On-Ramp Merging Strategies of Connected and Automated Vehicles Considering Communication Delay

Yukun Fang, Member, IEEE, Haigen Min, Member, IEEE, Xia Wu, Wuqi Wang, Xiangmo Zhao, Member, IEEE, and Guoqiang Mao, Fellow, IEEE

Abstract—Improper handling of on-ramp merging may cause severe decrease of traffic efficiency and contribute to lower fuel economy, even increasing the collision risk. Cooperative control for connected and automated vehicles (CAVs) has the potential to significantly reduce the negative impact and improve safety and traffic efficiency. Implementation of cooperative on-ramp merging requires the assistance of the vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication, wherein the communication delay may cause negative impact on CAV cooperative control. In this paper, scenario of on-ramp merging for CAVs considering the V2I communication delay are studied. Statistical characteristics of the V2I communication delay are explored from both literature and real field test, and a communication delay estimation model based on statistical techniques are proposed. Specifically, we firstly model the CAV on-ramp merging scenario using optimal control in ideal situation. Then, several statistical characteristics of the V2I communication are investigated especially the probability density function of the V2I communication delay in several application scenarios. Further, we proposed a communication delay estimation model and used the modified vehicle state to compute the corresponding control law. Real field test of V2I communication delay indicated that distribution of V2I communication delay could correlate with the application scenario and normal distribution can be generally adopted to approximate the probability density function (PDF) when the number of samples is large enough. Numerical simulation of the CAV on-ramp merging scenario considering the V2I communication delay revealed that dynamic performance of the control process would be deteriorated impacted by the V2I communication delay and it might further impact the final control effect and lead to potential lateral collision in the merging area.

Index Terms—Connected and automated vehicles, on-ramp merging, V2I communication delay, statistical techniques.

I. INTRODUCTION

ON-RAMP merging is a frequently encountered traffic scenario whose improper handling might cause heavy traffic congestion even accidents [1], [2]. It could form a traffic bottleneck since the merging vehicles may have to slow down or even stop at the ramp to wait for a proper opportunity to merge. To this end, collaborative control of connected and automated vehicles (CAVs) enables the vehicles to cooperate with each other and emerge as an appealing strategy to conquer the aforementioned challenges of on-ramp merging [3]–[6]. In the current studies, most researchers consider the on-ramp merging problems from two perspectives, i.e., allocation of the merging sequence (MS) and motion planning for vehicles [7]. MS reflects the priority of a vehicle to pass the ramp and MS allocation will directly influence the motion planning, while motion planning algorithms should firstly ensure the safety of all vehicles and then control the vehicles movement to pass the merging point with the expected MS.

Solutions for both problems require information exchange, and to achieve cooperative decision making and motion control of autonomous vehicles, advanced communication technologies [8], [9], including vehicle to vehicle (V2V), vehicle to infrastructure (V2I) communication etc. are required. Therefore, research on the V2V/V2I communication is of great significance in solving the on-ramp merging problem for CAVs. In [10], Biswas et al. pointed out that communication delay may cause negative impacts on CAV cooperative control, including increased risk of collision and violation of system stability, which has been neglected in many previous studies. Motivation of this paper is to explore the statistical characteristic of V2I communication delay and its impact on the control effect for the on-ramp merging problem. Further, we propose a communication delay estimation method to improve the dynamic performance of control.

In this paper, we studied the scenario of on-ramp merging for CAVs considering the V2I communication delay. We adopted the merging sequence generation approach.
proposed in our previous work [11] and the optimal control method proposed in [12] for trajectory planning. Then, negative effect caused by the V2I communication delay was considered. We firstly explored the statistical characteristics of the V2I communication delay, and then proposed a communication delay estimation model and use the revised vehicle state to compute the corresponding control law. Main contributions of this study are as follows:

1). Statistical characteristics of the V2I communication delay were explored from both literature and real field test. Distribution of V2I communication delay is related to the application scenario. The normal distribution can generally be used to approximate the probability density function (PDF) when the number of samples is large enough. However, several specific distributions might be more suitable than normal distribution in the specific scenarios.

2). A communication delay estimation model based on statistical techniques is proposed, which uses timestamp information to predict the communication delay and then the controller modifies the vehicle state information to compute the optimal control law;

3). Numerical simulations revealed that dynamic performance of the control process would be deteriorated impacted by the V2I communication delay and it might further impact the final control effect and lead to potential lateral collision in the merging area.

The rest of this paper is structured as follows. Related work is reviewed in Section II. Section III formulates the problem and illustrates the methodology. Results of the real field test and simulations are presented in Section IV, followed by the discussion of several issues in Section V, and we summarize our work in Section VI.

II. RELATED WORK

The majority of the existing researches for cooperative on-ramp merging focus on the merging strategy and motion planning (or trajectory planning) problems [13], [14]. Allocation of the merging sequence is one of the core issues for merging strategy and it is basically a scheduling problem that decides the traveling order for each vehicle. Chen et al. [15] categorized existing approaches to establishing a merging sequence as “rule-based methods” and “optimal methods”. Rule-based methods rely on explicit rules and typical approaches, including virtual mapping [16] and first-in-first-out rules [12] etc. Optimal methods are based on a global or a local performance evaluator to assess the expected benefits brought by the possible merging sequence. For example, in [17], Xu et al. adopted a car-following model to update vehicle accelerations, where vehicle accelerations are regarded to be a constant in the time intervals of interest and optimal merging sequence are obtained through performance evaluation by a genetic approach. Once the MS is determined, motion planning algorithms are required to ensure that vehicles pass the ramp smoothly without collision as well as meeting the goal of enhancing the traffic performance, like fuel economy, traffic efficiency and so on. Generally speaking, the control algorithms for CAVs on-ramp merging can be divided into centralized methods [18], [19] and decentralized methods [20], [21]. For the centralized approaches, there is a single central controller that globally decides the tasks for all vehicles, while, for the decentralized control, each vehicle makes decisions in accordance with the information it received from the other vehicles, or other sources of information [22]. Among these control methods, optimization is a frequently used approach where the researchers usually formulate the control problem as a bi-objective or multi-objective optimization problem and obtain the control law through solving the optimization problem analytically [7], [12] or numerically [11]. The optimization objectives include (but not limited to) travel time [19], fuel consumption [12], passenger comfort [7] and so on. In recent studies on the on-ramp merging problem, many researchers jointly consider the merging sequence (MS) and motion planning to improve the on-ramp merging performance. In [7], Jing et al. proposed a cooperative multi-player game-based optimization framework to coordinate vehicles movement and achieve the maximum global pay-off. The multi-player game was decomposed into multiple two-player games in the paper to allocate the merging sequence, and the on-ramp merging problem was then formulated as a multi-objective optimization problem to deal with motion planning. In [15], Chen et al. put forward a hierarchical control framework for CAVs to achieve cooperative and efficient on-ramp merging. In this control framework, there were two controllers addressing MS generation and trajectory planning respectively. The tactical layer controller employed a second-order car-following model with a cooperative merging mode to generate an optimal vehicle merging sequence, while the operational layer controller used a third-order vehicle dynamics model based on Model Predictive Control (MPC) and optimized desired accelerations for CAVs to complete the trajectory planning. In this paper, we also follow such paradigm and consider merging sequence (MS) and motion planning simultaneously when analyzing the on-ramp merging problem, and then explore the impact of communication delay to the control effect.

Currently, learning based method especially reinforcement learning (RL) is emerging in the literature of on-ramp merging research. It is researched in both emerging strategy and motion planning for on-ramp merging. In [23], Liu et al. firstly built a model for the unevenness of traffic flow between lanes and then established a lane selection model by reinforcement learning for the coordination of vehicles in multi-lane traffic. Unevenness of traffic flow between lanes is analyzed before vehicles enter the merging zone so that the decision of lane selection can be made to relieve potential congestion on the ramp. Triest et al. [24] applied a hierarchical method for decision making, where reinforcement learning is used for training a high-level policy and the output of the policy was executed via a low-level controller. Kherroubi et al. [25] considered the mixed traffic case for on-ramp merging and developed an Artificial Neural Network (ANN) to predict drivers’ intentions combined with a Deep Reinforcement Learning (DRL) agent that outputs the longitudinal acceleration for the merging vehicle. A recent survey [26] of reinforcement learning application to motion planning for
autonomous vehicles presented that RL approaches to merging often attempt to learn a direct mapping from observation to vehicle control. For example, Hu et al. [27] proposed an actor-critic-based approach to encourage vehicles maximizing their own performance while still acting cooperatively when merging. They incorporated the low-level controllers into the reinforcement learning algorithms via a masking mechanism. At a given state, feasible actions were determined via a low-level controller. Lin et al. [28] applied deep reinforcement learning for longitudinal control for high-speed on-ramp merging, where deep deterministic policy gradient (DDPG) was the algorithm for training to output continuous control actions.

To the best of our knowledge, we rarely see the study of the impact on communication delay in the on-ramp merging problem, despite that it may have severe negative impact on the cooperative control. In [10], Biswas et al. showed that, for a delivery latency of 0.4s, the occurrence of collision between longitudinally adjacent vehicles may significantly increase as there is no sufficient time to start decelerating in advance. In [29], simulation conducted by Hu et al. shows that communication delay badly deteriorates the dynamic performance of the vehicle, such as unexpected acceleration or deceleration. This conclusion is also partially verified in our simulation (See Section IV, Part B). Besides, Wang [30] proved that the feasible domain (the domain where control variable(s) satisfies (satisfy) all pre-defined constrains) deviation of the control variable caused by the delay may change or narrow the stability domain of the control system. Exploration of the probability density function (PDF) of V2I communication delay is insufficient in literature. We referred [31]–[40] and PDF of V2I communication delay can be sophisticated in real world since the external factors and application scenarios differ. Different PDF were adopted to model the V2I communication delay including Normal distribution [31], Rician distribution [32], Gamma distribution [33], Weibull distribution and Nakagami distribution [34] etc. In [35], Protzmann has described several PDFs suitable for different scenarios and most of them are the function of distance between transmitter and receiver. Thus, application scenarios and distance between transmitter and receiver could be two of the major factors that impact the distribution of the communication delay. If one or multiple bits of a packet are damaged due to unreliable wireless transmission, the packet is considered lost [41]. Due to continuous retransmissions, packet loss may also be expressed in the form of delay, which makes it more difficult to predict delay. Recently, there are few related works explore the impact of V2X (Vehicle to everything) delay on transportation system. Wang [31] proposed a consensus-based motion estimation approach to estimate the vehicle motion, considering periodic packet loss and time-variant communication delay, where the author just simply assumed that the V2X delay satisfied normal distribution. Whereas, results of the real field test in our work showed that the distributions of V2I communication delay could correlates with the application scenarios, although normal distribution was a reasonable assumption to a great extent. Hoque et al. [42] investigated several factors causing safety-critical automotive applications to become unreliable due to communication failures. The authors provided experimental testing data and analysis, and quantified the impacts of relative vehicle speeds, altitude differences between vehicles, and interior obstacles on V2V communication range and reliability for opposite traffic, in both city and highway environments, using the Dedicated Short-Range Communications (DSRC) devices. In comparison, our work investigated not only the specific indicators (communication delay and packet delivery rate (PDR)) for both DSRC and Long-Term Evolution for V2X (LTE-V) devices, but also explore the PDF of the V2I communication delay. Values of these indicators strongly correlated with the V2X devices themselves. Therefore, exploring the PDF of communication delay for the V2X devices in several typical scenarios have more general significance for the further study.

III. PROBLEM STATEMENT AND METHODOLOGY

A. Scenario Description

On-ramp merging is one of the primary reasons for the bottleneck of severe traffic congestion. Fig. 1 illustrates a common scenario where the single-lane ramp road merges onto the main road. Usually, the main road consists of multiple lanes, shown in Fig. 3. However, in this paper, we focus on the merging scenario and only consider the lane connected.
to the ramp road. Typically, the vehicles on the ramp road have to wait for a safe opportunity to merge into the traffic flow on the main road, and the stop-and-go situation for the vehicles on the ramp road becomes inevitable especially on highly congested road.

We consider on-ramp merging in a scenario that consists of a single lane of a main road and a ramp road, shown in Fig. 1. In practice, the main road would usually consist of multiple lanes. However, in this paper, we focus on the merging scenario especially the impact of the communication delay to the on-ramp merging. Thus, we just take into consideration the lane (on the main road) that is in conjunction with the ramp road to simplify the process of modeling. Denote the central axis of the single lane for the main road as \( X_m \) and the central axis of the ramp road as \( X_r \) respectively. The cross-point of the two axes is noted as \( O \). It is assumed that there is a centralized controller which can exchange messages with all vehicles in its communication range with random communication delay.

The region described in Fig. 1 are divided into delay estimation area, control area and merging area. The delay estimation area with adjustable length \( D \) is the zone where the vehicle and the controller exchange their messages including timestamp to estimate the communication delay. The control area with a known length \( L \) is the zone where all vehicles adjust their states under the control of the centralized controller to achieve a desired merging velocity \( v_m \) to prepare for the on-ramp merging. The beginning and the end of the control area are noted as Control Line and Merging Line respectively. The merging area with a known length \( M \) is the region where potential lateral collision of the vehicles exists, and in this paper, all vehicles pass this area with the same velocity \( v_m \) under the control, and there is only one vehicle in the merging area at a time due to the control effect of the centralized controller.

Here are some assumptions for this scenario listed as follow:

a) Overtaking is not allowed for vehicles on both main road and ramp road since we only consider a single lane for both the main road and the ramp road in this scenario.

b) Lateral control is not considered because there is only one vehicle in the merging area at a time.

c) All vehicles in our scenario are homogeneous. Because of the homogeneity assumption, difference of the internal delay, like actuator lag, among vehicles can be ignored [30], which simplifies the modeling.

d) Each vehicle can be seen as a mass point because of the assumption b) and c).

For each vehicle \( V_i, i = 1, 2, \ldots \), acceleration \( a_i(t) \) is the control input, and its state is depicted as

\[
\chi_i(t) = [p_i(t), v_i(t)]
\]

where \( p_i(t), v_i(t) \) represent respectively the position and velocity of vehicle \( V_i \) at time \( t \). For simplicity, we consider a second-order dynamic model, i.e.

\[
\ddot{p}_i(t) = v_i(t) \quad \ddot{v}_i(t) = a_i(t)
\]

Marking the entry of the control area as \textit{control line} and the entry of the merging area as \textit{merging line}, the time instant when the vehicle \( V_i \) arrives at the control line is denoted as \( t^0_i \), and the moment when the vehicle reaches the merging line is denoted as \( t^f_i \). The state vector of the vehicle \( V_i \) is noted as \( \chi^0_i = \chi_i(t^0_i) \) with components \( p^0_i = p_i(t^0_i), v^0_i = v_i(t^0_i) \) at the control line, and \( \chi^f_i = \chi_i(t^f_i) \) with components \( p^f_i = p_i(t^f_i), v^f_i = v_i(t^f_i) \) at the merging line.

\section*{B. Cooperative Merging Without Considering Communication Delay}

We firstly consider the cooperative merging model without considering the communication delay. Determination of merging sequence (MS) and motion planning are two crucial aspects for the cooperative merging problem. The former is essentially a scheduling problem which assigns the priority to pass the ramp to each vehicle under consideration, and is also the prerequisite for global motion planning. The latter considers the design of algorithms to ensure all vehicles pass the merging point smoothly without collision while improving the fuel economy and traffic efficiency.

We consider an increasing number of CAVs entering the control area (see Fig. 1). When a vehicle arrives at the control line at a time \( t \), the centralized controller first assigns a unique identity \( i \) as its global order to pass the ramp in accordance with the MS scheduling algorithm. In this paper, we adopt the algorithm proposed in our previous work [11] to determine the merging sequence.

Once the identity \( i \) is assigned, control law of the trajectory planning for the vehicle \( V_i \) will be computed by the centralized controller and then send to the \( V_i \). The optimal control method proposed by Rios-Torres and Malikopoulos in [12] formulates the trajectory planning problem as a bi-objective optimization problem considering the total fuel consumption and total travel time in the control area. However, it does not take communication delay into consideration, and the communication delay can cause transient dynamic deterioration. The rest of this section will shortly introduce the key points of the optimal control method proposed in [12] to facilitate the understanding of the subsequent analysis.

This model constrains the merging area to contain only one vehicle to avoid lateral collision, which means the moment vehicle \( V_i \) reaching the merging line (see Fig. 1) is the moment when the vehicle \( V_{i-1} \) exiting the merging area. Thus, relationship between \( t^f_i \) and \( t^f_{i-1} \) satisfies the following equation.

\[
t^f_i = t^f_{i-1} + \frac{M}{v_m}
\]

where \( v_m \) is the expected velocity for all vehicles to pass the merging area. Each vehicle is expected to pass through merging area at the same velocity \( v_m \) under the control effect of the centralized controller. From equation (3), we can conclude that all \( t^f_i \) can be determined once \( t^f_{i-1} \) is ascertained.

The control output of this method is the acceleration of each vehicle \( a_i \). Applying Hamiltonian analysis to solve the optimization problem based on the Pontryagin principle [47], the optimal control law is obtained as

\[
a^*_i(t) = b_i t + c_i
\]
Furthermore, according to the vehicle dynamics depicted in formula (2), the velocity function \( v_i^*(t) \) and position function \( p_i^*(t) \) under the optimal control law can be obtained.

\[
\begin{align*}
v_i^*(t) &= \frac{1}{2} b_i t^2 + c_i t + d_i \\
p_i^*(t) &= \frac{1}{6} b_i t^3 + \frac{1}{2} c_i t^2 + d_i t + e_i
\end{align*}
\]  

(5)  

(6)

where \( b_i, c_i, d_i, e_i \) are the coefficient which can be obtained by solving the integration using the Hamiltonian analysis [47]. Given the initial value conditions (vehicle state \( \chi_i^0 = \chi(t_i^0) \) at the control line) and final value conditions (vehicle state \( \chi_i^f = \chi(t_i^f) \) at the control line), coefficients in (4) - (6) can be obtained and then the optimal control law can be determined. Combining the initial value conditions and final value conditions, these coefficients can be obtained by solving the matrix equation below.

\[
\begin{bmatrix}
\frac{1}{6}(t_i^0)^3 & \frac{1}{2}(t_i^0)^2 & t_i^0 & 1 \\
\frac{1}{6}(t_i^0)^2 & t_i^0 & 1 & 0 \\
\frac{1}{6}(t_i^0)^2 & \frac{1}{2}(t_i^0)^2 & t_i^0 & 1 \\
\frac{1}{2}(t_i^0)^2 & t_i^0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
b_i \\
c_i \\
d_i \\
e_i
\end{bmatrix}
= 
\begin{bmatrix}
p_i(t_i^0) \\
v_i(t_i^0) \\
p_i(t_i^f) \\
v_i(t_i^f)
\end{bmatrix}
\]  

(7)

For the initial value conditions and final value conditions, \( t_i^0 \) is the known time instant when the vehicle \( V_i \) reaches the control line, and \( t_i^f \) is the time instant when the vehicle \( V_i \) arrives at the merging line and can be determined through (3) \( (t_i^f \text{ should be given manually}) \). \( p_i(t_i^0) \) is the position (or coordinate value) of the control line and \( p_i(t_i^f) \) is the position (or coordinate value) of the merging line. \( v_i(t_i^0) \) is the known velocity of vehicle \( V_i \) at the moment \( t_i^0 \), \( v_i(t_i^f) \) is the expected velocity to pass the merging area and \( v_i(t_i^f) \) equals to \( v_m \). Once these initial value conditions and final value conditions are given, coefficient \( b_i, c_i, d_i, e_i \) can be computed for the corresponding vehicle \( V_i \) so that the optimal control input and the velocity and trajectory profiles for each CAV are determined.

C. Statistical Characteristics of the V2I Communication Delay

Communication delay might have potential negative effect on the control process. Considering V2I communication delay is random variable impacted by the environmental factors, probability density function (PDF) of the communication delay is explored in this subsection. Several literatures [31]–[40] have presented that the PDF of V2I communication delay is various due to the complex external factors and complicated application scenarios. Moreover, different PDF of the V2I communication delay were studied, including Normal distribution [31], Rician distribution [32], Gamma distribution [33], Weibull distribution, and Nakagami distribution [34] etc. Real field tests on the PDF of the communication delay were also implemented and the details of the results are shown in TABLE I-II and Appendix A. We found that the distributions of V2I communication delay could correlates with the application scenarios, and all the aforementioned distributions could be adopted to model the communication delay in the specific scenario. However, according to Central Limit Theorem, Rician distribution [44], Gamma distribution [45], Weibull distribution [46] and Nakagami distribution [47] can be approximate to Normal distribution when the sample size is large enough and the density is concentrated at a certain value. In our scenario, the “delay estimation area” (shown in Fig. 1) is designed for collecting enough samples to guarantee that the approximation condition is satisfied. Sample size for estimating the communication delay is greater than 200, and we can adjust the Tx/Rx frequency and the length of the delay estimation area \( D \) to satisfy the condition, which can statistically estimate the communication delay with Normal distribution, i.e.,

\[
f(\tau \mid \mu, \sigma) \approx \frac{1}{\sigma \sqrt{2\pi}} \exp \left(-\frac{(\tau - \mu)^2}{2\sigma^2}\right)
\]

(8)

where \( \tau \) is the communication delay, \( \mu \) is the concentrated value (or mean value) and \( \sigma \) is the standard deviation.

Denote \( (\tau_1, \tau_2, \ldots, \tau_i, \ldots, \tau_n) \) as \( n \) samples \( (n \text{ is large enough}) \) from population \( \tau \sim f(\tau \mid \mu, \sigma) \), \( \bar{\tau} \) is the statistical average value of the \( n \) samples. We can obtain the expectation \( E(\bar{\tau}) \) and variance \( D(\bar{\tau}) \) of \( \bar{\tau} \) in accordance with (8).

\[
E(\bar{\tau}) = E \left[ \frac{1}{n} \sum_{i=1}^{n} \tau_i \right] = \frac{1}{n} \sum_{i=1}^{n} E \tau_i = \mu
\]

(9)

\[
D(\bar{\tau}) = D \left[ \frac{1}{n} \sum_{i=1}^{n} \tau_i \right] = \frac{1}{n^2} \sum_{i=1}^{n} D \tau_i = \frac{\sigma^2}{n} \overset{n \to \infty}{\to} 0
\]

(10)

Formula (9) indicates that \( \bar{\tau} \) is an unbiased estimation for \( \mu \) and (10) illustrates the consistency between the estimation \( \bar{\tau} \) and parameters \( \mu \). Therefore, when the number of samples is large enough and the density is concentrated around a value, we can use the statistical average value \( \bar{\tau} \) to estimate the random variable \( \tau \). According to several literature investigations and our exploration results in the real field test, distribution of the communication delay has the characteristic of central concentration tendency. When the sample size is large enough, distribution of communication delay shows the feature of central concentration. In such case, using mean value to estimate the communication delay would be representative and can mitigate the dynamic performance deterioration caused by communication delay.

D. Vehicle State Correction Considering Communication Delay

The previous subsection inspires us that we can estimate the communication delay based on statistical techniques if several aforementioned conditions are satisfied. Under these conditions, we propose a model applying statistical techniques to estimate the communication delay.

Assuming the controller receive a packet from a vehicle at time \( t \) and this packet contains the vehicle information \( p_i(t), v_i(t) \) and \( a_i(t) \). If communication delay is considered, denoted as \( \tau \), then the vehicle information depicts the vehicle state at moment \( t-\tau \). If the controller directly utilizes the information
controller computes the control law, it should estimate the vehicle state at moment \( t_{i_0} + \tau_V + \tau_C \) based on the information it obtained to optimize the computation of control law. Since the time interval \( \tau_V + \tau_C \) is short (average transmission delay for C-V2X in D2D (device to device) mode is less than 30ms when the number of vehicles is less than ten [48]), acceleration \( a \) is considered as constant in this short time interval, and the estimation of the vehicle state at time \( t_{i_0} + \tau_V + \tau_C \) is

\[
\begin{align*}
\dot{a}' &= a \\
\dot{v}' &= v + a(\tau_V + \tau_C) \\
\dot{p}' &= p + a(\tau_V + \tau_C) 
\end{align*}
\]  

(13) (14) (15)

where \( a', v', p' \) are the revised information of \( a, v, p \) respectively. Combine formula (13)-(15), the matrix formation is

\[
\begin{bmatrix}
p' \\
v' \\
a'
\end{bmatrix} =
\begin{bmatrix}
1 & \tau_V + \tau_C & 0 \\
0 & 1 & \tau_V + \tau_C \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
p \\
v \\
a
\end{bmatrix}
\]  

(16)

From the derivation above, we conclude that, if communication delay is considered when controller computes the control law, estimation of the vehicle state at moment \( t_{i_0} + \tau_V + \tau_C \) is necessary. From the state transition matrix in formula (16), we can see the core is to estimate \( \tau_V + \tau_C \). Combining Equation (11) and Equation (12), we can obtain

\[
\tau_V + \tau_C = \frac{1}{n} \sum_{i=1}^{n} (t_{iC} - t_i) + \frac{1}{m} \sum_{i=1}^{m} (t_{iO} - t'_i)
\]  

(17)

Plug formula (17) into (16), and then the estimation of the vehicle state at moment \( t_{i_0} + \tau_V + \tau_C \), i.e., the moment when the vehicle receives the control law, can be obtained, so that the control law can be computed in accordance with the revised vehicle state through formula (7).

IV. EXPERIMENTS AND NUMERICAL SIMULATION

To verify several conclusions illustrated in the methodology section, a real test field was firstly conducted to explore the statistical characteristics of V2I communication delay and packet delivery rate. Referring to the results obtained from the test field, we then numerically simulated the on-ramp merging scenario and illustrate the impact of the communication delay to the control. And finally, impact of the packet loss to the communication delay estimation was numerically simulated.

A. Exploration to the Statistical Characteristics of V2I Communication Delay

In this part, we test the communication delay and packet delivery rate (PDR, PDR=1-packet loss rate) of the V2I equipment (DSRC equipment and LTE-V equipment) in the Connected Autonomous Vehicle Test Field (the CAV Test Field, shown in Fig. 3) of Chang’an University.

Several scenarios were considered including 1) static, open environment; 2) static environment with many shelters (referring to trees in this experiment); 3) driving, open environment (in a radius within 200m around the receiver). The sender is firstly approaching the receiver and then going away from the
receiver). The vehicle terminal sends messages with timestamp and the RSU will directly return the messages it receives to the vehicle terminal. Round-Trip Time (RTT) was collected to depict the characteristics of the V2I communication delay, and the statistical average was adopted to represent the communication characteristic for a specific scenario, shown in Fig. 4 to Fig. 6.

Comparing the results shown in Fig. 4 and Fig. 5, we can conclude that shelters exert great negative impact on the V2I communication quality. Particularly, the PDR is severely impacted in the environment with shelters. According to Fig. 4 and Fig. 6, communication distance and driving velocity also have impact on the V2I communication quality in this test.

We then explored the distribution of the V2I communication delay (represented via RTT) in this field test. We selected Normal distribution, Rician distribution, Gamma distribution, Weibull distribution and Nakagami distribution to fit the communication delay. TABLE I and TABLE II present the closest PDF of the V2I communication delay in different scenarios. In these tables, the notations in the left side consist of three parts, the first term means the test metric, i.e., RTT, the second one means the V2I communication equipment, and the third one is the testing scenarios. For example, “rtt_dsrc_open100” means open environment using DSRC equipment, where the distance between the sender and the receiver is 100m; “rtt_lte-v_tree20” means the environment with many trees, using LTE-V equipment, where the distance between the sender and the receiver is 20m; “rtt_lte-v_10km/h” means the driving environment (open environment), where the velocity of the vehicle with the on-board LTE-V equipment is 10km/h, and so on. Corresponding PDF fitting curves (obtained via the Statistics and Machine Learning Toolbox in MATLAB) are shown in Appendix A. Some basic statistics of the V2I communication equipment in different scenarios are presented in Appendix B. And log likelihood (calculated via the Statistics and Machine Learning Toolbox in MATLAB) of each fitting PDF for the V2I communication delay is presented in Appendix C.

If the communication environment is an open environment, no matter the vehicle is in static environment or driving environment, the performance for both DSRC equipment and LTE-V equipment is acceptable in a certain communication distance. Generally, DSRC devices outperform the LTE-V equipment on communication delay in this test, but its performance on PDR is inferior to the LTE-V equipment once the communication distance increases.

TABLE I

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Closest PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>rtt_dsrc_open100</td>
<td>Gamma</td>
</tr>
<tr>
<td>rtt_dsrc_open200</td>
<td>Nakagami</td>
</tr>
<tr>
<td>rtt_dsrc_open300</td>
<td>Gamma</td>
</tr>
<tr>
<td>rtt_dsrc_open400</td>
<td>Gamma</td>
</tr>
<tr>
<td>rtt_dsrc_tree20</td>
<td>Nakagami</td>
</tr>
<tr>
<td>rtt_dsrc_tree40</td>
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</tr>
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<td>rtt_dsrc_tree60</td>
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</tr>
<tr>
<td>rtt_dsrc_tree65</td>
<td>Gamma</td>
</tr>
<tr>
<td>rtt_lte-v_10km/h</td>
<td>Nakagami</td>
</tr>
<tr>
<td>rtt_lte-v_20km/h</td>
<td>Gamma</td>
</tr>
<tr>
<td>rtt_lte-v_30km/h</td>
<td>Gamma</td>
</tr>
<tr>
<td>rtt_lte-v_40km/h</td>
<td>Nakagami</td>
</tr>
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<tr>
<td>rtt_lte-v_60km/h</td>
<td>Nakagami</td>
</tr>
<tr>
<td>rtt_lte-v_70km/h</td>
<td>Gamma</td>
</tr>
<tr>
<td>rtt_lte-v_80km/h</td>
<td>Nakagami</td>
</tr>
</tbody>
</table>

From TABLE I and TABLE II, we can conclude that Gamma distribution and Nakagami distribution are more suitable for V2I communication delay distribution in the open environment.
area as test field shown in Fig. 3, setting the length of the control et al. initial positions and random initial velocity as a case study. vehicles on each road are randomly given) with random coordinates 10 vehicles merging on the ramp (number of further impact the control performance. V2I equipment will affect the calculation of acceleration, and acceleration (deacceleration). Communication delay of the performance of the control process and potentially impact the communication delay distribution using the LTE-V equipment. In fact, the results of V2I communication delay distribution fitting could be very close among the above distributions (see details in Appendix A and Appendix C), and real distribution of the V2I communication could be strongly related to the external environment.

### B. Numerical Simulation for the Impact of V2I Communication Delay

Communication delay will deteriorate the dynamic performance of the control process and potentially impact the final control effect. The control law (i.e., the acceleration) calculated in [12] was pre-designed but did not consider the practical dynamic constraints of the vehicle. If the pre-designed acceleration satisfies the dynamic constraints, the vehicle would conduct the control law. However, if the pre-designed acceleration exceeds the range (According to the test to the automated electronic vehicle owned by our lab, the acceleration range for the automated electronic vehicle is \([-5, 5]\) m/s\(^2\), the vehicle would conduct the maximal acceleration (deacceleration)). Communication delay of the V2I equipment will affect the calculation of acceleration, and further impact the control performance.

Here we simulate the scenario where a centralized controller coordinates 10 vehicles merging on the ramp (number of vehicles on each road are randomly given) with random initial positions and random initial velocity as a case study. We referred to Chen et al. [15] and the real situation of the test field shown in Fig. 3, setting the length of the control area as \(L = 400\) m (i.e., \(p_f = 400\) m, considering the communication range) and the length of the merging area as \(M = 30\) m. Length of the delay estimation area \(D\) is set as 100m for V2I communication delay estimation. The speed of vehicles at the control line is randomly initialized and obey normal distribution. Specifically, the initial speed \(v_i (t_0) \sim N(15, 0.5^2)\), and all vehicles are expected to pass the merging area with \(7_{mm} = 13.4\) m/s (i.e., \(v_f = 13.4\) m/s) due to control effect of the centralized controller.

**Case 1 (The pre-Designed Acceleration Still Satisfies the Constraint Under the Impact of Communication Delay):** In this case, we set the communication \(\tau\) as an normal distributed random variable, where \(\tau \sim N(25, 12^2)\) (the unit is milliseconds. If the value is less than zero, the random variable would be regenerated until it is greater than 0). Since the acceleration still satisfies the constraint, the vehicle would conduct the calculated acceleration. Fig. 7-9 show the control effect.

In this case, trajectories are still pre-designed and Equation (3) can be guaranteed. Thus, the communication delay does not impact the final control results (trajectories in the merging area) once the final value conditions are given, using the control method proposed in [12]. Each vehicle passes through the merging area only after its previous vehicle has already left (i.e., there is one vehicle in the merging area at a time). All vehicles keep the constant distance that equals to the length of merging area \(M = 30\) m and keep the constant time headway which equals to the expected time headway \(M/\omega_m = 2.24\) s. While in Fig. 7, we can see that all control inputs are bounded within \([-3, 3]\) m/s\(^2\) if the influence of communication delay is considered, which means that communication delay might cause unexpected high acceleration (deacceleration) in the control process. Compared to the situation in which communication delay is not considered, estimation to the communication delay and correction to the vehicle state on the control line improve the dynamic performance of the control process.

**Case 2 (The pre-Designed Acceleration Exceeds the Constraint Under the Impact of Communication Delay):** In this case, if the pre-designed acceleration exceeds the range \(([-5, 5]) m/s^2\), the vehicle would conduct the maximal acceleration (deacceleration). Thus, Equation (3) cannot be guaranteed and potential lateral collision might occur, shown in Fig. 10-12.

In this case, we set the communication \(\tau\) as a normal distributed random variable, where \(\tau \sim N(500, 20^2)\) (the
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Fig. 8. Velocity profiles of the vehicles, Case 1.

Fig. 9. Position trajectories of the vehicles, Case 1.

Fig. 10. Control inputs (acceleration) of the vehicles, case 2.

unit is millisecond). Fig. 10 presents the case where the pre-designing of acceleration for some vehicles fails under the impact of the communication delay. In such case, trajectories of some vehicles are not pre-designed and Equation (3) cannot be guaranteed. Thus, potential lateral collision might occur (presented in Fig. 12) and the final control result (trajectories in the merging area) are severely impacted.

To summarize, the V2I communication delay would impact the pre-designing of the control variable (acceleration in the context) and further impact the control process. If the constraint of acceleration is still satisfied, dynamic performance would be deteriorated but the effect in the merging area would not change using the optimal control method proposed in [12]. However, if the vehicle acceleration exceeds the constraint under the impact of communication delay, the final control effect can be severely impacted and potential lateral collision might occur.

C. Simulation for the Impact of the Packet Loss to the Communication Delay Estimation

Impact of the packet loss to the communication delay estimation is mainly due to the retransmission or the message missing. Since V2V or V2I equipment usually adopt the communication protocol without retransmission mechanism (like DSRC) to assure the real-time performance in the practical application, we simulate the influence caused by the message missing in this part to validate the robustness of the statistical method proposed in the previous section.

In the simulation, we set $\tau_V$ and $\tau_C$ as two random normal variables with mean value as 25ms and standard deviation as 12ms (In a specific simulation step, if the value is less
TABLE III
RELATIVE ERROR FOR COMMUNICATION DELAY IN DIFFERENT SAMPLE SIZE, WITH FIXED PACKET LOSS RATE AS 0.5

<table>
<thead>
<tr>
<th>Sample size of the controller sender</th>
<th>10</th>
<th>50</th>
<th>100</th>
<th>500</th>
<th>1000</th>
<th>5000</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.12837</td>
<td>0.125398</td>
<td>0.14106</td>
<td>0.062615</td>
<td>0.095144</td>
<td>0.076689</td>
<td>0.108573</td>
</tr>
<tr>
<td>50</td>
<td>0.061102</td>
<td>0.085573</td>
<td>0.039555</td>
<td>0.035922</td>
<td>0.032915</td>
<td>0.069751</td>
<td>0.04906</td>
</tr>
<tr>
<td>100</td>
<td>0.116506</td>
<td>0.054712</td>
<td>0.037182</td>
<td>0.023306</td>
<td>0.023938</td>
<td>0.018356</td>
<td>0.02584</td>
</tr>
<tr>
<td>500</td>
<td>0.121518</td>
<td>0.076703</td>
<td>0.020107</td>
<td>0.01372</td>
<td>0.015802</td>
<td>0.00988</td>
<td>0.011872</td>
</tr>
<tr>
<td>1000</td>
<td>0.084223</td>
<td>0.030147</td>
<td>0.026576</td>
<td>0.01442</td>
<td>0.009725</td>
<td>0.009149</td>
<td>0.00867</td>
</tr>
<tr>
<td>5000</td>
<td>0.081073</td>
<td>0.044235</td>
<td>0.048143</td>
<td>0.009611</td>
<td>0.009374</td>
<td>0.004512</td>
<td>0.005346</td>
</tr>
<tr>
<td>10000</td>
<td>0.087842</td>
<td>0.063533</td>
<td>0.023385</td>
<td>0.021631</td>
<td>0.024451</td>
<td>0.004324</td>
<td>0.002845</td>
</tr>
</tbody>
</table>

Fig. 14. Relative error change with packet loss rate (fix the packet loss rate for one of the receivers as 0.6).

Fig. 15. Relative error with packet loss rate close to 1 (fix the packet loss rate for one of the receivers as 0.1).

Fig. 16. Relative error change with sample size (sample size for both receivers is the same).

Performance of communication delay estimation. From Fig. 15, we can see that the relative error sharply rises when the packet loss rate of either of the receiver is close to 1. One interesting phenomenon is that, when the packet loss rate is not so extreme (i.e., close to 1), the relative error is still acceptable even with the packet loss is as high as 0.8. The reason can be explained by the large sample size. In this simulation, both the vehicle and the controller will send 1000 packets in each step, i.e., the sample size is 1000. Thus, the receiver can still obtain a sufficient number of packets to estimate the communication delay. TABLE III and Fig. 16 illustrate the change of relative error with the sample size, with fixed packet loss rate as 0.5. Here, Fig. 16 is the plot of the diagonal element of TABLE III. We can conclude that the large sample size compensates the negative effect brought by the packet loss to some degree. If we can increase the number of samples somehow, the negative effect caused by the packet loss to communication delay estimation can be mitigated.

V. DISCUSSION

To simplify the model, this paper assumes that all vehicles are homogenous CAVs. We would like to extend the discussion from two aspects, i.e., heterogeneity and connection of the vehicles. Here, heterogeneity is represented by different (and uncertain) time constants for the driveline dynamics and possibly different (and uncertain) engine performance coefficients between vehicles [49]. If all the vehicles are CAVs but heterogeneous, their behaviors are still controlled by the...
centralized controller and their trajectories can be pre-designed to avoid the potential collision in the merging area. However, such heterogeneity may deteriorate the dynamic performance of the control process. Take actuator lag as an example, Wang [30] presented that actuator lag might have negative effects on string stability for a heterogeneous platoon and its impact to the vehicle string is uncertain unless the disturbance condition is given. If some of the vehicles are not connected, CAVs require to perceive the behaviors of the non-connected vehicles via the on-board sensors and plan the trajectory to avoid potential collisions. Therefore, even the CAVs are controlled by the centralized controller, the well-planned merging sequence for CAVs may be interrupted by the non-connected vehicles, and their trajectories can hardly be pre-designed. Thus, most global-optimization-based methods may not work in such case, and dynamic programming or game theory can be considered to solve the trajectory planning problem. For example, in [50], Huang and Sun developed a cooperative ramp merging mechanism using discrete optimization to capture the cooperative and non-cooperative behaviors, where the optimal control-based trajectory design problem was embedded in the merging sequencing problem, and a bi-level dynamic programming-based solution approach was proposed to solve the problem. In [51], Liao et al. proposed a game theory-based ramp merging strategy for CAVs in the mixed traffic, which was a decentralized agent-based algorithm and could provide the optimal merging sequence and respective speed trajectory for each CAV in real time.

In the previous context, we adopted normal distribution to approximate the probability density function (PDF) of the V2I communication delay under the condition that the number of samples is large enough and the density is concentrated around a value. Through adjusting the Tx/Rx frequency of the DSRC or LTE-V equipment or the length of the delay estimation area $D$, number of samples could be satisfied for the communication delay estimation. Distribution of the communication delay is related to application environment and the exploration of V2I communication delay under specific scenarios is still an open issue no matter in literature or in engineering application. However, normal distribution could approximate most of the cases in general, and statistically estimating the V2I communication delay to improve the system performance is a useful technique in the practical application.

VI. Conclusion

In this paper, we studied the scenario of on-ramp merging for CAVs considering the communication delay of the V2I
equipment. Generally, for a cooperative on-ramp merging problem, determination of merging sequence (MS) and trajectory planning are two basic aspects. The former is, in fact, a scheduling problem that takes the passing sequence for each vehicle into consideration, while the latter is an algorithm that ensures all vehicles pass the ramp smoothly without collision, and aims to improve the traffic performance. We adopted the methods proposed in our previous work [11] to ascertain the merging sequence and the optimal control method proposed by Rios-Torres and Malikopoulos [12] to solve the trajectory planning problem. On this basis, we further considered the influence caused by the communication delay. First, the statistical characteristics of the V2I communication delay were explored. Then, we proposed a communication delay
estimation model based on several statistical techniques and used the revised vehicle state to compute the corresponding control law. Real field test was implemented to explore the statistical characteristics of V2I communication delay and packet delivery rate. Referring to the results obtained from the test field, we then numerically simulated the on-ramp merging scenario and illustrated the impact of the communication delay to the control. Numerical simulation for the impact of V2I communication delay revealed that the communication delay would impact the pre-designing of the control variable (acceleration in this paper) and further impact the control process. If the constraint of acceleration is still satisfied, dynamic performance would be deteriorated but the effect in the merging area would not change using the optimal control method proposed in [12]. However, if the vehicle acceleration exceeds the constraint under the impact of communication delay, the final control effect can be severely affected and potential lateral collision may occur. Besides, simulation for the impact of the packet loss to the communication delay estimation indicated that the receiver with higher packet loss rate dominates the estimation accuracy to the communication delay, but the large sample size would compensate the negative impact brought by the packet loss to certain degree.

For the future work, first of all, length and width of the vehicles will be considered and lateral control methods should be added to avoid collision in the on-ramp merging scenario. Besides, factors would impact the communication delay in a realistic environment can be various and complex. According to [35], these factors may be the traffic volume, geometry of the roadway and the objects around the communication nodes, and whether conditions etc. Thus, more studies should be carried out on the communication delay and packet loss in the complex environment to explore their influence to the on-ramp merging problem and other transportation scenarios.

**APPENDICES**

**A. Probability Density Function Fitting Curves of the Vehicle-to-Infrastructure Communication in Different Scenarios**

In each sub-graph, the horizontal axis represents the round-trip time (RTT) value (unit: ms) and the vertical axis represents the probability density. Lines with different color in each sub-graph are different fitting probability density functions (PDFs), including Normal distribution, Rician distribution, Gamma distribution, Weibull distribution and Nakagami distribution. Notations of these sub-graphs consist of three parts, the first term means the test item, i.e., RTT, the second one means the V2I communication equipment, and the third one is the testing scenarios. For example, “rtt_dsrc_open100” means open environment using DSRC equipment, where the distance between the sender and the receiver is 100m; “rtt_lte-v_tree20” means the environment with many trees, using LTE-V equipment, where the distance between the sender and the receiver is 20m; “rtt_lte-v_10km/h” means the driving environment (open

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**TABLE VII**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Normal Log Likelihood</th>
<th>Rician Log Likelihood</th>
<th>Gamma Log Likelihood</th>
<th>Weibull Log Likelihood</th>
<th>Nakagami Log Likelihood</th>
<th>Closet PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>open100</td>
<td>-2939.09</td>
<td>-2918.68</td>
<td>-2893.55</td>
<td>-2909.71</td>
<td>-2902.91</td>
<td>Gamma</td>
</tr>
<tr>
<td>open200</td>
<td>-2970.57</td>
<td>-2885.00</td>
<td>-2812.71</td>
<td>-2874.34</td>
<td>-2847.86</td>
<td>Gamma</td>
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<tr>
<td>open300</td>
<td>-2875.84</td>
<td>-2857.59</td>
<td>-2837.01</td>
<td>-2849.71</td>
<td>-2843.32</td>
<td>Gamma</td>
</tr>
<tr>
<td>open400</td>
<td>-2760.12</td>
<td>-2741.73</td>
<td>-2719.41</td>
<td>-2733.70</td>
<td>-2727.03</td>
<td>Gamma</td>
</tr>
<tr>
<td>tree20</td>
<td>-2380.43</td>
<td>-2273.64</td>
<td>-2275.99</td>
<td>-2272.18</td>
<td>-2269.22</td>
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<tr>
<td>tree60</td>
<td>-1824.85</td>
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<td>-1240.82</td>
<td>-1257.29</td>
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<td>-1240.03</td>
<td>-1241.69</td>
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<td>-426.26</td>
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<tr>
<td>10km/h</td>
<td>2844.24</td>
<td>-2826.84</td>
<td>-2793.00</td>
<td>-2817.67</td>
<td>-2806.52</td>
<td>Gamma</td>
</tr>
<tr>
<td>20km/h</td>
<td>2840.73</td>
<td>-2823.81</td>
<td>-2782.56</td>
<td>-2813.87</td>
<td>-2800.18</td>
<td>Gamma</td>
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<tr>
<td>30km/h</td>
<td>2882.83</td>
<td>-2866.21</td>
<td>-2836.69</td>
<td>-2857.71</td>
<td>-2847.26</td>
<td>Gamma</td>
</tr>
<tr>
<td>40km/h</td>
<td>2915.15</td>
<td>-2893.19</td>
<td>-2858.03</td>
<td>-2883.43</td>
<td>-2872.67</td>
<td>Gamma</td>
</tr>
<tr>
<td>50km/h</td>
<td>2637.43</td>
<td>-2345.96</td>
<td>-2322.95</td>
<td>-2358.31</td>
<td>-2323.30</td>
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<tr>
<td>60km/h</td>
<td>2224.23</td>
<td>-2204.86</td>
<td>-2182.99</td>
<td>-2197.93</td>
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<tr>
<td>70km/h</td>
<td>2807.81</td>
<td>-2784.45</td>
<td>-2756.75</td>
<td>-2775.99</td>
<td>-2768.05</td>
<td>Gamma</td>
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<td>80km/h</td>
<td>2840.36</td>
<td>-2824.48</td>
<td>-2816.48</td>
<td>-2818.93</td>
<td>-2814.76</td>
<td>Nakagami</td>
</tr>
</tbody>
</table>
environment), where the velocity of the vehicle with the on-board LTE-V equipment is 10km/h, and so on.

Case 1: See Figure 17.
Case 2: See Figure 18.
Case 3: See Figure 19.

B. Some Statistics of the Vehicle-to-Infrastructure Communication Equipment in Different Scenarios in the Field Test

See Tables IV and V.

C. Log Likelihood of Each fitting PDF for the Vehicle-to-Infrastructure Communication Delay in Different Scenarios

See Tables VI and VII.

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Yukun Fang received the B.E. degree in communication engineering from Chang’an University, China, in 2019, where he is currently pursuing the Ph.D. degree in traffic information engineering and control. His current research interests include cooperative control for connected and automated vehicles, fault detection, and diagnosis for intelligent vehicles.

Xia Wu received the Ph.D. degree in traffic information engineering and control from Chang’an University, China, in 2020. Her current research interests include mixed traffic flow control, trajectory optimization in a mixed traffic flow with connected and automated vehicles, and human-driven vehicles.

Guoqiang Mao (Fellow, IEEE) has published over 200 papers in international conferences and journals, which have been cited more than 8500 times. His research interests include intelligent transport systems, applied graph theory and its applications in telecommunications, the Internet of Things, wireless sensor networks, wireless localization techniques, and network modeling and performance analysis. He is a fellow of IET. He was the Co-Chair of IEEE Intelligent Transport Systems Society Technical Committee on Communication Networks. He has served as the chair, the co-chair, and a TPC member of a number of international conferences. He is an Editor of the IEEE Transactions on Intelligent Transportation Systems (since 2018), IEEE Transactions on Wireless Communications (2014–2019), and IEEE Transactions on Vehicular Technology (since 2010), and received the “Top Editor” award for outstanding contributions to the IEEE Transactions on Vehicular Technology in 2011, 2014, and 2015.

Wuqi Wang received the B.E. degree in computer science from Chang’an University, China, in 2020, where he is currently pursuing the Ph.D. degree in traffic information engineering and control. His current research interests include simultaneous localization and mapping, high-precision positioning, and CAV decision-making.

Xiangmo Zhao (Member, IEEE) received the Ph.D. degree from Chang’an University, Xi’an, China. He is currently a Professor with the School of Information Engineering, Chang’an University. He is currently the Vice President of the Joint Laboratory for Connected Vehicles, Ministry of Education-China Mobile Communications Corporation, and the Shaanxi Road Traffic Intelligent Detection and Equipment Engineering Technology Research Centre, and also the Leader of the National Key Subjects-Traffic Information Engineering and Control, Chang’an University. His current research interests include connected vehicles, automated vehicles, intelligent transportation systems, and computer science. He is the Director of the Information Professional Committee; a member of the Advisory Expert Group of the China Transportation Association, the National Motor Vehicle Operation Safety Testing Equipment Standardization Committee, and the Leading Group of the National Traffic Computer Application Network; the Vice Chairperson of the Institute of Highway Association on Computer Professional Committee; and the Deputy Director of the Institute of Computer in Shaanxi Province.

Haigen Min (Member, IEEE) received the B.S., M.S., and Ph.D. degrees from the Department of Traffic Information Engineering and Control, Chang’an University, and he is currently a Lecturer with Chang’an University. His research interests include high-precision localization, environment perception, and cooperative control for connected and automated vehicles and its fault detection and diagnosis.