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Accommodation of Freeway Merging in a Mixed Traffic Environment Including Connected Autonomous Vehicles

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ABSTRACT

The use of connected autonomous vehicles (CAVs) can help reduce gaps between vehicles. However, smaller gaps may cause challenges for on-ramp vehicles merging into the freeway. This study introduces several strategies that allow on-ramp vehicles to merge safely and efficiently to the mainline by providing adequate merging gaps or resolving merging conflicts in a mixed traffic environment. Eight methods are proposed to facilitate merging. These strategies are simulated in a mixed traffic environment and with different traffic characteristics, including different proportions of CAVs. The results indicate that operational performance is affected by CAV penetration rate and traffic management strategy. For relatively low freeway traffic volume, or 100% CAV penetration rate, traffic operations under the do-nothing option performs almost as well as the best traffic management strategy. However, at lower CAV penetration rates and high freeway traffic volumes, the proposed strategies are more viable than the do-nothing option.

Keywords: Connected autonomous vehicles, freeway operation, freeway merging

INTRODUCTION

New vehicle technologies, such as autonomous vehicles (AVs) and connected autonomous vehicles (CAVs) are moving closer to market-readiness, and are expected to cause profound changes in the road transportation system (Shladover 1997). Among other features, CAVs can operate with greater precision, and smaller gaps compared to driver-operated vehicles (DVs) (Marczak et al. 2013), thus increasing roadway capacity and reducing emissions and fuel consumption (Ploeg et al. 2011; Van Arem et al. 2006). Furthermore, experts predict that these cars can reduce the adverse effects of driver behaviour, improve safety, and enhance traffic management (Fragnant and Kockelman 2015).

The Society of Automotive Engineers (SAE 2016) categorized vehicle automation into six levels, ranging from a vehicle with no-automation (L0) to fully AV (L5), where the vehicle controls all driving tasks in different traffic conditions without any driver interference. Connectivity is an added feature, allowing a CAV to exchange information with other CAVs, other road users, and road infrastructure. During the period of transition of vehicle technology, until all vehicles reach L5, vehicles with different automation levels will be present on the road network at different penetration rates.

The presence of CAVs in a mixed fleet environment during the transition period will give rise to some challenges. With shorter gaps between AVs and CAVs in the traffic stream compared to DVs, AVs and CAVs can form long platoons making lane changing manoeuvres more difficult. For example, such platoons forming on a freeway right lane (FRL) would block on-ramp vehicles from merging onto the freeway (Figure S1¹). This problem has the potential to increase conflicts and the risk of crashes at merging points.

Different strategies have been suggested in the literature to accommodate freeway merging in a fully CAV fleet environment and overcome the challenges of small FRL headway. Park et al. (2011) applied a lane-changing advisory algorithm using a connectivity system that encourages some FRL vehicles in the

¹ Supplementary Data

vicinity of the merge area to change lanes into the left lanes to create gaps large enough to accommodate merging vehicles. The simulation results for a traffic volume at level of service (LOS) C revealed that the strategy can produce around 6.4% increase in the average travel speed. Scarinci et al. (2017) applied a cooperative concept using a communication system between vehicles and road infrastructure. To release an on-ramp vehicle behind a ramp traffic signal to merge onto the mainline, the systems sends a message to FRL CAVs upstream of the merge area asking them re-arrange and increase their headways by decreasing speed to provide proper gaps for the merging vehicles. Simulation results indicated that this strategy could reduce traffic congestion on the mainline and reduce the average travel time for merging vehicles. Similarly, Karbalaieali et al. (2019) developed an adaptive algorithm in a fully CAV environment where merging vehicles can communicate with the upstream FRL CAVs to provide merging gaps by encouraging these vehicles to speed up, slow down, or change lane. The simulation results showed that using this algorithm can reduce delay for ramp vehicles and increase the travel time reliability index for the mainline. However, this merge problem has not been widely addressed in the literature for the case of a mixed traffic environment.

To accommodate freeway merging manoeuvres efficiently and safely, eight viable strategies are presented as different options for traffic management in freeway merging during the period of transition from current vehicle fleet to a fully CAV fleet. These strategies are simulated in Vissim v2020 along with the do-nothing scenario to assess the comparative operational and safety performance of all proposed strategies. It should be noted that AVs without connectivity allows drivers to set different behaviour profiles (e.g., aggressive, normal, or cautious). Although such AVs have different characteristics compared to DVs (e.g., faster reaction time), their lack of connectivity makes them similar to DVs in terms of their inability to receive or send messages. Therefore, the consideration of AVs in the simulation is essentially similar to that of DVs, where more classes of vehicles can be added to the vehicle fleet with the expected AV characteristics. Therefore, this paper considers the vehicle fleet to be composed only of DVs and CAVs. Although some strategies can be implemented by programming requirements in CAVs based on their

location, vehicle-to-infrastructure (V2I) connectivity is the main tool to communicate the commands required for CAVs to implement the proposed strategies.

METHODOLOGY

As explained earlier, this paper develops eight potential strategies for managing the merging process for a traffic environment assumed to be a mix of DVs and CAVs. Then, the traffic and safety performance of these strategies are evaluated using micro-simulation software to find the optimum strategy for each traffic condition using a specific site with characteristics that represent a typical entrance ramp as a study area. In addition, Strategy 0 (S0), do nothing, is assumed as a reference condition, where vehicle automation and connectivity would help CAVs reduce their reaction time and accept shorter gaps without any traffic management protocol on speed change lanes (SCL) or FRL. Figure 1 illustrates the eight proposed strategies, referred to as S1–S8, which are described in the following sections.

S1: Allocate Large Headway for FRL CAVs

S1 involves increasing the minimum headway between successive CAVs on the entire FRL from the normal low value that helps forming tight platoons to a headway that is large enough to allow on-ramp vehicles to merge. This large CAV headway is expected to reduce the capacity of FRL at high CAV penetration rates. S1 may be effective with freeway entrances and exits with frequent short separation distances. It should be noted, however, that large gaps between the FRL CAVs might invite DVs from the adjacent lane to shift to the FRL within these gaps.

S2: Adjust Headways of FRL CAV Upstream of Merge Area

This strategy allows CAVs to operate with their normally small headways on FRL until they approach a merge area where CAVs start to travel with larger headways to provide adequate merging gaps. This strategy minimizes capacity reduction. The headway can be increased by vehicles in FRL decelerating or performing lane-changing manoeuvres when recognizing merge locations using V2I communication or the vehicle's GPS. Once the CAVs pass the merge areas, their headway would be restored to the original lower minimum headway. However, dissolving the CAV platoons upstream the merge area may create a

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shockwave that would negatively impact the travel speed on the mainline at high traffic volumes. As in S1, DVs might change lanes to occupy the large gaps created between the FRL CAVs in this strategy.

S3: Allocate Lower Desired Speed for CAVs in Merge Areas

Like S2, this strategy aims to dissolve FRL CAV platoons, but does so by reducing the desired speed of CAVs in the merge area, which can also be achieved using V2I communication or the vehicle's GPS. When the desired speeds are reduced to a value below the operating speed of DVs before the merge area, gaps between CAV platoons and DVs will increase, providing acceptable gaps for merging vehicles. The speed difference would also induce some FRL DVs to change lane and move to a left lane if the next lane has acceptable gaps. Lower speeds would only be allocated for the FRL merge areas, and the original CAV desired speed will be reinstated after the merge area. This strategy requires the presence of both CAVs and DVs in the traffic flow to create speed differences that lead to large gaps or prompt lane changes. Therefore, S3 is not applicable for a 100% CAV penetration rate.

S4: Prohibit CAVs on FRL

In S4, CAVs are restricted from travelling in the FRL, and only DVs may travel in the FRL, with CAVs allowed only when entering or exiting the freeway. The entire FRL is set as a CAV-restricted zone except for the segment from the gore area to the end of the SCL. This scenario, however, may impact traffic flow for the other lanes at high CAV penetration rates or may cause most DVs to travel on the FRL and thus reduce the number of large gaps. Obviously, S4 can only be utilized in a mixed vehicle environment, where DVs are available to utilize the FRL.

S5: Prohibit CAVs in FRL in the Merge Area

This strategy is similar to S4, where CAVs may be restricted from travelling in the FRL in the merge area. However, unlike S4, CAVs are free to travel in the FRL before and after the merge area. This strategy requires setting a segment upstream the gore area as a CAV-restricted zone, forcing the FRL CAVs to change lane before the merge area. However, depending on the percentage of CAVs in traffic flow and the total traffic volume, not all FRL CAVs would necessarily be able to move away from the FRL,

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depending on the ability of the left lanes to absorb this traffic volume. In addition, at high traffic volume, forcing CAVs to change lane away from FRL before the merge area then returning to the FRL after the merge area may increase traffic conflicts around the merge area and reduce travel speed on the mainline.

S6: Restrict the Size of CAV Platoons

In S6, the size of CAV platoons is limited to a specific number of vehicles to prevent long platoon formation with small intra-platoon headways on FRL. The gap between successive restricted platoons would then accommodate merging manoeuvres. The maximum platoon size is set based on the on-ramp traffic volume and the required frequency of acceptable gaps on the FRL. This frequency would, in turn, depend on the freeway traffic volume and the percentages of DVs and CAVs. A V2I system can recognize the traffic volumes of the freeway and the ramp and authorize the maximum size of a platoon of CAVs. This strategy can be effective at high CAV penetration rates, where frequent large gaps would be created between frequent limited-size platoons. However, at high traffic volumes and low CAV penetration rates, the gaps between the CAV platoons will likely be occupied by DVs.

S7: Use Ramp Metering for Ramp Vehicles

In S7, a traffic signal is set on the ramp to control the flow of on-ramp vehicles. Ramp vehicles are only allowed to merge onto the freeway when an acceptable gap is available in the FRL. Since DVs do not have a connectivity system, a camera or pavement sensor can check and detect the availability of acceptable merging gaps in the FRL upstream of the ramp terminal. The location of instruments would be determined based on the average speed of freeway and travel time of ramp vehicle from the ramp traffic signal to the merging point. This strategy prioritizes traffic on the mainline and causes the least interruption to mainline traffic. Therefore, it is expected to be appropriate if the merging traffic is relatively low, while high ramp traffic volume could produce significant delays and long queues on the ramp. Another benefit of this strategy for mainline traffic is that ramp metering will reduce the probability of ramp vehicles merging at low speeds.

S8: Accommodate Merging Requests

In S8, CAVs on the ramp communicate with CAVs on the FRL to request merging. Because ramp DVs lack the connectivity required to make such a request, sensors may be required on the ramp to send the merging requests, especially at low CAV penetration rates. When a ramp vehicle requests merging to the FRL and there is no sufficient gap between the FRL CAVs, some CAVs will try to change lanes. If a lane change is not possible, the CAV platoons will try to create larger headways amongst vehicles within the platoon by accelerating or decelerating individual CAVs. In simulating this strategy, it is noted that Vissim allows courtesy merging, but it is not necessarily performed by all vehicles. In addition, Vissim does not use vehicle connectivity for traffic management. Therefore external Python script was created to set the V2I communications and the characteristics of CAVs in the platoon once a merging accommodation is requested. Similar to S1, S2, and S6, it is possible that a larger gap created in the FRL to accommodate a merging vehicle gets occupied by a DV shifting from an adjacent lane, especially in high traffic volumes.

Traffic Microsimulation

Traffic micro-simulation in PTV Vissim with external COM interface programming was performed to evaluate the performance of each strategy. Vissim v2020, used in this paper, was capable of directly simulating all strategies using internal parameters except for S7, which required developing a signal control logic using VisVap, and S8, which required a COM interface to process the merging requests and command CAVs to accommodate them.

The simulation results were analyzed to assess the efficiency of each strategy based on traffic performance measures, including travel time and the traffic volume that cannot be accommodated by the road segment. In addition, the percentage of vehicles with low merging speed (VLMS) was extracted as a surrogate safety measure to identify potentially unsafe merging manoeuvres. The VLMS percentage was estimated as the percentage of merging vehicles that slow down on the SCL to merge onto the freeway below a specific speed threshold. This behaviour is generally not expected for drivers who attempt to

accelerate while merging onto the FRL, and the potential for collisions is expected to increase with the increase of VLMS.

All eight strategies plus S0 (do-nothing) were simulated. Traffic parameters affecting the traffic operation include:

- Traffic volume:
 - Different freeway traffic volumes were selected for simulations based on the threshold of LOS D and E. These thresholds were calculated as 2,100 and 2,400 pc/h/ln in accordance with the Highway Capacity Manual (HCM, 2016). In addition, as the capacity of freeway segments is expected to increase with increasing CAV penetration rate, a 20% increase in LOS E threshold, resulting in a volume of 2,880 pc/h/ln, was selected as a new LOS, named E*.
 - Two values of ramp traffic volumes (400 and 1,300 pc/h) were selected to correspond to high and low merging volumes on the main freeway within the City of Ottawa, Canada, used as the study area for this paper (Ahammed et al. 2008).
- The design speed of the freeway is 110 km/h.
- Preliminary results indicated that performance is not very sensitive to changes in ramp design speed. Therefore, ramp design speeds of 40 and 80 km/h were used to provide a wide range for possible design ramp speeds.
- Four different CAV penetration rates were considered: 25, 50, 75, and 100%. The 0% CAV penetration rate was also considered in S0 (do-nothing) to represent current conditions as a basis for comparison.
- Three traffic arrival types based on random simulation seeds (22, 32, and 42) were selected in the simulation runs.

Consequently, 48 different scenarios (3 freeway volumes $\times$ 2 ramp volumes $\times$ 2 ramp speeds $\times$ 4 CAV penetration rates) were simulated for each strategy except S3–S5. As explained earlier, the 100% CAV penetration rate was not relevant to these latter strategies. For S3–S5, only 4 CAV penetration rates were simulated resulting in 36 scenarios. An additional 0% CAV penetration rate was simulated for S0,

resulting in a total of 180 simulation runs corresponding to 60 different scenarios for S0. Therefore, a total of 1,224 simulation runs corresponding to 408 simulation scenarios were performed in this study.

Study Site

Highway 417 is the main freeway within the City of Ottawa, Canada, with a posted speed limit of 100 km/h. The freeway on-ramp from St. Laurent northbound to Highway 417 westbound (**Figure 2**) was used as a typical ramp entrance in this study. The ramp terminal comprises a loop ramp and a 295-m tapered SCL. As the SCL length matches the TAC (2017) design guidelines, the results of the study should be applicable to many similar locations. It should be noted that the ramp design is controlled by the ramp design speed and is reflected in the vehicle operating speed on the ramp and beginning of the SCL. By taking the ramp design speed as a variable in the simulation scenarios, the results would not be restricted to the loop ramp design of the study site. Finally, there are six freeway lanes at the selected site (three per direction), and it is expected that increasing the number of lanes will not have a significant effect of the generality of the results.

As shown in **Figure 2**, the study section was divided into six segments for simulation strategies:

- The first is 5.2-km long and ends 900 m before the ramp area to provide enough distance for a minimum of four CAVs to form a platoon. The length was calculated based on a 35 pc/mi/ln (22 pc/km/ln) density at LOS D, with an average headway distance of approximately 46 m.
- The next three segments are also upstream of the SCL and function as a space to manage CAV traffic behaviour and change the minimum headway or desired speed depending on the selected management strategy. These segments are further explained in the following section.
- The fifth segment, which is 295 m long, is along with the SCL.
- The sixth segment is downstream of the SCL and is 500 m long—slightly longer than the HCM recommendation for merge influence area of 450 m (HCM, 2016). This distance allows CAVs to resume their original driving behaviour.

SIMULATION REQUIREMENTS

To simulate the proposed strategies, the default traffic behaviour parameters in the simulation software were calibrated based on the study by Wang and Gu (2019) and local traffic behaviour. Also, as explained earlier, S7 and S8 required external programming for traffic management. This section explains all requirements implemented to run the simulations for this study. Each simulation was run for one hour following a 15-minute warm-up period.

Vehicle and Driver Behavior Characteristics

This study considered only passenger cars in the simulations and parameters to be calibrated for DVs or predicted for CAVs. The distribution of vehicles' lengths was selected based on the distribution of vehicles' models representing the top 31 selling vehicles in Canada over a 12-month period between February 2018 and 2019. Together, these vehicles account for almost 56% of total Canadian vehicle sales in this period, while each of the remaining 240 vehicles accounted for less than 1% of sales. Based on the lengths of these vehicles, vehicles in the simulation were categorized into seven groups as shown in Table S1².

The minimum reaction time and headway for DVs, 0.5 and 1.0 s, respectively, were selected based on the work of Taieb-Maimon and Shinar (2001). For CAVs, Ploeg et al. (2011) noted that a minimum headway within a CAV platoon can be less than 0.5 s when the wireless link is optimized. The 0.5 s value was used as the minimum CAV headway for this study. The driving behaviour of DVs and CAVs was modified to allow for courtesy merging in the simulation.

The desired speed on the mainline lanes of this study area for DVs was chosen based on the speed distribution of the sample collected from UAV videos (Figure S2²). A normal speed distribution was assumed for ramp vehicles, with the mean and standard deviation for the design speeds (40 and 80 km/h) estimated based on a previous study on Highway 417 (Fatema and Hassan 2013).

² Supplementary data

Traffic Management in S7 and S8

As explained earlier, S7 uses ramp metering to allow on-ramp vehicles to merge onto the freeway when an appropriate gap is detected in FRL. This control strategy was built in simulation using VisVAP, a user-friendly tool to define signal control logic using the vehicle actuated programming language. The flowchart created for S7 in VisVAP causes the ramp traffic signal to open when the detector on FRL detects a minimum gap of 0.8 s (equivalent to 1.0 s headway), allowing a single vehicle to pass and complete a merging manoeuvre. The minimum 0.8 s gap was determined to be optimal by trial-and-error.

A collaborative merging model was developed for simulating S8, which uses vehicle connectivity to send a merge request and provide an acceptable gap for the merging vehicle in a mixed traffic environment (Figures S3 and S4³). This model was translated to a COM interface program using Python.

Management of Traffic Behavior on FRL

Depending on the control strategy selected, some vehicle parameters are varied on FRL compared to the other freeway lanes (cross-sectional variation) and/or at the merge area compared to upstream and downstream of the merge area (longitudinal variation). To avoid shockwaves, longitudinal variations of vehicle parameters on the FRL are introduced gradually within different segments upstream the merge area (as described in Table 1). The assumed values in Table 1 are explained as follows:

- A selected headway of 2.0 s for S1 and S2 can be an acceptable gap for CAVs at an average speed of 100 km/h based on a CAV lane change model and the laws of kinematics.
- An acceptable headway of 2.0 s for the merge area on FRL can be provided for S3 by a 9 km/h speed differential between DVs and CAVs within 900 m at an average CAV speed of 100 km/h.
- In S5, a 600-m segment is required to allow a high CAV volume to switch lanes before the merge area. Shorter segments will not allow CAVs to safely change lane without creating shockwaves.
- The platoon size for ramp traffic volumes of 400 and 1,300 pc/h was assumed as follows:

³ Supplementary data

- The average headway for a traffic volume of 400 pc/h is 9.0 s, which means there should be an available gap for merging vehicles every 9.0 s on the FRL. Based on the average car length and operating speed on the freeway, a platoon of 14 vehicles can provide sufficient gaps to accommodate ramp vehicles.
- The average headway for a traffic volume of 1,300 pc/h is 2.77 s; thus, the size of the platoon on the FRL is assumed to be two vehicles.
- The headway detector in S7 was placed 190 m from the gore point to allow ramp vehicles to build enough speed to merge with FRL vehicles.
- A 200 m segment was used in S7 to prevent right lane changes to prevent disturbances in headway detection. Any vehicles that merge onto the FRL after the detector cannot be detected.
- A 600 m segment before the merge area is required in S8 to allow CAVs to decide whether they need to accelerate, decelerate, or switch lanes without causing shockwaves. The length is also required for CAVs to switch lanes safely.

Collecting Simulation Data

Detailed vehicle trajectories containing the values of different variables such as speed and travel lane are collected every 0.5 s for each vehicle in the simulations. In addition, data are collected for travel time for each vehicle along a 2,300 m segment of the freeway (1,600 m before and 700 m after the gore point) and on the 895 m length of the ramp (195 m before and 700 m after the gore point). As mentioned earlier, the average travel time for both the mainline and ramp vehicles and the percentage of merging vehicles with merging speed below a specific threshold (VLMS) were selected as performance measures to evaluate and compare the traffic operation and safety of the different strategies. Finally, the difference between the traffic volume assigned upstream the merge area and the actual number of vehicles counted downstream the merge area serves as a measure of unaccommodated traffic demand. This measure, referred to as the drop in road capacity, is estimated for each simulation run.

RESULTS AND DISCUSSION

This section summarizes the main findings based on the average results for the three seed numbers for each simulation scenario.

Average Ramp Travel Time

Figure 3 presents the results of average travel times for ramp vehicles for all strategies (S0–S8) simulated with ramp design speed 40 km/h at LOS D, E and E*. The main findings observed are:

- In general, at LOS D, most strategies had similar ramp travel times, with the values almost independent of CAV penetration rate. In this scenario, S3 had noticeably higher ramp travel time regardless of ramp traffic volume. S7 was expected to increase ramp travel time, and that trend was confirmed for low freeway traffic volumes, with almost all other strategies outperforming S7.
- As freeway traffic volume increases, differences between scenarios become more pronounced, especially in cases with high ramp traffic volume. Even in these cases, as the CAV penetration rate increases, the ramp travel time generally decreases, and all strategies ultimately converge to a narrow range of ramp travel time at 100% CAV penetration. This occurs because CAVs can use smaller gaps to merge. In addition, 100% CAV penetration increases the number of vehicles in CAV platoons and the frequency of large headways between these CAV platoons. It is also noted that as freeway traffic volume increases, S7 starts to perform better than other strategies.
- At LOS E and E* with high ramp traffic volume, S2 outperforms other strategies for ramp travel time, S2 also outperforms S1 at high ramp traffic volumes, as the CAV desired headway on FRL is restored to a low value after the merge area in S2. This reduction in desired headway can help reduce the travel time for merging vehicles, which do not have to adjust their behaviour if they stay on the FRL.
- AT LOS E* and 25% CAV penetration rate, most strategies show better results than S0. However, with increasing ramp traffic volume and CAV penetration rate, only S2 and S5 outperform S0. S1 and S3, which impose more restrictions on the CAVs in the FRL even after the merge area, do not perform as

well as S2 and S5, as in the former strategies, merging vehicles must adapt their behaviour to restrictions beyond the merge area.

- S4 and S5 were expected to have the lowest ramp travel times, as the FRL would be free from platoons with small intra-headways around the merge area, but the results of simulation show that this was not the case. This phenomenon may be due to the increased DV volume in FRL to balance the traffic volumes on all mainline lanes in S4. As the CAV penetration rate increases, the ramp travel time in S4 decreases, as fewer DVs are available in the traffic stream to occupy the FRL. But this improvement in ramp travel time is likely at the expense of higher travel time for freeway traffic. For S5, the conflicts resulting from CAVs shifting back to the FRL after the merge area may reduce the FRL operating speed. Creating another segment for the FRL after the merge area where CAVs are not allowed to switch back for a certain length might enhance the performance of S5.
- In high traffic volume conditions, the minimum DVs headway of 1.0 s is not adequate for merging vehicles, and there are not enough acceptable gaps among DVs. However, in S5, which aimed to prevent CAVs on FRL only in the vicinity of the merge area, DVs do not have enough time to switch lanes onto the FRL to re-balance traffic lanes in the vicinity of the merge area, so there are fewer DVs on FRL and more acceptable gaps than in the S4 scenario.
- Increasing the design speed of the ramp from 40 to 80 km/h resulted in slightly lower travel time for ramp vehicles in most scenarios.

Average Freeway Travel Time

Figure 4 summarizes the results of average travel time for freeway vehicles (referred to as freeway travel time) for a ramp design speed of 40 km/h. Similar to ramp travel time, most strategies had very close results for freeway travel time at LOS D, with the values almost independent of CAV penetration rate. Again, S3 had noticeably higher freeway travel time regardless of the ramp traffic volume, which is expected given the reduction in CAVs' desired speed on the FRL.

- Again, the differences between scenarios become more pronounced as the freeway traffic volume increases, especially when high ramp traffic volume is also present. Even in these cases, as the CAV penetration rate increases, freeway travel time generally decreases, and all strategies ultimately converge to a narrow range of freeway travel time at 100% CAV penetration apart from some strategies at LOS E*.
- At LOS D and E, S8 slightly outperforms other strategies for mainline vehicles. This may not be an expected outcome, but the small difference between most strategies do not appear substantial and may not indicate an actual trend.
- For high freeway traffic volume (LOS E*), different strategies seem to be favourable at different CAV penetration levels.
- Generally, S7 has the lowest freeway travel time because ramp metering prioritizes travel on the freeway mainline lanes. For example, for LOS E*, 1,300 pc/h ramp volume, and 25% CAV penetration rate, S7 produces the lowest ramp and freeway average travel times with a difference of over 170 s when compared to S0 for the ramp travel time (an approximately 45% reduction) and 80 s for the freeway travel time (48% reduction). However, not all on-ramp vehicles were able to merge due to the queue building up behind the traffic signal, and at high ramp traffic volume and LOS E*, approximately 60% of the ramp vehicles (780 out of 1,300 vehicles) were not able to merge onto FRL.
- The generally worst performing strategies were S1, S3, and S5. S1 performed poorly overall, especially at a CAV penetration rate of 25% with high ramp traffic volume, which may have resulted from the need for FRL CAVs to keep adjusting their speed to maintain the 2 s minimum headway when a ramp vehicle merges onto the FRL. S5 had the worst results at LOS E* and high CAV penetration rate, due to the congestion created by the shifting of CAVs to the freeway middle and left lanes. S4 offered better freeway travel time results on high traffic volumes than S5 because there are fewer lane-changing conflicts.

Drop of Road Capacity

As mentioned earlier, the drop in road capacity was estimated as the difference between the traffic volume assigned upstream of the merge area and the actual number of vehicles counted in the simulation downstream of the merge area. Table 2 summarizes the simulated results of the percentage drop in capacity for both the freeway mainline lanes and the ramp. For each combination of LOS on the freeway mainline and ramp traffic volume, the maximum drop in capacity for CAV penetration rates of 25% and 50% is shown as the value for low CAV penetration (L), while the maximum value for CAV penetration rates of 75% and 100% is shown as the value for high CAV penetration (H). Higher capacity drops are experienced with low CAV penetration.

Vehicles with Low Merging Speed

As noted earlier, the percentage of VLMS is analyzed as a surrogate safety measure to assess the relative safety performance of the proposed strategies. Low merging speed or speed reduction at the merging point is an unexpected driver behaviour that creates a potentially unsafe high-speed differential between the merging vehicle and other vehicles on the FRL. Therefore, a high percentage of VLMS is expected to indicate a poor merging strategy.

Figure 5 illustrates the percentage of VLMS for a ramp design speed of 40 km/h. The threshold for these graphs is a merging speed of 30 km/h. The main observations from these graphs can be summarized as follows:

- Similar to travel time results, most strategies had very close results of VLMS at LOS D, with the exception of S3.
- In almost all scenarios, the worst-performing strategy was S3, with the difference more pronounced at high ramp traffic volumes. Most other strategies performed slightly better than S0. At 100% CAV penetration rate, all strategies show similar results.
- In general, most ramp vehicles were able to merge with a speed higher than the selected threshold of 30 km/h in S7, as the ramp metering in this strategy allowed merging only when an acceptable gap was

detected in the FRL. The released ramp vehicle was able to utilize the SCL to speed up before merging into the available gap.

- For LOS E and E*, a spike in VLMS is noted for most strategies depending on the traffic volumes on the freeway and ramp, including S0 at 25% or 50% CAV penetration. For most strategies, this spike diminishes at 100% CAV penetration. This trend matches the trends of ramp and freeway travel times, which also spike for some strategies at low CAV penetration, then decrease when the whole vehicle fleet is CAVs.
- At high traffic volume (LOS E*), many strategies are noticeably more favorable than S0. For example, for ramp traffic volume of 400 pc/h, S1, S2, S5, and S7 have at least 5% lower VLMS compared to S0. This difference is approximately 60% for S2 and 55% for S1 and S7 at 25% CAV penetration.
- Proposed strategies S2 and S7 can reduce VLMS by approximately 75% at LOS E* and a ramp traffic volume of 1,300 pc/h, including 75% CAVs.
- S8 at LOS E* and 400 ramp traffic volume with a 50% CAV penetration rate shows high VLMS value compared to S0. This is due to the relatively high volume of DVs on the FRL that do not receive a merging request and do not adjust behaviour to accommodate this request.

General Notes

It is believed that an increase in CAV adoption or penetration rate would increase road capacity (Fragant and Kockelman 2015). However, at high traffic volumes (more than the current threshold of LOS E), the presence of CAVs at relatively low penetration rates (up to 50%) can create traffic congestion at merge areas and reduce travel speeds for both ramp and freeway vehicles. As shown in Figures 3 and 4, both ramp and freeway vehicles experience a spike in travel time at a 25% CAV penetration rate with high freeway traffic volume (LOS E*) if no traffic management is applied. This spike diminishes as the CAV penetration rate increases.

Based on the results of freeway and ramp travel times, the do-nothing alternative (S0) can be acceptable for LOS D and E. However, S0 may lead to safety issues at LOS E with high ramp traffic

volumes when the CAV penetration rate is low (up to 50%). For LOS E* and a CAV penetration rate below 100%, a management strategy should be adopted to improve travel time and safety. The best strategies that can be implemented for different combinations of traffic volumes and CAV penetration rate are summarized in Table 3.

CONCLUSIONS

It is widely expected that CAVs will have very short reaction times, allowing them to form platoons with minimal gaps. While this travel pattern is expected to increase road capacity, it will cause complications for vehicles merging from on-ramps to freeways. Eight different strategies were proposed to create acceptable merging gaps on the FRL or to resolve the expected merging conflicts. The simulations of these strategies were tested with different CAV penetration rates, mainline LOS, and ramp volumes. Different measures of performance were compared including average travel time, unaccommodated demand on the freeway mainline and ramp, and percentage of ramp vehicles that merge below a specific speed threshold (VLMS).

The results indicate that operational performance is affected by the CAV penetration rate and the traffic management strategy implemented. For relatively low freeway and ramp traffic volumes, the do-nothing strategy (S0) performs well in terms of all performance measures considered. If traffic volumes increase beyond LOS E, other strategies become more viable, especially during the period of the vehicle fleet transition with a CAV penetration rate is below 100%.

Platoon dissolving strategies are effective at low ramp and freeway traffic volumes. However, ramp metering expectedly has the lowest freeway travel times, with the differences more pronounced for high traffic volumes. However, as this strategy prioritizes the mainline traffic flow, the ramp vehicles might get heavily congested due to the traffic signal queue. Utilizing vehicle connectivity to process merging requests in S8 generally outperforms other strategies at LOS D and E in terms of travel time of freeway vehicles, which is comparable with previous studies (Park et al. 2011; Scarinci et al. 2017; Karbalaieali et al. 2019).

The 2.0 s desired headway for CAVs in S1 and S2, and between successive platoons in S6, is assumed based on a freeway operating speed of 100 km/h. However, at high traffic volumes of LOS E or E*, the operating speed drop under 100 km/h, and the 2.0 s headway may not be sufficient for merging vehicles. One solution could be to set the desired headway in these strategies using a dynamic method that calculates the desired headway based on the measured freeway operating speed. However, increasing the desired headway because of reduced operating speed can further aggravate the congestion when the CAVs reduce their speeds to maintain the higher desired headway, and would increase the probability of more DVs changing lanes within these relatively large headways.

The traffic microsimulation completely does not assess the safety of operation. In this paper, the percentage of VLMS was used as a surrogate measure of safety for many reasons. Future work should also evaluate safety performance with another surrogate measure, such as the probability of non-compliance, which correlates with collision frequency at freeway entrance ramps (Fatema and Hassan 2013).

Finally, this study considered a freeway segment with only one merging ramp. These travel conditions are close to those of rural freeways, where the ramp density is low enough for the traffic at one interchange not to be affected by disturbances at the previous interchange.

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Table 1. Segment accommodations for simulation strategies

Strategy	Segment 2 (300 m)	Segment 3 (300 m)	Segment 4 (300 m)	Note
S1	h_{min} for segment 1, 2, 3, 4, and 450m after segment 5 is set to 2.0 s.			After gore area, along with segment 5 and 450m after that the h_{min} for FRL is set to 0.5 s. h_{min} for other freeway lanes is set to 0.5 s.
S2	Increase h_{min} from 0.5 to 1.0 s	Increase h_{min} from 1.0 to 1.5 s	Increase h_{min} from 1.5 to 2.0 s	Gradually dissolving CAV platoon on FRL upstream the merge area. After gore area, 0.5 s h_{min} is restored
S3	Reduce max. desired speed of CAVs by 3.0 km/h	Reduce max. desired speed of CAVs by another 3.0 km/h	Reduce max. desired speed of CAVs by another 3.0 km/h	Gradually increase speed differential between CAVs and DVs upstream of the merge area. After the merge area, the speed differential will be removed.
S4	CAVs are not allowed to use FRL upstream the gore area			At the merge area, merging CAVs will merge into FRL and use it until they have chance to change to the freeway middle lane.
S5	CAVs use the FRL as a travel lane	CAVs are not allowed to travel on the FRL		After the merge area, CAVs can use the FRL as a travel lane.
S6	Max. platoon size is set to 14 vehicles for ramp traffic volume of 400 pc/h, while for ramp traffic volume of 1300 pc/h, max. platoon size is set to 2 vehicles.			The gap between CAV platoons is set to 1.8 s, an acceptable gap for merging vehicles.
S7	700 m: no accommodations		200 m: no left lane changes are allowed into the FRL.	Headway detector was located 190 m before gore point on FRL and traffic signal was located 20 m before gore point on the entrance ramp.
S8	No accommodations	600 m: CAVs can receive merging requests & decide to decelerate, accelerate, or switch lanes to provide an acceptable gap for merging vehicles.		A merging vehicle can request for an acceptable gap from CAVs on FRL, based on the communication system.

Table 2. Drop in freeway mainline and ramp capacity (ramp design speed 40 km/h)

Mainline LOS	D				E				E*			
Ramp traffic volume (pc/h)	400		1300		400		1300		400		1300	
CAV penetration	L	H	L	H	L	H	L	H	L	H	L	H
S0	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	4/6	6/-	8/46	-/3
S1	-/-	-/-	-/-	-/-	-/-	-/-	-/23	1/-	6/-	-/-	12/23	16/6
S2	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	1/-	-/-	11/24	-/-
S3	-/-	-/-	1/-	-/-	-/-	-/-	-/47	-/2	11/1	-/-	14/57	12/22
S4	2/-	-/-	-/-	-/-	-/-	-/-	-/5	-/-	7/5	-/-	11/45	4/7
S5	-/-	-/-	-/-	-/-	-/-	-/-	-/14	-/-	5/3	5/-	13/38	9/8
S6	-/-	-/-	-/-	-/-	-/-	-/-	-/2	-/-	7/-	15/-	12/38	13/36
S7	-/-	-/-	-/39	-/37	-/-	-/-	-/50	-/44	5/2	-/-	6/65	-/58
S8	-/-	-/-	-/-	-/1	-/-	-/-	-/6	-/1	5/6	-/-	11/45	1/41

Low and high CAV penetration refer to rates of up to 50% and greater than 50%, respectively; numbers in each cell are the percentage of capacity drop for mainline/ramp; values < 1% are replaced with “-”.

Table 3. Summary of feasible strategies for different traffic conditions

Mainline LOS	D		E		E*	
Ramp traffic volume	Low	High	Low	High	Low	High
(a) Based on freeway travel time.						
Low CAV%	S1, 2, 4, 5, 6, 7 & 8	S2, 5, 7 & 8	S1, 2, 4, 5, 6, 7 & 8	S2, 7 & 8	S2, 6 & 7	S7
High CAV%			S1, 2, 6, 7 & 8		S7 & 8	S2 & 7
(b) Based on ramp travel time.						
Low CAV%	S8			S2	S1, 2, 5 & 6	S1, 2, 5, 6 & 7
High CAV%					S2, 5 & 8 (after CAV 75%).	S2
(c) Based on freeway capacity drop						
Low CAV%	S1, 2, 3, 5, 6, 7 & 8	S1, 2, 4, 5, 6, 7 & 8	S1, 2, 3, 4, 5, 6, 7 & 8	S1, 2, 3, 4, 5, 6, 7 & 8	S2	S7
High CAV%	S1, 2, 3, 4, 5, 6, 7 & 8			S2, 3, 4, 5, 6, 7 & 8	S1, 2, 3, 4, 7 & 8	S2 & 7
(d) Based on ramp capacity drop						
Low CAV%	S1, 2, 3, 4, 5, 6, 7 & 8	S1, 2, 3, 4, 5, 6 & 8	S1, 2, 3, 4, 5, 6, 7 & 8	S2	S1, 2, 3, 5, 6 & 7	S1, 2, 4, 5, 6 & 8
High CAV%		S1, 2, 3, 4, 5 & 6		S1, 2, 4, 5 & 6	S1, 2, 3, 4, 5, 6, 7 & 8	S2
(e) Based on VLMS						
Low CAV%	S1, 2, 4, 5, 6, 7 & 8	S1, 2, 5, 6, 7 & 8	S1, 2, 5, 6, 7 & 8	S1, 2 & 7	S1, 2, 5, 6 & 7	S1, 2, 6 & 7
High CAV%	S1, 2, 4, 5, 7 & 8	S1, 2, 6, 7 & 8	S1, 2, 4, 5 & 7	S2, 6, 7 & 8	S1, 2, 5 & 7	S2, 4, 6 & 7

Low and high CAV penetration refer to rates of up to 50% and greater than 50%, respectively.

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Figure 1 Configuration of proposed strategies

Figure 2 Plan of the study site (Maps data: Google © 2021 CNES Airbus Maxar Technologies)

Figure 3 Average travel time for ramp vehicles (40 km/h ramp design speed)

(a) LOS D, ramp volume 400 pc/h.

(b) LOS D, ramp volume 1,300 pc/h.

(c) LOS E, ramp volume 400 pc/h.

(d) LOS E, ramp volume 1,300 pc/h.

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(f) LOS E*, ramp volume 1,300 pc/h.

Figure 4 Average travel time for freeway vehicles (40 km/h ramp design speed)

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Figure 5 Percentage VLMS, speed threshold of 30 km/h (40 km/h ramp design speed)