

Effect of dynamic route guidance on urban traffic network under Connected Vehicle environment

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Although Connected Vehicle technology is developing rapidly, connected vehicles (CV) are going to mix with the traditional vehicles (i.e., non-connected vehicles) for a long time. The effects of deploying CV on urban traffic systems are actually not clear. The main objective of this study is to evaluate the potential effects of route guidance under connected vehicle environment on an urban traffic network in terms of traffic mobility and safety. Microscopic simulation approach is used to conduct CV environment simulation and the rolling horizon approach is used for information updating among the connected vehicles. Meanwhile, driving behavior is modeled through aggressiveness and awareness of drivers. Traffic mobility for the road network was measured by average trip time and average vehicle trip speed. A surrogate measure, i.e., the time-to-collision involved incident rate for one kilometer driven, was used to assess the safety of the road network. Based on a real urban traffic network, the impacts of market penetration levels of connected vehicles and information updating intervals were studied. Simulation results showed that market penetration level of connected vehicles has little impact on the mobility and safety of road network. In addition, according to the simulation conducted in this paper, shorter updating interval is shown to be likely to lead to better mobility, while the safety of road network is likely to decline, under the assumptions embraced in the simulation. By contrast, the

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simulation also showed that longer updating interval is likely to lead to better safety and decreased mobility.

Keywords: *connected Vehicle, driving behaviors, dynamic route guidance, traffic mobility, traffic safety, vehicle-to-vehicle communication.*

1. Introduction

Connected Vehicle (CV) technology is a rapidly growing paradigm shift in transportation that aims to develop and deploy connected transportation systems in order to promote road safety and mobility (Olia et al., 2016; Ubiergo and Jin, 2016). CV technology has the ability to enable vehicles to “talk” to one another. Using wireless communication technologies, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication can be realized through collecting, transmitting, and receiving all kinds of information such as vehicles’ position, velocity, origin/destination, trajectory, and travel time. As such, V2V could dramatically reduce the number of fatalities and serious injuries caused by accidents on the roads and highways; meanwhile, it also promises to reduce travel times. To this end, dynamic route guidance could be further exploited to seek time-dependent traffic assignment that satisfies the Wardrop equilibrium principles (Wardrop, 1952), i.e., user equilibrium or system optimal (USDOT, 2013; Lee et al., 2017; Hoang et al., 2018).

CV offers a promising means through dynamic route guidance to improve road network mobility and safety, by adjusting the driver behavior in the routing process. The mobility of road network is the overall efficiency of the road network, which can be measured through average trip time or average trip speed of all the vehicles on the road network. Before CV technologies emerged (e.g., advanced driver assistance systems, in-vehicle information systems, and intelligent co-operative systems), previous studies showed a close relationship between driver behavior and mobility (Peeta and Mahmassani, 1995; Yang and Meng, 2001) and a relationship between driver behavior and safety (Robertson and Baker, 1975; Jonah, 1986; de Winter and Dodou, 2010). The former relationship was mainly affected by the application of route guidance. For the latter, almost all traffic accidents which happen in urban areas were directly or indirectly caused by improper driving operations, which can be easily influenced by tendencies for anger or anxiety as well as by temporary emotions (Reason et al., 1990; Parker et al., 1998; Shinar and Compton, 2004; King and Parker, 2008). Therefore although driving assistance technologies developed have significantly improved traffic safety, the behaviors of drivers themselves are essential for traffic safety (Shinar and Compton, 2004; Young et al., 2011; Birrell et al., 2014). Therefore, it is worth to explore the impact of applying dynamic route guidance under CV environment on road network.

Since CV technology has not been widely used in reality, many researchers and engineers have adopted microscopic simulation approach to access the impacts of CV technologies on road network. As an important implementation of CV technology, applying the route guidance in a large area has the potential of improving the mobility and safety of road network under various traffic conditions, such as work zones (Olia et al., 2013; Genders and Razavi, 2015) and random incidents (Kattan et al., 2010). While, in a small area, CV technology can also improve the intersection operation efficiency (Lee et al., 2013) and average lane speed (Tian et al., 2016). Considering the application of CV technology, there are two important factors which are market penetration level of connected vehicles and information updating intervals. For the V2V, the information updating interval is defined as the time gap between two successive information exchange between connected vehicles through wireless communication, which determines the communication frequency between connected vehicles. Almost all of the aforementioned research considered the market penetration levels of connected vehicles. However, the information updating intervals among connected vehicles received little attention.

The objective of this paper is to investigate the effects of route guidance through deploying connected vehicles on an urban traffic network in terms of both traffic mobility and safety. The CV environment is constructed to realize V2V communication based on traffic microscopic traffic simulation. Driver behaviors were modeled in terms of driver awareness and aggressiveness. Different simulation scenarios were used to assess the effects of connected vehicles on traffic mobility and safety. Performance of mobility was measured by the average trip time (ATT) and average vehicle trip speed (AVS). Performance of safety was reflected by a surrogate measure, i.e., the time-to-collision involved incident rate (TTC-IR) for one kilometer driven. The remainder of this paper is organized as follows. The next section includes a literature review. Then, a description of the simulation environment and driver behaviors is presented. Afterward, simulation experiment was designed and conducted. Finally, the paper summarizes the research findings and provides recommendation for further research.

2. Literature review

2.1 Market penetration levels of connected vehicle

It is reported that CV market penetration in the US was 9.33% in 2016 and is expected to reach 27.66% in 2020, and around 98% of the US fleet is likely to have connectivity in 2030 (Bansal and Kockelman, 2017; Mostafizi et al., 2017). For a long time, the number of connected vehicles is going to increase, they will mix with the traditional traffic flow in urban traffic systems, and they have to incorporate the complexity of urban traffic systems under various kinds of traffic conditions. Based on this consideration, multiple equilibrium behaviors were employed to model the potential impacts of connected vehicles, for instance, a mixed user-equilibrium (UE) for connected vehicles and stochastic user-equilibrium assignment (SUE) for vehicles unequipped with CV technology were employed to model the potential effect of market penetration levels of connected vehicles (Yang et al., 1999; Yang and Meng, 2001; Yin and Yang, 2003). In these studies, sensitivity analysis was used to estimate the CV benefits over a wide range of market penetration levels. Recent decade, many studies have focused on modeling CV applications and assessing their benefits through microscopic traffic simulation approaches (Kattan et al., 2010, 2012; Paikari et al., 2014, 2013; Genders and Razavi, 2015; Dey et al., 2016; Jia and Ngoduy, 2016; Luo et al., 2016).

Many simulation studies have demonstrated the effectiveness of deploying connected vehicles under various environmental conditions. Kattan et al. (2010, 2012) employed PARAMICS to conduct simulation environment for assessing the impact of connected vehicles in a network with incidents and adverse weather conditions, and network travel time was improved at high and moderate congestion levels. Genders and Razavi (2015) used PARAMICS to evaluate the potential safety benefits of developing a CV system on traffic network in the presence of work zone, finding that under 40% market penetration of connected vehicles contributes to a safer traffic network. Tian et al. (2016) proposed a lane-speed monitoring application based on V2V communication to estimate real-time traffic states at the lane level. A comprehensive simulation study demonstrated the effectiveness of this application, including safety, mobility, and environmental impacts, under various scenarios. Olia et al. (2016) focused on micro-simulation modeling and demonstrated the potential of connected vehicles to improve mobility, enhance safety, and reduce greenhouse gas emissions at the network-wide level. The results also showed quantitatively how market penetration of connected vehicles proportionally affects the performance of the traffic network. Mostafizi et al. (2017) developed both analytical and simulation models to investigate the effects of market penetration and connection range of connected vehicles on the mean travel time of a traffic network. Overall, the magnitude of CV benefits depends on different market penetration rates of connected vehicles.

2.2 Information updating intervals among connected vehicles

CV technology can provide real-time information for connected vehicles on route selection. From the perspective of traffic system operations, a traffic control center seeks to specify paths to network users in real time that satisfy certain equilibrium objective while accounting for real-time unexpected variations in network condition (Peeta and Mahmassani, 1995). Peeta and Mahmassani (1995) presented a rolling horizon framework for addressing the real-time traffic assignment problem, which can be solved in quasi-real time for a near term future duration to determine an optimal path assignment. The rolling horizon approach has been proven to be a practical approach to update information in dynamic route guidance approach (Mahmassani, 2001; Paz and Peeta, 2009). The shorter the updating interval, the more timely the traffic information will be received by drivers. The shorter updating interval at the same time requires very fast data transmission and very strong computing power in CV. Note that computing power could also be needed in traffic management centers (TMC). Although employing the rolling horizon approach to address the time-dependent assignment, the information updating intervals still need more attention.

2.3 Information updating intervals among connected vehicles

There has been a large amount of studies on driver behavior. The relationship between driving behavior and traffic safety was established over decades (Goldstein, 1972; Rumar, 1985). Some variables such as age, gender, driving style, experience, and intentional driving violations make significant contributions to traffic accidents (Reason et al., 1990; Elander et al., 1993; Parker et al., 1995, 1998; Underwood et al., 1999; Simons-Morton et al., 2005; Ozkan et al., 2006). Retting et al. (1999) found that the gender of a driver is a contributing factor to driver behavior as males are more aggressive than females. Porter and Berry (2001) found through a telephone survey that young drivers are likely to be more aggressive than those in other age groups. King and Parker (2008) investigated the relationships between aggressiveness, self-reported driving violations, and perceptions of the commission of driving violations by others, and found that drivers who related highly to aggressiveness and hostility were more likely to be involved in a road traffic accident. Overall, without considering the specific characteristics of drivers, traffic safety mainly involves two factors related to drivers, including aggressiveness and awareness. According to Underwood et al. (1999), there is a strong link between driver aggression/anger and subsequent near accidents, and driver awareness is associated with driving experience (Elander et al., 1993). These two factors of driver behavior are directly or indirectly related to traffic accidents.

Also, dynamic route guidance will influence drivers' decisions, such as whether to travel, by what route and when (Hall, 1996). For this purpose, the route guidance based on shortest path, or the all-or-nothing assignment, has been widely applied. However, to reflect more realistically the driver behavior in real world, more advanced driver route choice models have been proposed. For example, dynamic traffic assignment have been widely applied to handle the changing traffic condition in which the drivers are making routing choices (Mahmassani 2001; Merchant and Nemhauser, 1978).

In summary, although many studies have investigated the effects of CV technology on traffic systems, little study has taken into account the information updating intervals among connected vehicles. In addition, as there is still a long period during which connected vehicles will mix with traditional vehicles in urban traffic systems, the magnitude of CV benefits need to be shown with respect to market penetration rates of connected vehicles.

3. Research Methodology

In this section, first, the simulation environment for the CV technology is developed. Then, the characteristics of driver behavior are modeled. Finally, the performance measures of traffic mobility and safety are defined, respectively.

3.1 Information updating intervals among connected vehicles

In order to construct the CV environment-based simulation, the Applications Programming Interface (API) was developed in a PARAMICS microscopic simulation through C++ language programming. Two types of vehicle were simulated in the CV environment, connected vehicles and non-connected vehicles. A vehicle released into a traffic network is either a connected vehicle or a non-connected vehicle. The former type has the ability to exchange information about the specific road-travel time with other connected vehicles and then re-route through dynamic route guidance, while the latter type cannot communicate or exchange any information with any vehicles and always take the fixed route (i.e., shortest path by distance) to destination. In the microscopic traffic modeling, the motion of each individual vehicle mainly involves car-following, lane-changing, and route choosing. The framework of the CV environment-based simulation is shown in Figure 1.

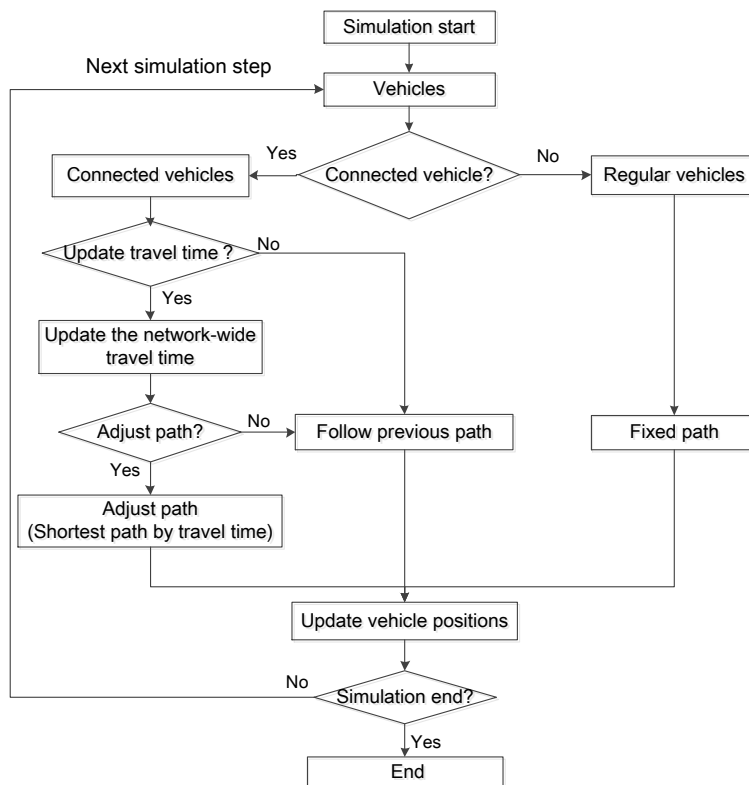


Figure 1. Framework of a connected vehicle in the simulation

As shown in Figure 1, the positions of all vehicles on the network should be updated every simulation step, however, connected vehicles will dynamically re-route their path through updating the network-wide travel time through dynamic route guidance before reaching their destination. In this regard, the time interval between two successive updates of network-wide travel time determines the frequency of communicating the network-wide travel time among connected vehicles. That means a smaller update interval of shortest path information computed based on the network-wide travel time can make connected vehicles adjust their route in time. In this sense, the update interval is an important factor for connected vehicles. In PARAMICS, each vehicle state is iteratively updated every simulation step. Based on this, rolling horizon approach (Peeta and Mahmassani, 1995) is used to address the implementation of dynamic traffic assignment in simulation. In this end, simulation step is set as time unit for roll horizon approach, and the entire simulation can be divided into multiple stages, and each stage consists of h time intervals, i.e., h simulation steps. Two consecutive stages are showed in figure 2, in which the roll period is assumed as l simulation steps. In the current stage of $\sigma-1$, link travel time is collected to obtain the average link travel time for all the links in the network, i.e., the network-wide travel

time. Consequently, in the next stage of σ , this average link travel time will be used to compute the shortest path for each connected vehicles. Meanwhile, the network-wide travel time is updated in the next stage. The rolling horizon framework terminates when simulation is complete.

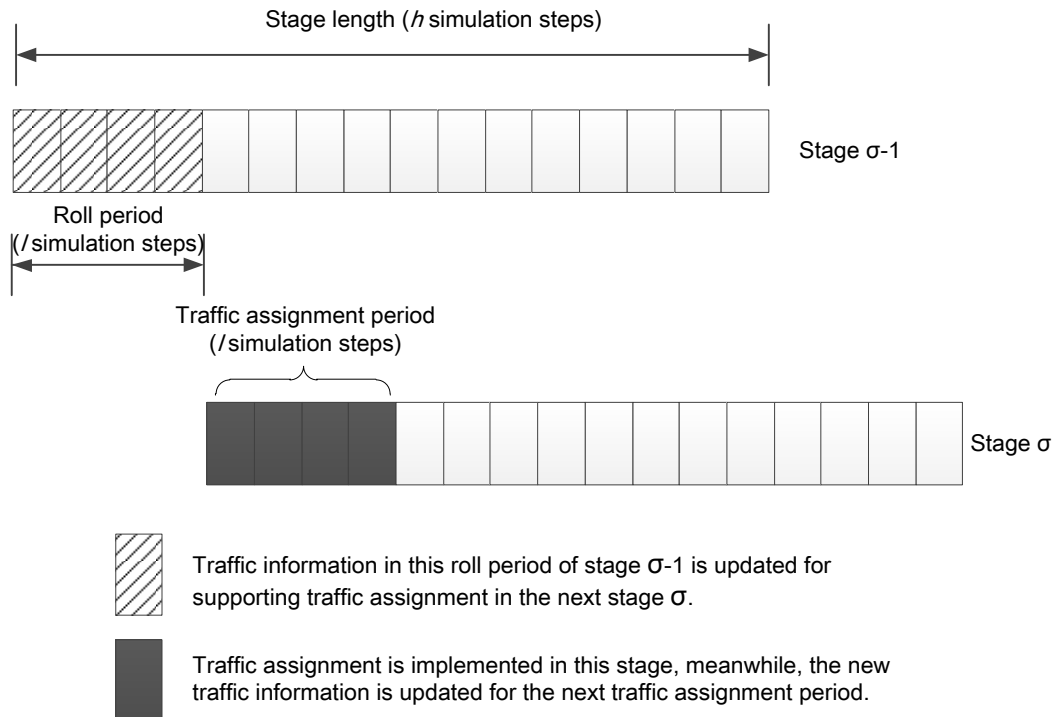


Figure 2. Rolling horizon implementation for updating the traffic network information

It should be noted that one simulation step is defined as 0.5 second by default in PARAMICS. One rolling period consists of l simulation steps. In addition, the driving force of the simulation network in PARAMICS is an O-D demand. The demand on the network between each OD pair can vary in time.

In the framework of CV environment simulation, some assumptions used in this study are as follows:

- (1) All the connected vehicles comply with dynamic route guidance decisions.
- (2) All the wireless V2V communications are successful and transmit information with 0% lost. Meanwhile, the range of wireless communication is unlimited. Note that in reality the success rate of wireless communication between connected vehicles is lower than 100%, and the range is always limited.
- (3) Connected vehicles share travel time information with other connected vehicles at a specific update interval and then re-route their paths through dynamic route guidance before reaching their destination.
- (4) Connected vehicles can calculate their position accurately, and dynamic route guidance can navigate the connected vehicles based on the shortest path in terms of travel time.

3.2 Modeling driver behaviors

Most research about driver behaviors is carried out through a driver behavior questionnaire (DBQ) to distinguish different types of driver behavior. Among the types of driver behavior, angry and aggressive driving behaviors are very common, and are associated with accidents and

near accidents (Underwood et al., 1999). This type of driver behavior mainly includes intentional speeding and tailgating. In order to reach the destination as quickly as possible, angry and aggressive driving behaviors could be characterized as deliberately risky driving behaviors.

Driver behavior can be modeled in terms of two components, aggressiveness and awareness. Specifically, in PARAMICS, before being released to a road network, each vehicle will be randomly assigned awareness and aggressiveness values. The values for aggressiveness and awareness are quantified as integer values from zero to eight, where higher integers indicate greater amounts of aggressiveness and awareness. A high level of aggressiveness would cause drivers to adopt smaller vehicle gaps, i.e., following a lead vehicle more closely. Similarly, a high level of awareness would make drivers use longer headways near lane drops to yield to merging traffic. Lane changing is also based on gap acceptance which is affected by driver aggressiveness and awareness. With an increase in driver aggressiveness and awareness, the accepted gap would decline.

Driver aggressiveness and awareness are both assumed to follow normal distribution as $X \sim N(\mu_1, \sigma_1^2)$ and $Y \sim N(\mu_2, \sigma_2^2)$, respectively. Additionally, a random perturbation was employed into each driver behavior:

$$\hat{c}_i = \left(\frac{100 - P}{100} + N \right) c_i \quad (1)$$

where \hat{c}_i is the final aggressiveness or awareness value of driver behavior for the i^{th} vehicle, c_i is the original awareness or aggressiveness value of driver behavior for the i^{th} vehicle, P is the perturbation percentage, and N is a random integer in the range of 0 to 2. Note that the random perturbation is cyclical and its value is determined at each simulation step. Every vehicle was perturbed only once.

In this study, we focused on the collective characteristics of driver behavior, instead of individual driver behavior. The collective characteristics of driver behavior can be represented through averaging the aggressiveness or awareness of all the drivers.

3.3 Performance measures

Two measures were used to evaluate traffic mobility, i.e., average trip time (ATT) and average vehicle trip speed (AVS). Meanwhile, a surrogate measure, i.e., the time-to-collision involved incident rate (TTC-IR) for one kilometer driven, was used to evaluate traffic safety. These measures are defined as follows:

$$ATT = \frac{1}{N} \sum_{i=1}^N T_i \quad (2)$$

$$AVS = \frac{1}{N} \sum_{i=1}^N S_i = \frac{1}{N} \sum_{i=1}^N \frac{M_i}{T_i} \quad (3)$$

$$\left\{ \begin{array}{l} TTC-IR = \frac{\sum_{i=1}^M incident_i}{D}, \quad \begin{cases} incident_i = 0, \text{ if } TTC \geq 1.5s \\ incident_i = 1, \text{ if } TTC < 1.5s \end{cases} \\ \\ TTC = \frac{(X_l - X_f) - L_l}{V_f - V_l}, \text{ if } V_f > V_l \end{array} \right. \quad (4)$$

where N is the number of vehicles departing, T_i is the trip time of the i^{th} vehicle, S_i is the trip speed of the i^{th} vehicle, M_i is the trip distance of i^{th} vehicle that arrived at the destination, X is the position of the vehicle, V is the speed, and L is the length of the vehicle; l represents the leading vehicle, f represents the following vehicle, and D represents the total length of roadway in the road network.

TTC was calculated for a leading vehicle and following vehicle with a potential of having a rear-end collision. The threshold value of TTC was set as 1.5 s (Van der Horst, 1991). That is to say that if the TTC computed is less than the threshold value, it indicates a high probability of collision between a leading vehicle and a following vehicle. In PARAMICS, at each time step, the position and speed of all vehicles can be acquired to measure the TTC and compare it with the threshold value. Consequently, TTC-IR is obtained as the incident rate in one kilometer.

4. Simulation experiment

4.1 Simulation area

The study area is located in the south of Nanjing, China. This area is around 30 km², about 3 km from east to west and around 10 km from north to south, linking the main urban region and the suburb region. It contains two urban expressways, the north-south S55 Expressway and east-west G2501 Expressway. It was modeled in PARAMICS, as seen in Figure 3. This traffic network was chosen because of three considerations: (a) it is a typical urban corridor bearing traffic congestion during the morning/evening peak period; (b) with the rapid increase in vehicles in Nanjing, traffic congestion in this area has become worse compared with previous years; and (c) multiple routing options exist within the network. After determining the study area, the geometric characteristics of the study area (e.g., traffic zones, lane configuration, intersection locations, and turning movements) were collected and coded from roadway maps and field observations. It is noteworthy that the traffic zones identify vehicles' origin and destination (OD) information. The network characteristics are summarized in Table 1.

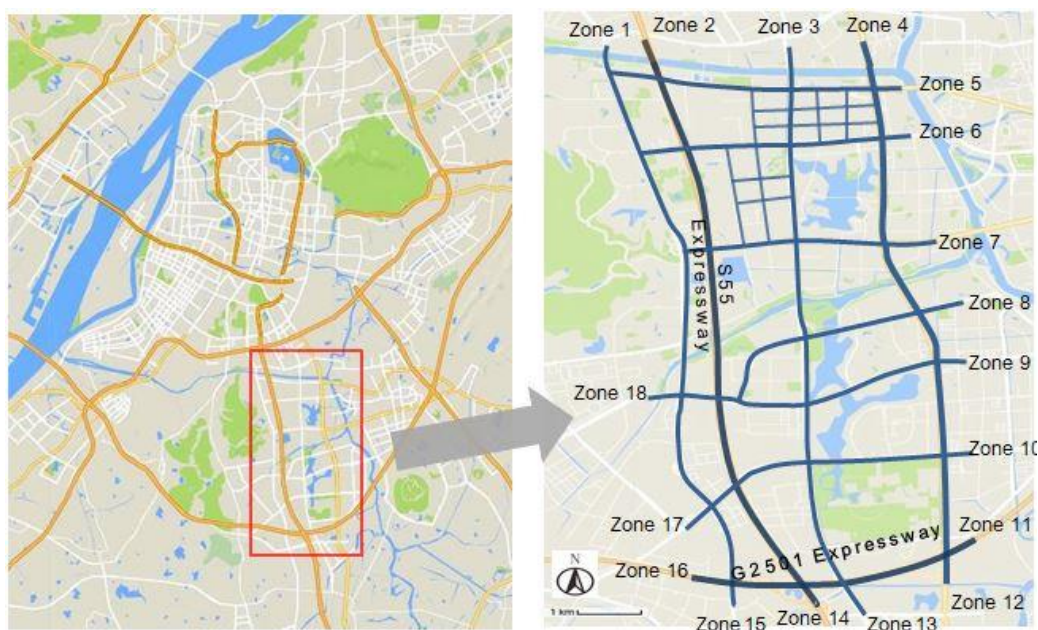


Figure 3. Study area of the city of Nanjing, China

Table 1. Simulation model characteristics

Network characteristic	Value
Simulation area (km ²)	30
Number of road sections	218
Number of traffic zones	18
Number of intersections	47
Length of roadway (km)	81

4.2 Experimental design and set-up

Based on the selected study area, experiment was designed to evaluate the effects of route guidance under connected vehicles on traffic mobility and safety. Firstly, collection of input information for simulation was obtained from the Annual Report of Nanjing Traffic Development 2016, including two types of data, i.e., OD demand information and vehicle information.

Secondly, congested and acceptable vehicle flow were adjusted by adding an additional advance (green) phase at specific intersections. According to related micro-simulation research, headways and reaction time were set as 1 s by default. As the purpose of this study was to ascertain the effects of connected vehicles, it did not involve specific micro-simulation calibration and validation.

Thirdly, driving behavior was modeled into three situations, normal, moderate, and radical. In the normal situation, awareness and aggressiveness of each driver behavior is assumed to follow a Normal distribution. Consequently, in the moderate and radical situation, awareness and aggressiveness of each driver behavior could be generated based on the normal situation. Additionally, a perturbation was added into the three models of driver behavior. The perturbation for normal, moderate, and radical was 5%, 10%, and 20%, respectively. It should be noted that the collective characteristic of driving behavior was represented through averaging the aggressive and awareness of all the drivers. In the simulation, the vehicle information and driving behavior were showed in Table 2.

Table 2. Overview of vehicle attributes and driving behavior in the simulation

Type	Share (%)	Length (m)	Width (m)	Max. ACC (m/s ²)	Max. DEC (m/s ²)	Normal	Moderate	Radical
Car	78.6	4	1.6	2.5	4.5	$x1 \sim N(4, 1.5)$	$x2 = x1 + 1$	$y3 = y1 + 2$
Mini-truck	12.8	6	2.3	1.8	3.9	$x1 \sim N(4, 1.5)$	$x2 = x1 + 1$	$y3 = y1 + 2$
Medium truck	6.6	8	2.4	1.1	3.2	$x1 \sim N(4, 1.5)$	$x2 = x1 + 1$	$y3 = y1 + 2$
Large truck	2.0	11	2.5	1.1	3.2	$x1 \sim N(4, 1.5)$	$x2 = x1 + 1$	$y3 = y1 + 2$

Finally, effects of market penetration level and the information updating interval will be investigated. The market penetration levels varied from 0% to 100% with an increment of 10%. Meanwhile, the updating intervals were selected as 1-min, 2-min, 3-min, 5-min, 7-min, 10-min, 12-min, and 15 min.

Based the aforementioned experimental design, the set-ups are as below. The selected study area was simulated for morning peak rush hour traffic, the trials of which ran for a simulation time of 1:15:00. The first 15 min was warming-up time. Evaluation of the connected vehicles was conducted by analyzing the data collected for the remaining 1 h only. In addition, for PARAMICS, each simulation scenario used different seeds, and was replicated 10 times. Therefore, each simulation scenario can be evaluated by averaging the replicated trials.

4.3 Comparison of collective characteristics of driving behavior

The collective characteristics of driving behavior under different situations were statistically compared in terms of awareness and aggressiveness which were reflected through the kernel density estimation in Figure 4. For normal situation, averaging the awareness of all the drivers can obtain its mean and variance, which are 3.97 and 1.47. Similarly, the mean and variance of aggressiveness are 3.89 and 1.51. Compared to those for moderate and radical situation, the increased awareness and aggressiveness values signify that the collective driving characteristics for all drivers become more aggressive before reaching their destination.

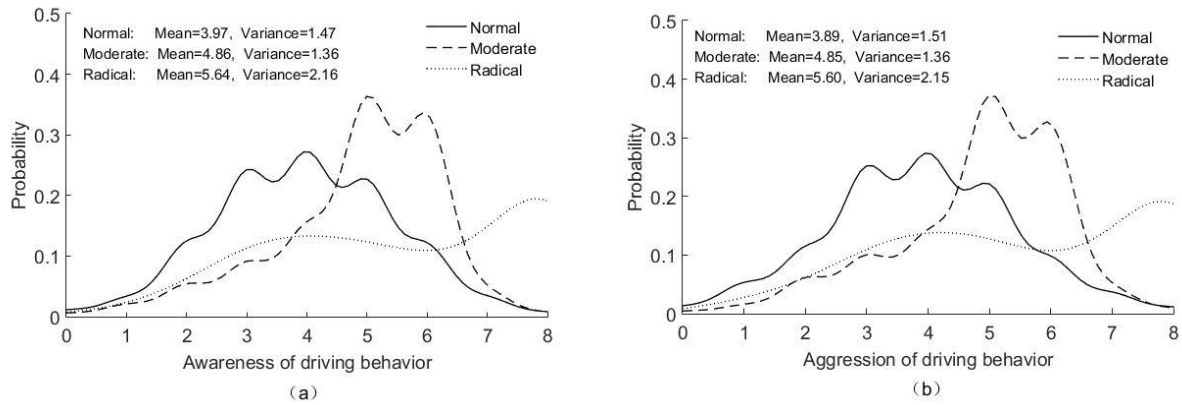


Figure 4. Different characteristics of driver behaviors: (a) Awareness distribution; (b) Aggression distribution

4.4 Comparison of collective characteristics of driving behavior

The sensitivity analysis of market penetration levels and information updating intervals was shown on normal situation. On varying the market penetration rate, traffic mobility of the road network is affected by different updating intervals. First, in term of ATT, the effect of market penetration level and information updating interval on mobility is presented in Figure 5. It is clear that there is a gradual decrease in ATT as the market penetration level increases from 0% to 50%, and then ATT increases by different degrees for different updating intervals when the market penetration level is greater than 50%. It is noteworthy that under shorter updating intervals (1 and 2 min), ATTs are smaller than other longer updating intervals. Considering separately the connected vehicles and non-connected vehicles, the comparison of their ATTs is shown in Figure 6. It is clear that ATTs of connected vehicles and non-connected vehicles are affected by each other. With increased market penetration levels of connected vehicles, ATTs of connected vehicles gradually increase. ATTs of non-connected vehicles gradually decrease. It is clear that shorter information updating intervals (i.e., 1 and 2 min) are more beneficial for reducing ATTs of connected vehicles.

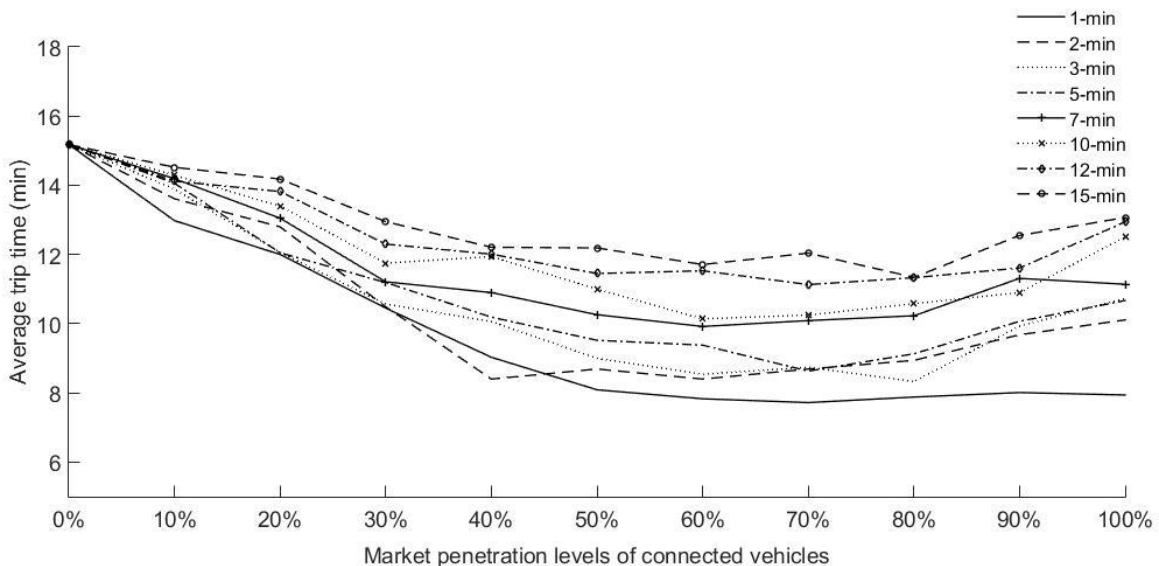


Figure 5. ATT for different updating intervals on varying the market penetration level

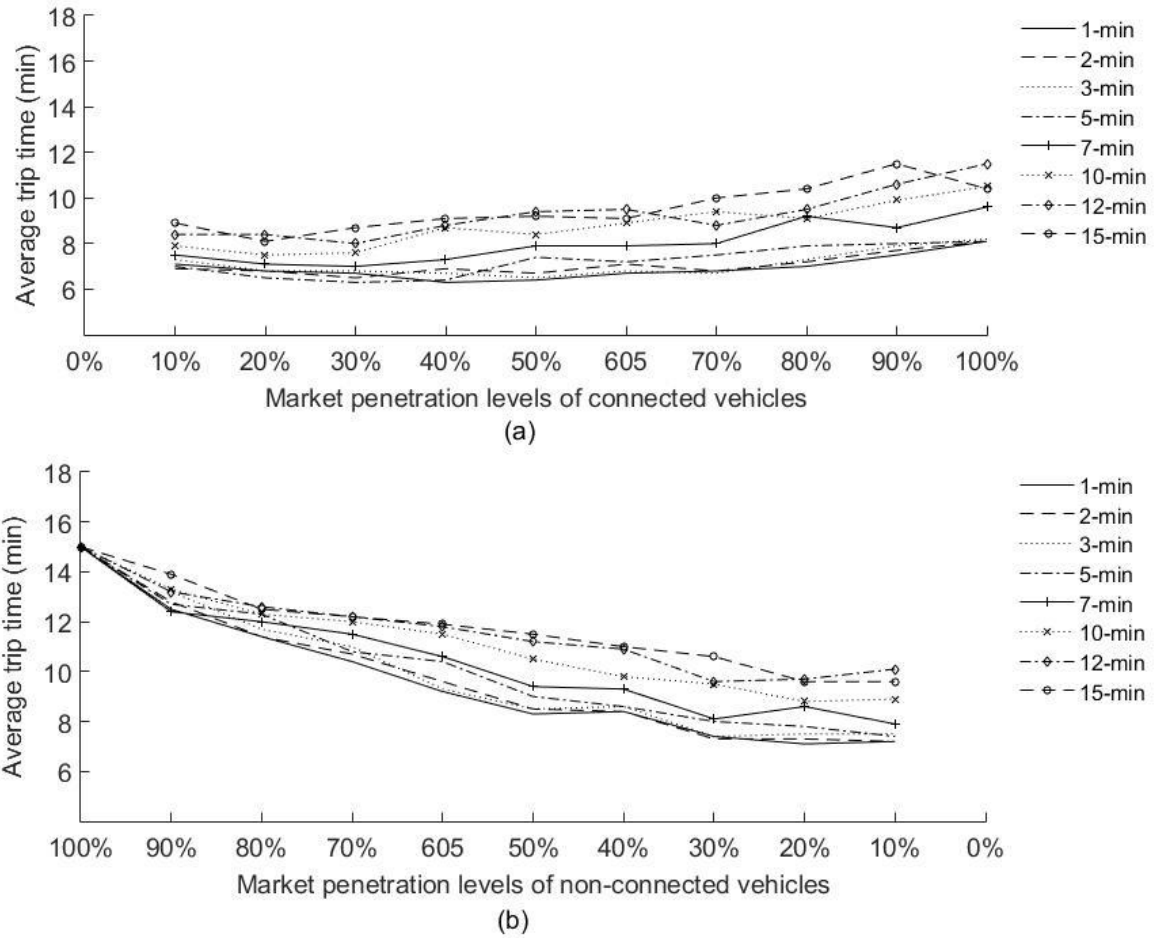


Figure 6. Comparison of the ATTs for connected vehicles and non-connected vehicles: (a) Connected vehicles; (b) Non-connected vehicles

Second, in term of AVS, the effect of market penetration level and information updating interval is shown in Figure 7. For all the updating intervals, AVS decreases slightly from around 31 to 28 km/h with an increase of market penetration level. There is no significant difference among them. AVSs of connected vehicles and non-connected vehicles are compared separately in Figure 8. AVSs of connected vehicles decline by around 8 k/h with increased levels of connected vehicles. Simultaneously, AVSs of non-connected vehicles could improve.

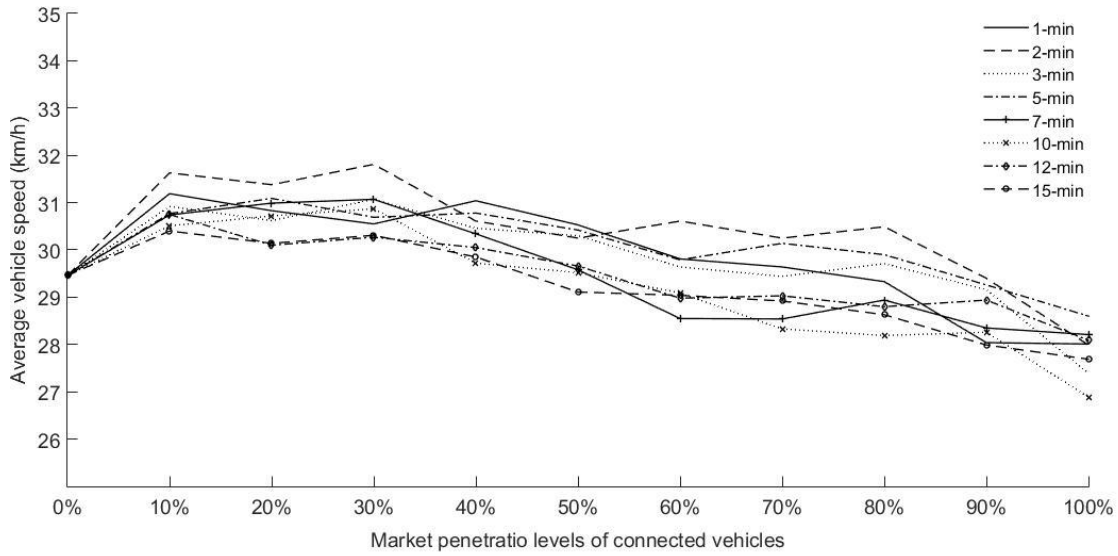


Figure 7. AVS for different update intervals on varying the market penetration level

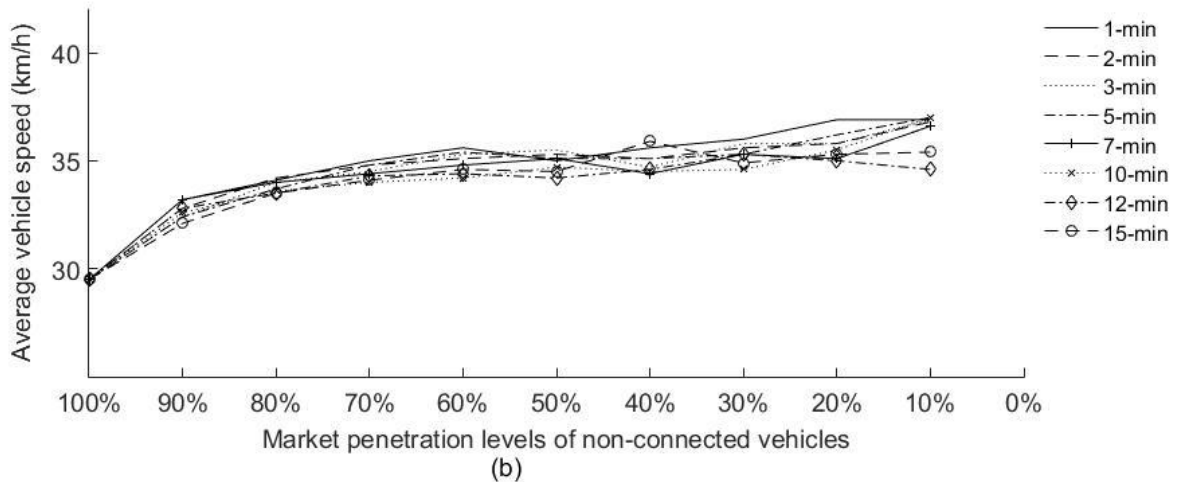
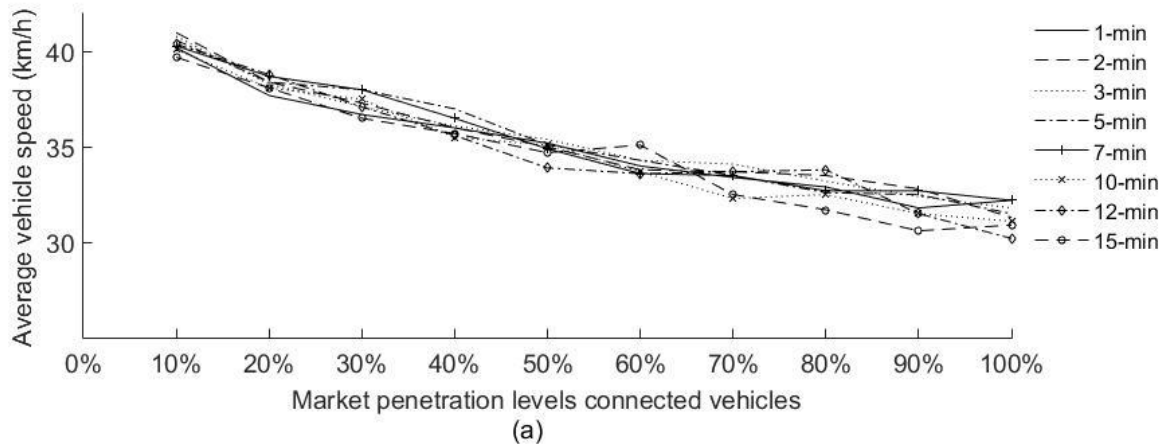


Figure 8. Comparison of AVSs for connected vehicles and non-connected vehicles: (a) Connected vehicles; (b) Non-connected vehicles

4.5 Effect of market penetration levels and information updating intervals on safety

Figure 9 shows the effect of market penetration level and information updating interval on safety. It is clear that TTC-IR initially decreases as the market penetration level increases from 0% to 10%,

and it gradually reaches a peak when the market penetration rate is around 50%, and then it fluctuates when the market penetration rate ranges from 50% to 100%. When the market penetration level is below 50%, TTC-IR at the 1-min interval is worse than that at 2 min or longer intervals. Therefore, it seems that when the market penetration level is above 50% or more, long information updating intervals are more appropriate. On reflection, for shorter updating intervals, the entire traffic might be disturbed *heavily* due to the high percentage of CVs receiving frequent travel time information updates, so that potentially unsafe maneuvers might be caused under such circumstances.

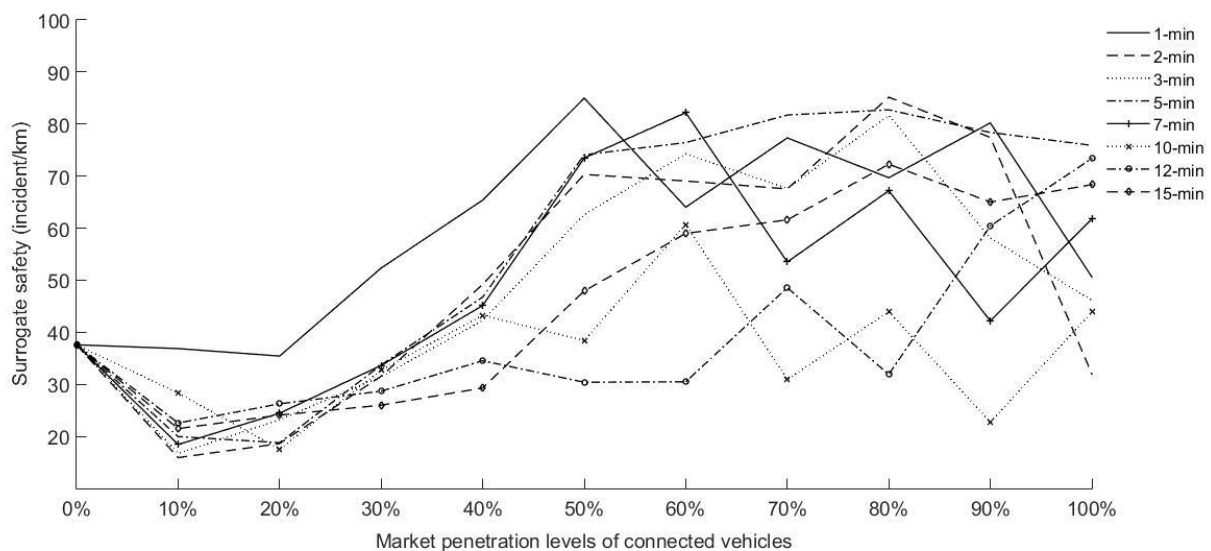


Figure 9. Surrogate safety measure

4.6 Overall performance of dynamic route guidance on road network

Traffic pressure on the road network will ascend with an increase in traffic demand. Meanwhile, traffic safety will be vulnerable when driving behavior becomes more aggressive. Considering the market penetration level of connected vehicles at 50% with four updating intervals, the results of increased traffic demand affecting the performance of road network are resented in Table 3.

As shown in Table 3, firstly, it is clear that increased traffic demand could lead to a decrease on both traffic mobility and safety. Secondly, for the same traffic demand, shorter updating intervals (1 and 2 min) lead to a better mobility, and longer updating intervals (10 and 12 min) lead to a better safety. Finally, comparing three driving behaviors, only a slight advantage in traffic mobility can be observed with increased aggressiveness and awareness of drivers, by contrast, the traffic safety is significantly declined.

Overall, considering the application of dynamic route guidance under CV environment, traffic mobility and safety seems influence each other. The market penetration level of connected vehicles and information updating interval are two important factors. Improving traffic mobility might reduce traffic safety with an increase in the market penetration level of connected vehicles over different time intervals.

Table 3. Impacts of the increased traffic demand levels on the traffic mobility and safety

Demand level	Interval	Normal			Moderate			Radical		
		AVS	ATT	TTC-IR	AVS	ATT	TTC-IR	AVS	ATT	TTC-IR
100%	1 min	30.0	8.5	78.5	30.6	8.0	91.9	30.9	7.8	102.2
120%	1 min	27.6	11.0	114.1	28.3	9.9	127.9	29.4	9.9	146.7
140%	1 min	26.2	13.5	120.2	26.3	12.0	139.5	26.5	13.1	167.9
160%	1 min	24.4	15.3	128.4	24.7	14.3	158.1	25.2	14.7	182.4
100%	2 min	30.3	8.7	70.4	29.8	8.5	84.8	30.0	8.5	96.1
120%	2 min	27.7	11.3	80.4	28.2	10.5	111.5	28.4	10.6	133.3
140%	2 min	25.8	12.5	100.4	26.1	12.5	115.9	26.2	13.9	108.2
160%	2 min	24.3	15.5	90.3	24.5	14.7	93.2	23.2	16.7	155.7
100%	10 min	29.5	11.0	38.7	29.3	10.9	62.9	29.6	10.3	84.8
120%	10 min	27.4	12.4	62.2	27.5	12.9	67.2	27.8	13.3	101.5
140%	10 min	25.2	15.1	71.6	25.7	15.2	87.8	25.2	15.8	92.5
160%	10 min	25.1	16.5	90.6	23.9	17.7	142.1	23.8	17.5	185.9
100%	12 min	29.7	11.5	31.0	29.4	11.0	59.2	29.4	11.0	74.5
120%	12 min	27.2	13.7	48.8	27.2	13.5	53.0	26.8	14.6	93.2
140%	12 min	25.6	15.9	72.0	26.1	15.2	79.1	26.1	16.0	97.9
160%	12 min	25.2	16.7	110.6	23.2	17.7	125.7	23.4	19.1	187.5

5. Limitations and Discussions

This study has three limitations. The first one is that the key factors selected in this study are the market penetration rate of connected vehicles and update time intervals of connected vehicles sharing their travel time. These two factors are the important issues related to the application of CV technology, and this study did not involve any specific technical problems with an assumption of perfect technical implementations. The second one is that driver behavior is supposed to be only related to the drivers themselves, not to CV technology. In fact, if CV technology is widely used in reality, driver behavior has to be affected and may become different, indicating that driver behavior and the application of CV technology are not independent of each other. However, in this study, we ignored the correlation between driver behavior and the application of CV technology. The last one is that in the simulation platform PARAMICS, the non-CVs are assumed to use all-or-nothing shortest path based on distance, which is highly unrealistic, non-optimal assumption.

In addition to above limitations, some discussions are provided as follows. First, market penetration level of connected vehicles was found to impact heavily on the mobility and safety of road network. As CV technology gradually matures, this market penetration level would be expected to reach a stable state. Second, information updating interval was also found to impact significantly on the mobility and safety of road network. Therefore, traffic management department should explore appropriate updating interval under different traffic conditions, e.g., morning and evening peak hour, weekends, and/or different weather conditions, e.g., rain, snow, and fog. Third, traffic safety is also crucial to transportation systems. However, in this paper, only a surrogate measure was selected for investigating the effect of route guidance on road safety. This leaves much space for future investigations into other measures of traffic safety.

6. Conclusions

The primary purpose of this study is to investigate the effects of route guidance in connected vehicles environment on traffic mobility and safety through microscopic traffic simulation

approach. In this paper, two important factors were investigated, including market penetration levels of connected vehicles and information updating intervals among connected vehicles. Connected vehicles can use V2V communication to share travel time with other connected vehicles and re-route their paths through dynamic route guidance before reaching their destination. Experiments were carried out using PARAMICS microscopic simulation. Traffic mobility was reflected by two measures, ATT and AVS, and traffic safety was reflected by TTC-IR. Different market penetration levels of connected vehicles were utilized to show its effects on traffic mobility and safety. Meanwhile, driver aggressiveness and awareness were taken into account, along with effect of different levels of traffic demand.

Simulation results show that market penetration level of connected vehicles has little direct impact on the mobility and safety of road network. Traffic mobility gradually improves on increasing the market penetration rate of connected vehicles from 0% to around 50%, and then declines on deploying more connected vehicles. By contrast, simulation results showed that the information updating interval could directly and significantly affect the mobility and safety of road network. From the simulation conducted in this paper, shorter updating interval is likely to lead to better mobility, while the safety of road network seems to decline. In contrast, longer updating interval is likely to lead to better safety and decreased mobility. Overall, the findings of this study indicate that as the development of connected vehicles, appropriate information updating interval would be carefully explored by the traffic management department under different traffic conditions.

Future research is needed to take into account the technical limitations of CV in real world applications, such as limited range of wireless communication and failure of information transmission among connected vehicles. In addition, for different traffic conditions, appropriate information updating intervals need to be investigated so that the most appropriate interval can be found to make full use of the CV technology. Finally, impact of CV technology on traffic safety should be further investigated through exploring other measures such as driver distraction.

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