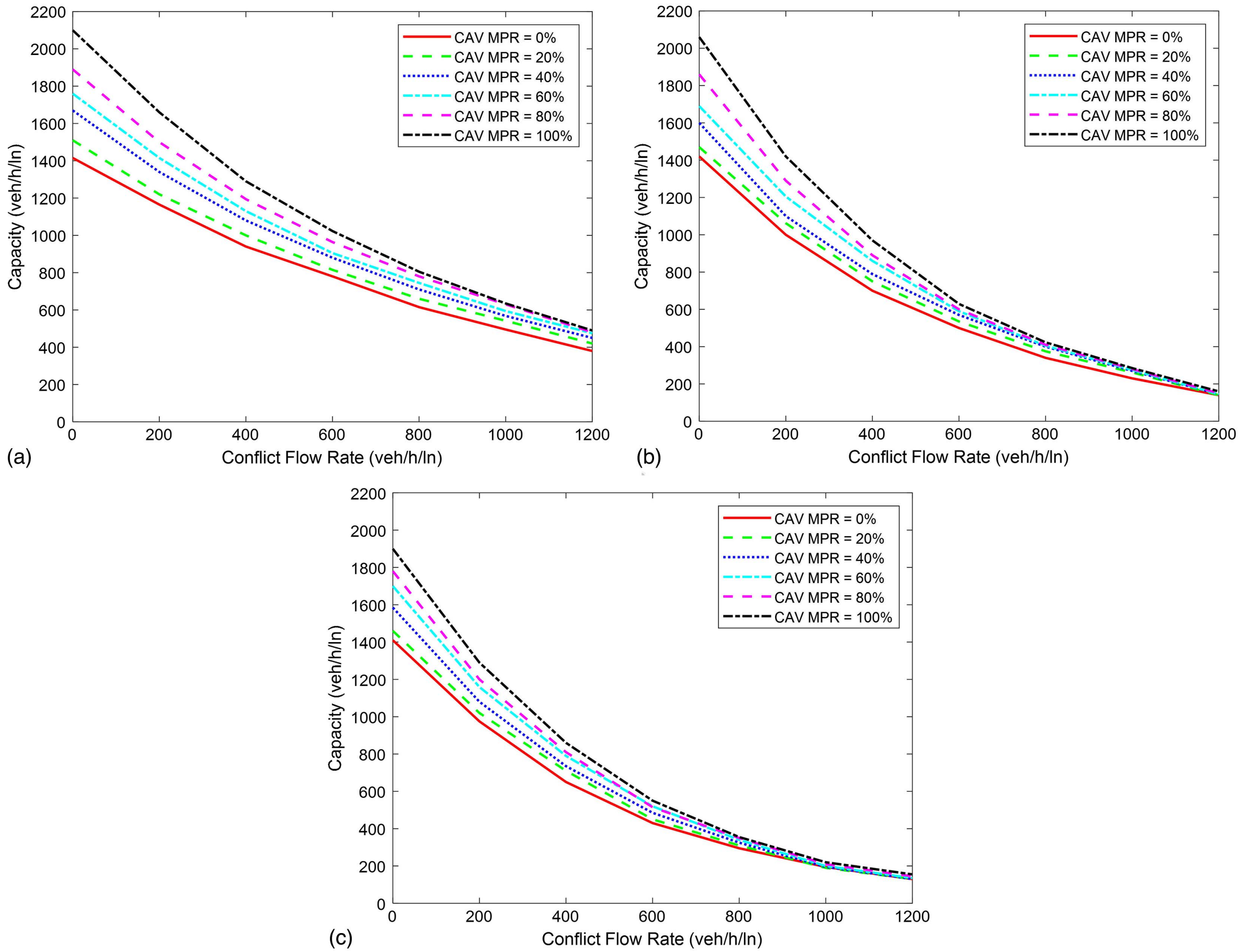

Fig. 5. Capacity curves for single-lane and double-lane roundabout under different CAV MPRs: (a) single-lane roundabout; (b) double-lane roundabout, left entry; and (c) double-lane roundabout, right entry.

Specifically, we use 0% and 100% MPR scenarios for detailed comparison. When the conflicting flow rate is 0 veh/h, the increase in capacity is 36% for the single-lane roundabout. As the conflicting flow rate rises, the capacity increase between 0% and 100% MPR becomes less significant for all three entry lane scenarios.

The same characteristics can be found in the double-lane roundabout cases in Figs. 5(b and c). As the conflicting flow rate increases, the capacity increase caused by increasing CAV MPR is less significant.

Effects of CAV MPR on Follow-Up Headway and Critical Headway

Table 2 gives the critical headway results of all analysis entry lanes under different CAV MPRs. The table shows that the CAV application has a very limited impact on the value of critical headway. It reveals that CACC can only influence the vehicles' car-following behavior at the entry, but not the acceptance of the gap itself. To test whether the impact is generated by other conflicting movements,

Table 2. Simulation results of critical headway

MPR	Single roundabout (s)	Double roundabout, left entry (s)	Double roundabout, right entry (s)
0%	4.9	4.6	4.3
20%	4.9	4.6	4.3
40%	4.9	4.7	4.4
60%	4.9	4.6	4.2
80%	4.9	4.7	4.3
100%	4.9	4.6	4.4
HCM suggestion	5.0	4.7	4.3

Table 3. Simulation results of follow-up headway

MPR	Single roundabout (s)	Double roundabout, left entry (s)	Double roundabout, right entry (s)
0%	2.6	2.7	2.6
20%	2.4	2.5	2.5
40%	2.2	2.3	2.3
60%	2.1	2.2	2.2
80%	2.0	2.1	2.0
100%	1.9	2.0	1.9
HCM suggestion	2.6	2.7	2.5

the data of three different entry lanes are collected separately, i.e., the data for each movement is collected in isolated simulations.

As for the follow-up headway, as given in Table 3, the value of each roundabout case decreases with the increment of CAV MPR. This reveals the apparent improvement of space utilization due to the more compact platooning behavior of CACC with a smaller intraplatoon gap and better car-following behavior.

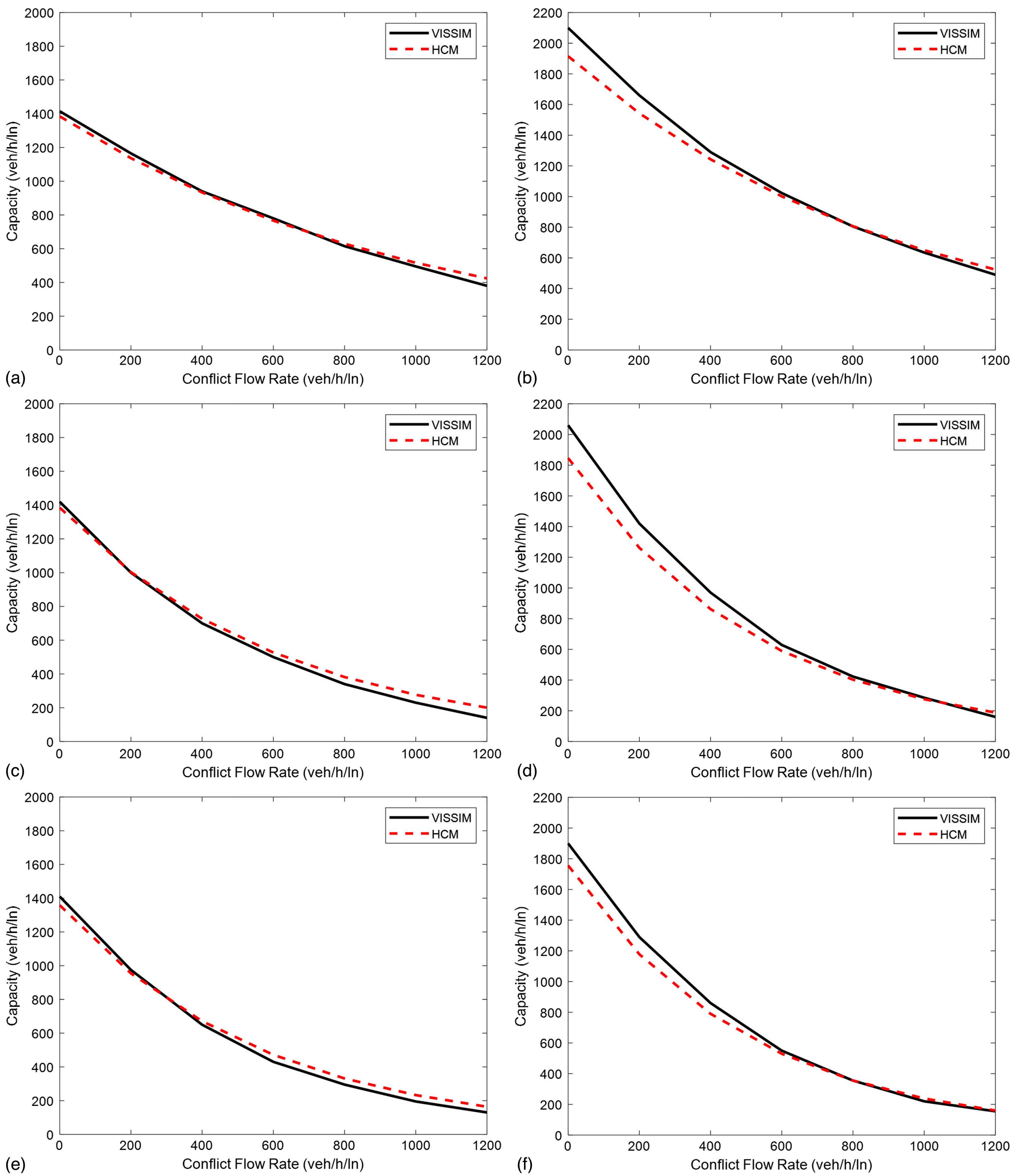

Fig. 6. Comparison between VISSIM simulation results and HCM results under different MPR: (a) single-lane, 0% CAV; (b) single-lane, 100% CAV; (c) double-lane, right entry, 0% CAV; (d) double-lane, right entry, 100% CAV; (e) double-lane, left entry, 0% CAV; and (f) double-lane, left entry, 100% CAV.

According to Eq. (7), the smaller the follow-up headway, the larger the potential capacity. In terms of headway generation, the behavior of CAVs benefits the passage of vehicles on entry lanes and the calculation of potential capacity by the HCM method.

Comparing the HCM Results with the Simulation Results

As discussed in the "Methodology" section, the HCM capacity model can be generalized as the Siegloch model by using the exponential expressions in Eqs. (7)–(9). Furthermore, the HCM capacity model in the Siegloch form can be calibrated by using two parameters: the critical headway t_c and the follow-up headway t_f. In the previous section, we measured the critical headway and the follow-up headway for each MPR scenario. Therefore, the capacity curve of each MPR scenario can be estimated using the specific t_c and t_f measured for each test case as listed in Tables 2 and 3.

In the meantime, we have measured the traffic volume for each entering lane over the 2-h simulation period in all test cases. This volume data can be converted to hourly rated capacity data using the peak 15-min flow method as described in the methodology.

To investigate the goodness of fit of the HCM estimated capacity, we compared the HCM results with the VISSIM measured results as shown in Fig. 6. The three figures on the left give the comparison between simulation results and HCM results under the 0% CAV scenario, while the three figures on the right show the comparison between simulation results and HCM results under the 100% CAV scenario. Fig. 6 shows that the goodness of fit of the two results reduces as the CAV MPR increases. Specifically, as the MPR switches from 0% to 100%, the accuracy of capacity estimation of the HCM method decreases. The deviation is especially prominent near the low conflicting flow area. When CAV MPR reaches 100%, the simulated capacity of the entry lane is significantly larger than that estimated by the HCM empirical equation. This trend is significant when conflict flow rates are below 600 veh/h/ln. When conflicting flow rates are greater than 600 veh/h/ln, the results generated by the HCM method and the simulation have a rather good fit. This variance of the accuracy of capacity estimation using the HCM method indicates that the Siegloch model adopted by the HCM cannot provide a valid prediction of the lane capacity with low conflict flow rates under high CAV MPR conditions.

CAF Results

The major objective of this study is to investigate how the roundabout entry capacity is impacted by the CAVs. The impact of CAVs on capacity is revealed by CAFs for three roundabout entries under varying CAV MPR scenarios. Table 4 gives the result of the CAFs for all the scenarios tested in the simulation. The results for the single-lane roundabout, the left entry lane of the double-lane roundabout, and the right entry lane of the double-lane roundabout are presented separately in three segments.

As given in Table 4, the entry lane capacity increases with the increase of CAV MPR. This tendency is consistent for all three roundabout cases. As the CAV MPR increases, the probability of CAVs forming into platoons at the roundabout entrance becomes larger. The entry lane capacity is therefore enhanced greatly. The improvement of capacity is more significant under low conflict flow rates, while it is less obvious under high conflict flow rates. This is mainly because the accepted gap length created by conflicting traffic gets shorter as the conflicting flow rate increase. As the gap length gets shorter, there are fewer chances that CAVs can enter the roundabout in platoons. That is, the advantage of CAVs over HDVs is largely eliminated. Another insight indicated from Table 4 is that CAVs benefit roundabout entries to varying degrees. When CAV MPR increases from 0% to 100%, the entry lane of the single-lane roundabout has the most significant improvement in lane capacity. The capacity improvement to the right entry lane of a double-lane roundabout is less than that of a single-lane roundabout, while the benefits to the left entry lane of a double-lane roundabout are the least among the three entries.

Table 4. CAF results

	Conflicting flow rate (veh/h/ln)						
MPR	0	200	400	600	800	1,000	1,200
Single-lane roundabout							
0%	1	1	1	1	1	1	1
20%	1.08	1.08	1.07	1.07	1.07	1.05	1.04
40%	1.19	1.19	1.19	1.17	1.17	1.12	1.1
60%	1.24	1.21	1.21	1.18	1.18	1.15	1.12
80%	1.3	1.27	1.27	1.24	1.24	1.22	1.2
100%	1.4	1.37	1.36	1.31	1.34	1.29	1.26
Double-lane roundabout, right entry							
0%	1	1	1	1	1	1	1
20%	1.05	1.04	1	1	1	1.03	1.03
40%	1.14	1.07	1.07	1.07	1.07	1.05	1.05
60%	1.19	1.16	1.15	1.15	1.07	1.07	1.05
80%	1.28	1.23	1.19	1.18	1.08	1.08	1.08
100%	1.39	1.31	1.24	1.19	1.1	1.1	1.1
Double-lane roundabout, left entry							
0%	1	1	1	1	1	1	1
20%	1.05	1.05	1.05	1.04	1.02	1.02	1
40%	1.14	1.11	1.09	1.05	1.03	1.02	1
60%	1.2	1.17	1.16	1.13	1.07	1.04	1.03
80%	1.26	1.21	1.18	1.12	1.08	1.04	1.04
100%	1.3	1.25	1.23	1.17	1.12	1.07	1.06

Conclusions and Future Research

This paper has introduced an approach to evaluate the impact of CAVs on the entry lane capacity of both single- and double-lane roundabouts. The impact of CAVs at different levels of conflicting flow rates and CAV MPRs are analyzed to address the limitations in the existing HCM method to handle CAVs on roundabout lane capacity. A table of CAFs is presented to show the influence of CAV on capacity. The CACC application is integrated to enhance the car-following behavior of CAVs at the roundabout entry. All the corresponding results presented in this paper are evaluated based upon the aforementioned assumptions. According to the simulation results, major findings and conclusions from this research are summarized as follows:

- With the increase of CAV MPR, the entry lane capacities of both single- and double-lane roundabouts are well improved. The benefits of increasing CAV MPR are more significant under low conflict flow conditions while less effective under high conflict flow scenarios.
- The benefits of CAVs to the entering traffic mainly come from the platooning behavior during the entering process at the roundabout entrance. By maintaining a lower car-following time gap, CAVs can utilize an accepted gap more efficiently than HDVs. Intuitively, with more CAVs, the follow-up headway of the entering flow is significantly decreased, leading to a higher lane capacity.
- The impact that CAVs have on roundabout entry lane capacity are different depending on the roundabout's configuration.

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The improvement in entry lane capacity is the most pronounced in the single-lane roundabout while least obvious in the left entry lane of the double-lane roundabout. For single-lane roundabouts, the capacity increase is significant even at high conflict flow rates. In contrast, the capacity improvement in both entry lanes of the double-lane roundabout decays significantly at high conflict flow rates.

Future work is needed in this research. More complicated scenarios with a higher resolution of conflicting flow can be integrated into future studies. Other roundabout models, such as single-entry lane against two conflicting lanes and double-entry lane against one conflicting lane, can be investigated as well. In addition, the combined effect of other types of CAV applications may be considered in future studies.

Data Availability Statement

All data, models, or code generated or used during the study are available from the corresponding author by request.

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