Evaluation of Merging Behavior of Connected and Automated Vehicles at On-ramps

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Abstract: Merging of vehicles at on-ramps leads to significant delay and is a safety concern. With the tremendous progress in vehicle automation and connectivity over the last few years, connected and automated vehicles (CAVs) are expected to address these concerns. In this study, we evaluate the merging behavior of CAVs at on-ramps in a typical expressway in Japan using a traffic microsimulation software (VISSIM). The simulation was conducted for different volumes of mainline traffic and merging traffic. Also, the percentage of CAVs was considered to be 0%, 50% and 100%. The effect of the presence of CAVs was determined based on the average delay of the vehicles passing through the intersection. We found that the presence of CAVs reduced delay significantly for high volume of traffic (about 4000 veh/h) and did not have an effect during low traffic volumes.

Keywords: Merging, simulation, traffic flow, connected vehicles, automated vehicles.

1. INTRODUCTION

Merging is the process in which different streams of traffic combine to form a single stream of traffic. This typically happens at roundabouts, ramps, and at lane-reduced sections. Merging of vehicles at intersections is a complex process (Hidas 2002, 2005). This is because the merging process involves interaction between the vehicles travelling at different speeds and acceleration levels. During the merging process, the vehicles adjust their speed and join together into one stream. Usually, in cases where merging happens between a major road (higher priority) and a minor road, the vehicle from the minor road waits for a suitable gap in the major road traffic before merging with the major road. Thus, the merging process requires significant attention from the drivers of the merging vehicles.

With the rapidly advancing research in vehicle automation and communication technologies, connected and automated vehicles (CAVs) are expected to be widespread in the next 5-10 years (Fagnant and Kockelman, 2015; Kyriakidis et al., 2015; Bansal and Kockelman, 2017). CAVs are capable of controlling and maneuvering the vehicle on their own using vehicle-to-vehicle and vehicle-to-infrastructure communication systems. This would limit the role of a driver to a large extent. Some of the latest models of cars already have inbuilt driver assistance systems which could steer the vehicle on uninterrupted sections of expressways. However, the feasibility of CAVs to manoeuver safely at intersections which involves considerable interactions between different vehicles in unknown.

One of the main arguments supporting CAVs is the increase in the safety of the road users (drivers, passengers, and pedestrians) (Rios-Torres and Malikopoulos, 2017). Several studies indicate that the majority of the road accidents can be attributed to human errors including driver inattention (Hancock et al., 2001; Beanland et al., 2013; Carney et al., 2018). Beanland et al. (2013) studied the crashes from 2000 to 2011 using data from the Australian National Crash In-depth Study to investigate the role of driver distraction and inattention. The study found that the majority of the serious injury crashes involved driver inattention which was preventable. Thus, if all the vehicles are CAVs, accidents can be reduced significantly.

Although, CAVs are capable of steering the vehicle at straight and uninterrupted sections, intersections pose a significant challenge due to higher interactions between the vehicles approaching the intersection (van Beinum et al., 2018). Thus, the effect of CAVs on the safety and efficiency of the merging process is unknown.

2. LITERATURE REVIEW

This section reviews some of the relevant research on merging of vehicles at on-ramps.

Scarinci et al. (2015) developed a system called Cooperative Merging Assistant that grouped main carriageway vehicles together and collected the spaces between vehicles that are used by merging traffic. This system provided a coordinated entry of platoons of vehicles released from an on-ramp signal. The performance of this system was evaluated using microscopic simulation. The study found decrease in congestion and increase of merging capacity due to the use of the proposed cooperative system.

Ntousakis et al. (2016) developed and presented a longitudinal trajectory planning methodology to assist the merging of vehicles on highways. The objective of the methodology was to ensure safe and traffic-efficient merging, while reducing engine effort and passenger discomfort. The authors formulated the problem as a finite-horizon optimal control problem and solved it analytically.

Park et al. (2011) developed an enhanced IntelliDrive enabled lane changing advisory algorithm using a variable gap size concept to address freeway merge conflicts. The developed algorithm calculates anticipated lead-lag gap sizes using the equations of motion. Then, a lane changing advisory is provided to freeway main-line vehicles to create space in the merging area. The proposed algorithm was evaluated using a simulation model developed in VISSIM. The study reported a 6.4% higher average speed in the freeway main line due to the reduction in merge conflicts after adopting the proposed algorithm.

Letter and Elefteriadou (2017) presented a longitudinal freeway merging control algorithm assuming all the vehicles are fully automated connected vehicles with an objective to increase the average speed of all the vehicles in the freeway. A road side controller was assumed to communicate with the merging vehicles and transmit optimized trajectories to the vehicles entering the merging area. The vehicle simulation software CORSIM was used to generate the merging vehicles and the optimization software LINGO was used to solve the optimization problem generated at each time step. The study found reduction in travel time, increase in average speed and throughput due to the implementation of the proposed merging algorithm.

Thus, the objective of this research was to determine the efficiency of the merging process at a typical merging section of an expressway for the case of CAVs. We simulate a typical merging section of an expressway in Japan using VISSIM microsimulation software. We propose two scenarios for the merging process and test their performance based on average speed and delay time. The results of this study would help in providing insights for field deployment of CAVs at merging sections.

3. METHODOLOGY

Figure 1 shows the network used in the simulation for this study. The network consists of three sections (A, B, and C). The lengths of section A, section B, and section C are 1 km, 0.7 km, and 1 km respectively. Section A is the road section before the merging, section B is the section where merging takes place and thus is provided with an additional lane for the merging vehicles to accelerate before entering the main lanes. Finally, section C is where the merged vehicle moves similar to the vehicles in the mainline. The mainline consists of two lanes and is assumed to be a straight section.

The distribution of the running speeds of the simulated vehicles on the expressway is shown in Figure 2. The desired speed is the speed at which the drivers want to travel and is usually close to the speed limit of the expressway. We see that as the traffic volume increases, velocity decrease and hence delay increases. Moreover, all the simulated vehicles were passenger cars and heavy vehicles were not considered.

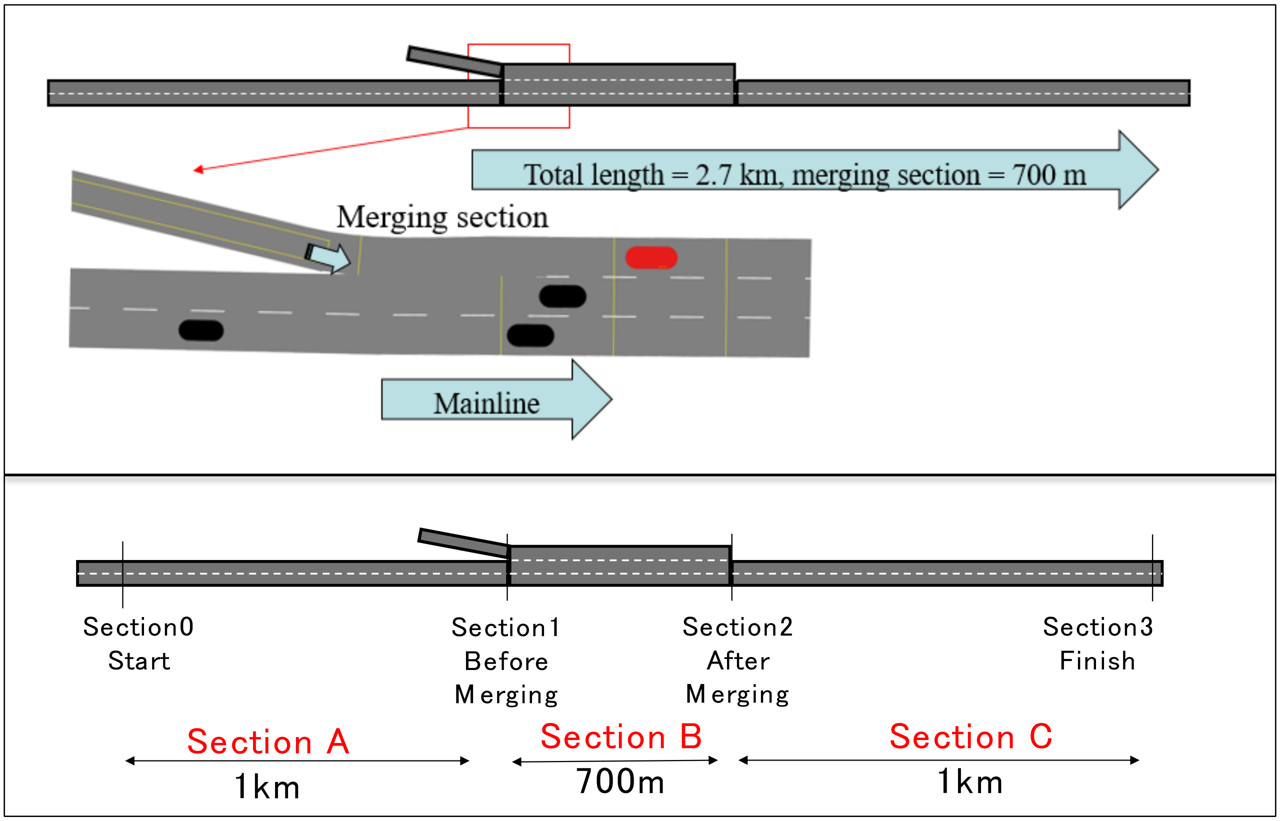


Figure 1. Simulation network used in this study

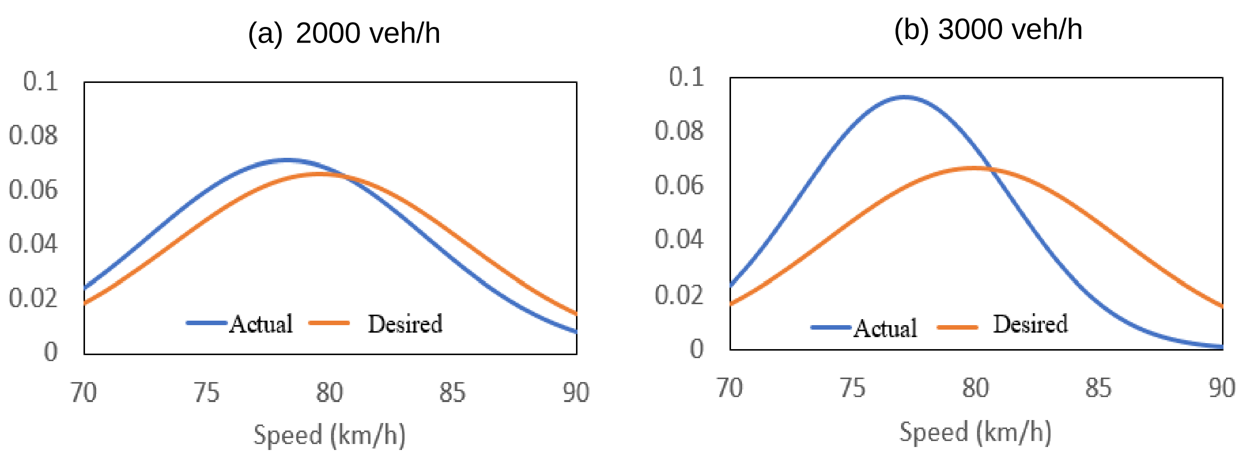
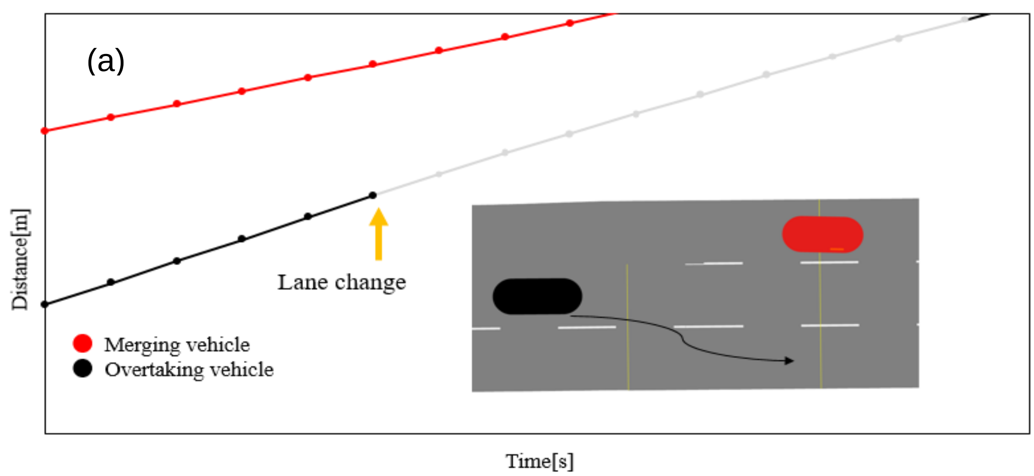


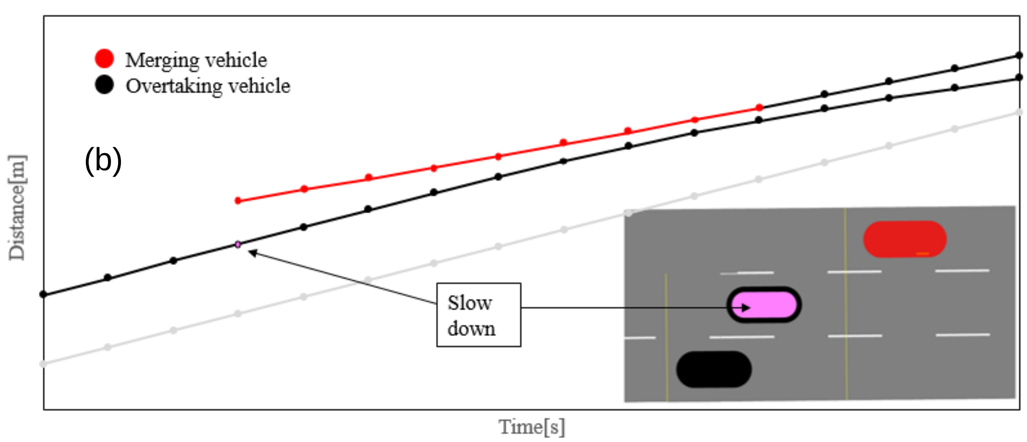
Figure 2. Distribution of running speed on the expressway

The Driver Model interface was used to adjust the running speeds of vehicles on the lanes. Through Driver Model interface, an external program can communicate with the traffic flow models within VISSIM. In our study, the interface uses computer program in C++ programming language to determine the speeds of the vehicles at the mainline and the merging section. The attributes such as the desired speed of the vehicles can be controlled by using the Driver Model interface. In addition, the C++ script can be run at the beginning of the simulation or at fixed intervals during the simulation process.

The Driver Model in VISSIM was used to control the acceleration of the connected vehicles. The main concept to determine the acceleration of the connected vehicle is to maintain the desired distance between the connected vehicle and the lead vehicle. The distribution of the speeds of vehicles is varied from 70 to 90 km/h. When running speed of the connected vehicle is about 90 km/h, the driver model attempts to keep the desired distance. This means the Driver Model orders the connected vehicle to slow down. Then, the delay under the connected conditions becomes greater than that under un-connected conditions.

Figure 3 shows the different kinds of interactions between the mainline vehicle and the merging vehicle. One of the possibilities for the mainline vehicle is to change lanes to avoid delay due to the merging vehicle. This is possible if the mainline vehicle is on the lane away from the median and there is no vehicle in the lane near the median. In Figure 3(a), the mainline vehicle changes lane to avoid the merging vehicle. It is also possible for the mainline vehicle to slow down and allow the merging vehicle to shift to the main lanes. In Figure 3(b), the mainline vehicle slows down to allow the merging vehicle to merge safely. Besides, in case the merging vehicle is far away from the merging area, the mainline vehicle can accelerate to prevent delay due to the merging vehicle. In Figure 3(c), the mainline vehicle accelerates to avoid delay due to the merging vehicle.





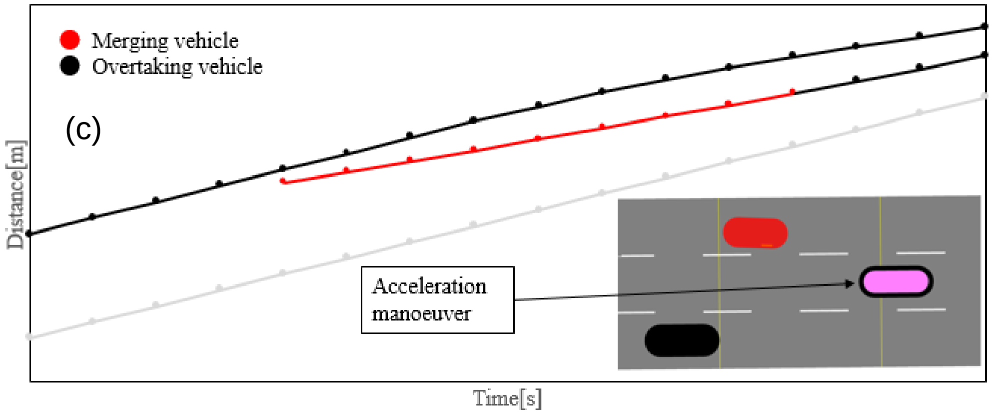


Figure 3. Different interactions between merging vehicle and mainline vehicle

We developed three scenarios for the simulation based on the volume in the mainline. The three volumes considered were 1000 vehicles/hour, 2000 vehicles per hour, and 3000 vehicles/hour. Also, ten simulation runs were conducted for each of the scenarios and we took the average of the delay of all the simulation runs. The volume of the merging vehicles was considered to be either zero, 10%, or 30%. Thus, we varied both the volume in the mainline and the volume of vehicles merging into the mainline.

4. RESULTS

Table 1 shows the speeds of the vehicles at the four positions – Section 0, Section 1, Section 2, and Section 3. At the merging section, the average speed of the vehicle decreases. Also, Table 2 presents the distance between the vehicles for different traffic volumes. We see that as the traffic volume increases, the distance between the cars decreases substantially. In addition, if we compare section wise, the distance between the cars is lowest at the merging section (Table 3).

Table 1. Running speed as a function of merging ratio at the four positions

	Section	Section 0 (start 100m)	Section 1 (before joining)	Section 2 (Concluding Merging)	Section 3 (End of merging)
Average speed [km/h]	No merging	76.25	74.78	77.58	77.15
	Merging 1	76.25	74.77	73.71	77.09
	Merging 3	76.25	74.77	70.62	76.78

Table 2. Traffic volume and average distance between the cars

Mainline traffic volume	1000 vehicles/h	2000 vehicles/h	3000 vehicles/h

Average number of vehicles	164.4	333.9	503.7
Distance between the cars (m)	78.4	75.2	49.7

Table 3. Average distance between two cars as a function of merging ratio at the four positions

	Section	Section 0 (start 100m)	Section 1 (Before joining)	Section 2 (Concluding Merging)	Section 3 (End of merging)
Distance between the cars (m)	No merging	50.66	49.44	49.36	-
	Merging 1	50.66	48.33	43.66	-
	Merging 3	50.66	47.57	35.76	-

Figures 4, 5 and 6 show the total delay time (in seconds) at the sections A, B and C. The vehicular volumes in the mainline is 1000, 2000 and 3000 vehicles/hour for the three figures. From figure 4, we can see that as the total volume in the mainline increases, the total delay increases substantially. Also, for the same given volume, section C has higher delay compared to sections A and B.

Figures 4, 5 and 6 compares the delay times for 0%, 50%, and 100% penetration of CAVs in the traffic stream. Since CAVs will not reach 100% penetration overnight, this comparison is important. On comparison, we observed similar patters as for the conventional vehicles, i.e., higher delays at section C as compared to sections A and B. Moreover, the delay times increased with increase in the percentage of merging vehicles. For a particular section, the delay was highest in the case of 30% merging vehicles.

However, we did not observe significant reduction in delay times in the 100% CAV case as compared to the 50% CAV case. We found significant reduction in delay time only when the volume was 3000 vehicles/h and 30% of the traffic was merging. Thus, at low traffic volumes, the effect of connected vehicles is not significant in reducing delay times.

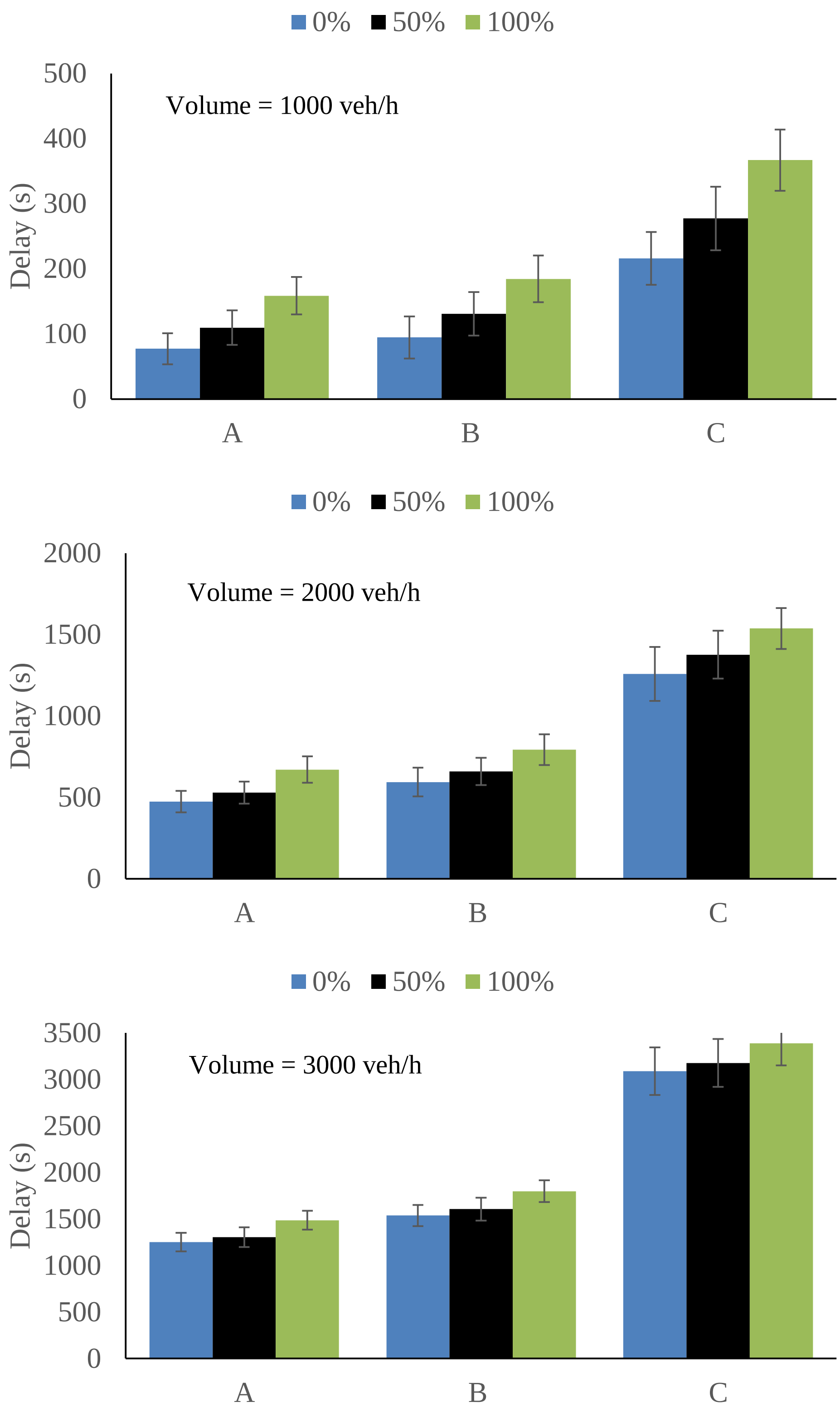


Figure 4. Total delay time (in seconds) at sections A, section B, and section C for zero percent merging vehicles

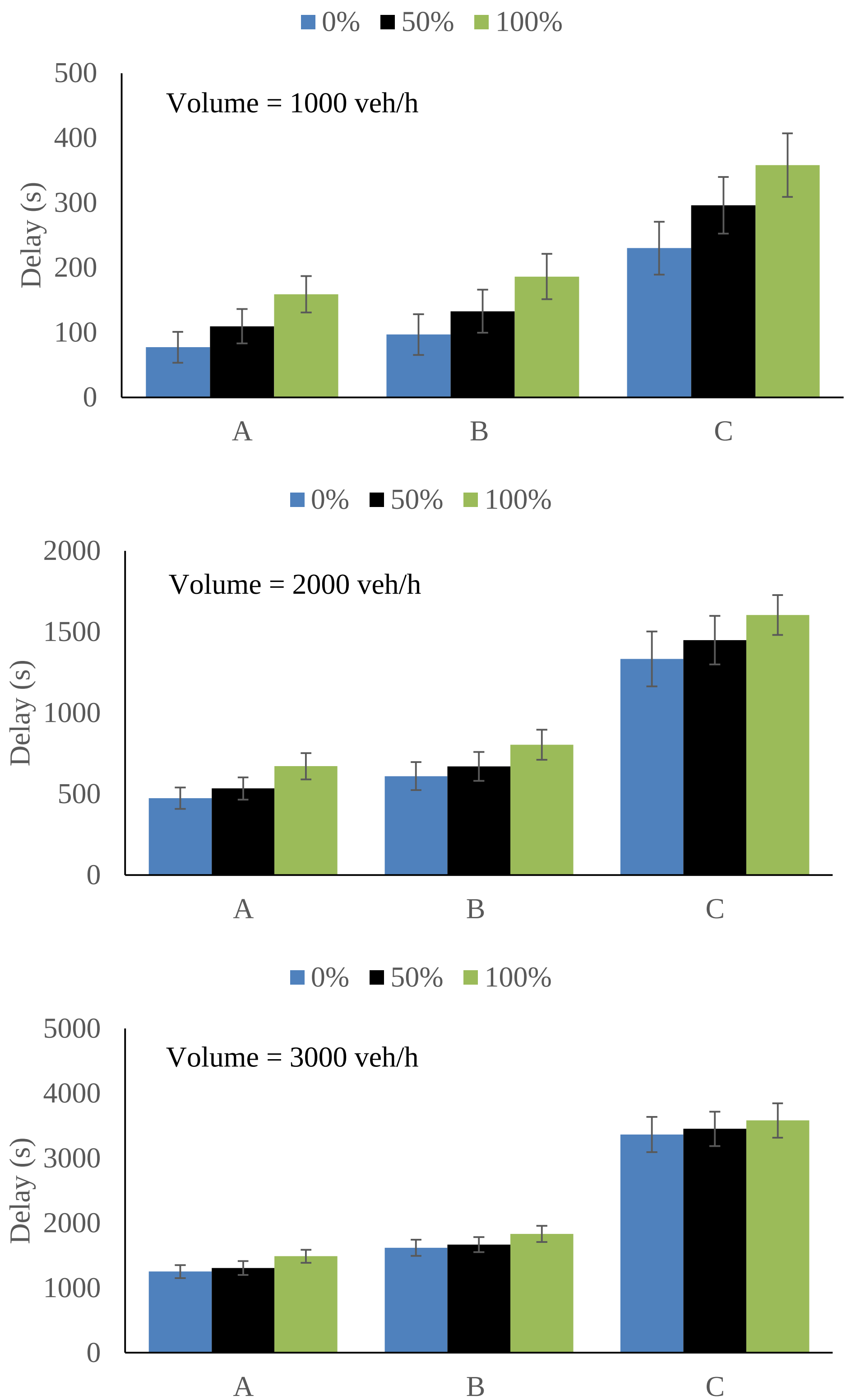


Figure 5. Total delay time (in seconds) at sections A, section B, and section C for 10 percent merging vehicles

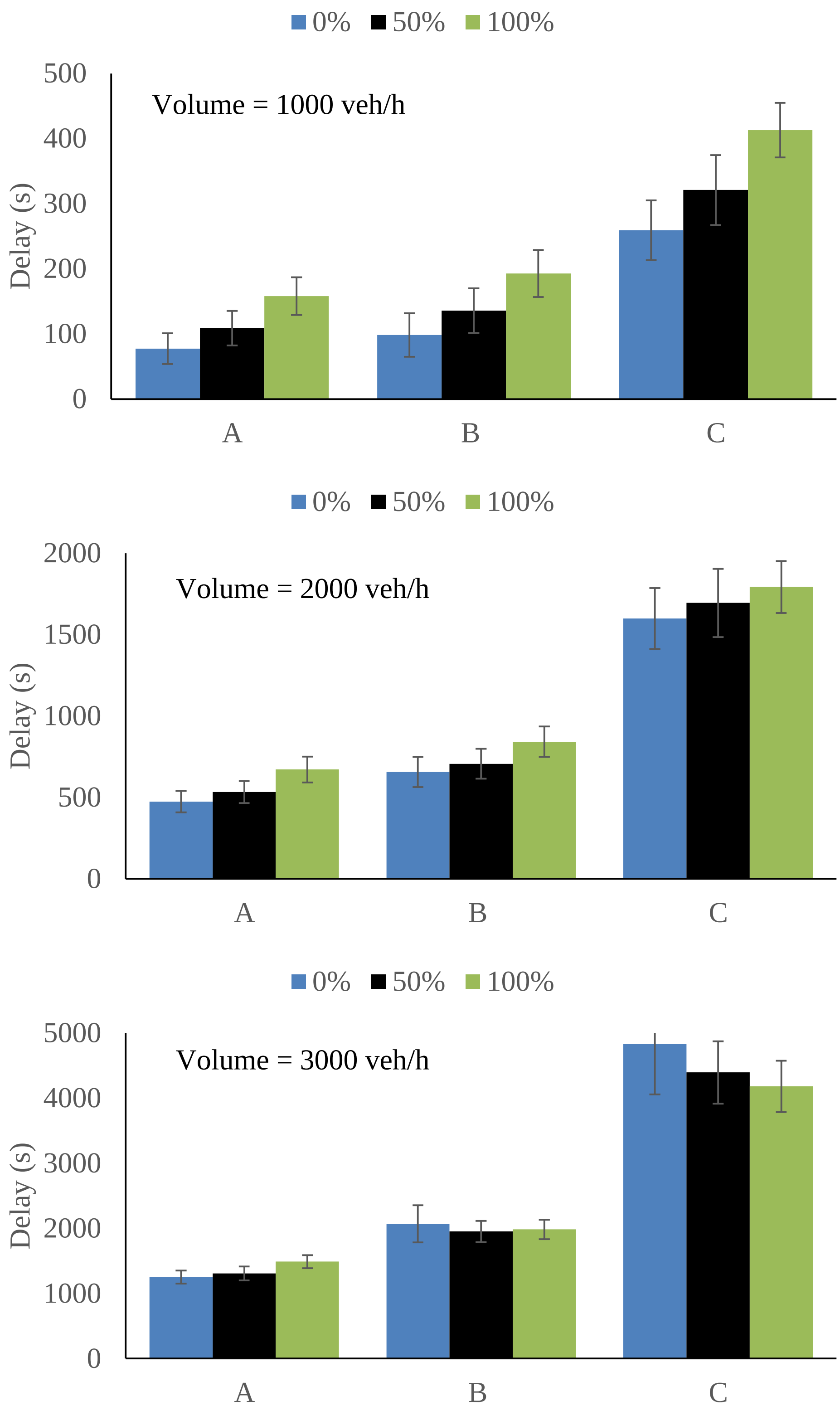


Figure 6. Total delay time (in seconds) at sections A, section B, and section C for 30 percent merging vehicles

5. CONCLUSIONS

In this study, we simulated a merging section of a freeway in the presence of connected and automated vehicles (CAVs). The simulation was conducted considering different traffic volumes, different volumes of merging vehicles, and for various penetration levels of CAVs. The driver model in VISSIM was used to simulate the vehicles as the driver model can control the acceleration and deceleration of the vehicles accurately. For simulating the connected vehicles, the default control system in the driver model was used. We observed that as the mainline traffic volume increased, the running speed in the merging section decreased and the distance between the vehicles became shorter. From the simulation results, we observed that at low traffic volumes, the effect of connected vehicles is not significant in reducing delay times. The effects of connected vehicles on delay became prominent under congested conditions. Also, the delay time increased with increase in the mainline and merging traffic. However, the results of this study are limited to passenger cars only. Further research is necessary to understand the effect of different composition of vehicles (including motorcycles and heavy vehicles) on the merging behavior.

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