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

Yukun Fang, 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.**

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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

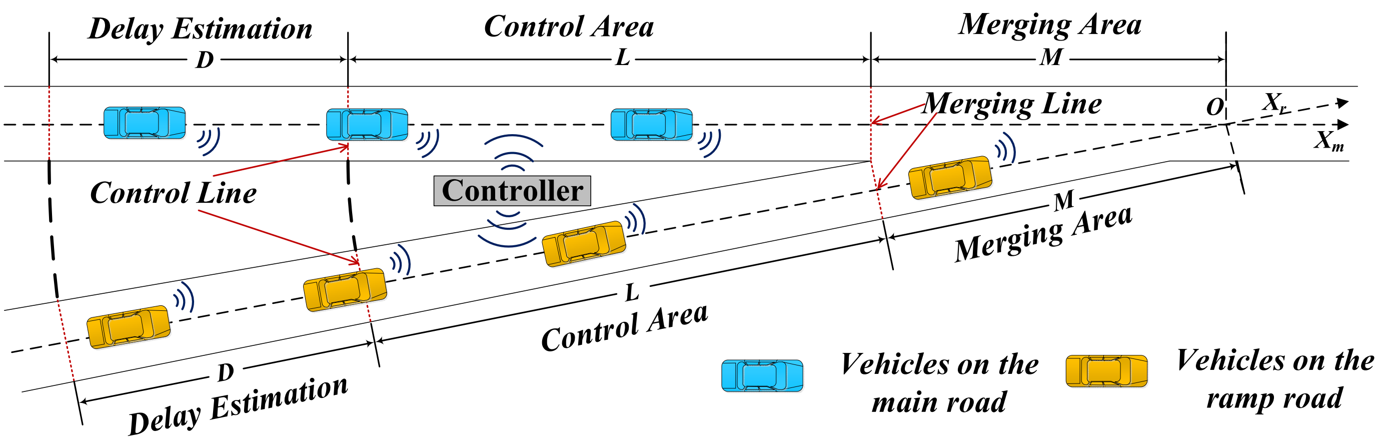


Fig. 1. General description for the on-ramp scenario.

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 partiality 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

$$\chi_i(t) = [p_i(t), v_i(t)] \tag{1}$$

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.

$$\dot{p}_i(t) = v_i(t) \quad \dot{v}_i(t) = a_i(t) \tag{2}$$

Marking the entry of the control area as *control line* and the entry of the merging area as *merging line*, the time instant when the vehicle V_i arrives at the control line is denoted as t_i^0, and the moment when the vehicle reaches the merging line is denoted as t_i^f. The state vector of the vehicle V_i is noted as $\chi_i^0 = \chi_i(t_i^0)$ with components $p_i^0 = p_i(t_i^0)$, $v_i^0 = v_i(t_i^0)$ at the control line, and $\chi_i^f = \chi_i(t_i^f)$ with components $p_i^f = p_i(t_i^f)$, $v_i^f = v_i(t_i^f)$ at the merging line.

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 instant 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_i^f and t_{i-1}^f satisfies the following equation.

$$t_i^f = t_{i-1}^f + \frac{M}{v_m} \tag{3}$$

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_i^f can be determined once t_1^f 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

$$a_i^*(t) = b_i t + c_i \tag{4}$$

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.

$$v_i^*(t) = \frac{1}{2}b_i t^2 + c_i t + d_i \tag{5}$$

$$p_i^*(t) = \frac{1}{6}b_i t^3 + \frac{1}{2}c_i t^2 + d_i t + e_i \tag{6}$$

where b_i, c_i, d_i, e_i are the coefficient when calculating the integration using the Hamiltonian analysis [47]. Given the initial value conditions (vehicle state $\chi_i^0 = \chi_i(t_i^0)$ at the control line) and final value conditions (vehicle state $\chi_i^f = \chi_i(t_i^f)$ 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

$$\begin{bmatrix} \frac{1}{6}(t_i^0)^3 & \frac{1}{2}(t_i^0)^2 & t_i^0 & 1 \\ \frac{1}{2}(t_i^0)^2 & t_i^0 & 1 & 0 \\ \frac{1}{6}(t_i^f)^3 & \frac{1}{2}(t_i^f)^2 & t_i^f & 1 \\ \frac{1}{2}(t_i^f)^2 & t_i^f & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} b_i \\ c_i \\ d_i \\ e_i \end{bmatrix} = \begin{bmatrix} p_i(t_i^0) \\ v_i(t_i^0) \\ p_i(t_i^f) \\ v_i(t_i^f) \end{bmatrix} \tag{7}$$

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_1^fshould 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.,

$$f(\tau \mid \mu, \sigma) \approx \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\tau-\mu)^2}{2\sigma^2}\right) \tag{8}$$

where τ is the communication delay, μ is the concentrated value (or mean value) and σ is the standard deviation.

Denote $(\tau_1, \tau_2, \ldots, \tau_i, \ldots, \tau_n)$ as n samples (n is large enough) from population $\tau \sim f(\tau|\mu,\sigma)$, $\bar{\tau}$ 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),

$$E(\bar{\tau}) = E\left[\frac{1}{n}\sum_{i=1}^{n}\tau_i\right] = \frac{1}{n}\sum_{i=1}^{n}E\tau_i = \mu \tag{9}$$

$$D(\bar{\tau}) = D\left[\frac{1}{n}\sum_{i=1}^{n}\tau_i\right] = \frac{1}{n^2}\sum_{i=1}^{n}D\tau_i = \frac{\sigma^2}{n} \xrightarrow{n\to\infty} 0 \tag{10}$$

Formula (9) indicates that $\bar{\tau}$ is an unbiased estimation for μ and (10) illustrates the consistency between the estimation $\bar{\tau}$ and parameters μ. 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 τ. According to several literature investigations and our exploration results in the real field test, distribution of the communication delay has the characteristic of 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 τ_V, then the vehicle information depicts the vehicle state at moment t-τ_V. If the controller directly utilizes the information

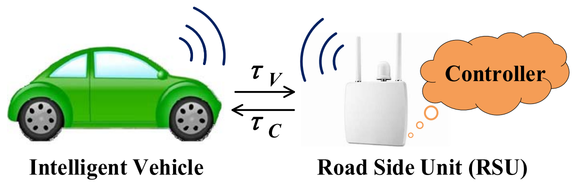


Fig. 2. Schematic of the communication delay.

to compute the control law, it may cause obvious deviations. Therefore, correction of the vehicle state $\chi = [p_i(t), v_i(t)]$ is required if time delay is taken into consideration.

The signal delay sent by an intelligent vehicle to a controller RSU (Road Side Unit) is Denoted as τ_V, and the delay of the signal sent by the controller to the vehicle is expressed as τ_C, shown in Fig. 2. $\Delta \in \mathbb{R}$ is the constant offset between the clocks of the intelligent vehicle and the controller, and Δ can be positive or negative. Here, Δ is defined as the offset of the vehicle's clock in relation with the controller's clock. Assuming the random error caused by the environment is Gaussian distributed and the controller receives n packets $(t_1, p_1, v_1, a_1), (t_2, p_2, v_2, a_2), \ldots, (t_i, p_i, v_i, a_i), \ldots, (t_n, p_n, v_n, a_n)$ from the vehicle at moment $t_{1c}, t_{2c}, \ldots, t_{ic}, \ldots, t_{nc}$ respectively, then, τ_V satisfies

$$\frac{1}{n}\sum_{i=1}^{n}(t_{ic} - t_i) = \tau_V + \Delta \tag{11}$$

Here, $t_1, t_2, \ldots, t_i, \ldots, t_n$ are the time stamps information defined according to the clock of the vehicle, and time instants $t_{1c}, t_{2c}, \ldots, t_{ic}, \ldots, t_{nc}$ are defined in accordance with the clock of the controller, and for each $i = 1, 2, \ldots, n$, $t_{1c} < t_{2c} < \ldots < t_{ic} < \ldots t_{nc}$, $t_1 < t_2 < \ldots < t_i \ldots < t_n$.

To estimate τ_C, the controller will also send its time stamps to the vehicle. Assuming the vehicle receives m time stamps $t_1, t_2, \ldots t_i, \ldots t_m$ at time instants $t_{1v}, t_{2v}, \ldots t_{iv}, \ldots, t_{mv}$ respectively, the equation that estimate τ_C can be formulated as

$$\frac{1}{m}\sum_{i=1}^{m}(t_{iv} - t_i') = \tau_C - \Delta \tag{12}$$

Here, $t_1, t_2, \ldots t_i, \ldots t_m$ are the time stamps information defined according to the clock of the controller, and time instants $t_{1v}, t_{2v}, \ldots t_{iv}, \ldots, t_{mv}$ are defined in accordance with the clock of the vehicle, and for each $i = 1, 2, \ldots, m$, $t_{1v} < t_{2v} < \ldots < t_{iv} < \ldots t_{mv}$, $t_1 < t_2 < \ldots t_i < \ldots < t_m$.

Process of the signal transmitting can be briefly summarized as follow. First, at time t_{iv}, the vehicle sends a packet including its state information $\chi = [p, v]$, the acceleration information a, and time stamps information, and the controller receives the packet. Communication delay of this process is τ_V. Then, the controller computes the control law and sends a packet containing the control law output and the time stamps information to the vehicle, and the vehicle receives the packet. Communication delay of this process is τ_C. Therefore, the total time interval from the vehicle sending its state information to the vehicle receiving the control law is $\tau_V + \tau_C$, and the vehicle will receive the control law at the moment $t_{iv} + \tau_V + \tau_C$. When controller computes the control law, it should estimate the vehicle state at moment $t_{iv} + \tau_V + \tau_C$ 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 $t_{iv} + \tau_V + \tau_C$ is

$$a' = a \tag{13}$$

$$v' = v + a(\tau_V + \tau_C) \tag{14}$$

$$p' = p + v(\tau_V + \tau_C) \tag{15}$$

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

$$\begin{bmatrix} p' \\ v' \\ a' \end{bmatrix} = \begin{bmatrix} 1 & \tau_V + \tau_C & 0 \\ 0 & 1 & \tau_V + \tau_C \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p \\ v \\ a \end{bmatrix} \tag{16}$$

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 $t_{iv} + \tau_V + \tau_C$ 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

$$\tau_V + \tau_C = \frac{1}{n}\sum_{i=1}^{n}(t_{ic} - t_i) + \frac{1}{m}\sum_{i=1}^{m}(t_{iv} - t_i') \tag{17}$$

Plug formula (17) into (16), and then the estimation of the vehicle state at moment $t_{iv} + \tau_V + \tau_C$, 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

Fig. 3. Test field for V2I data collection.

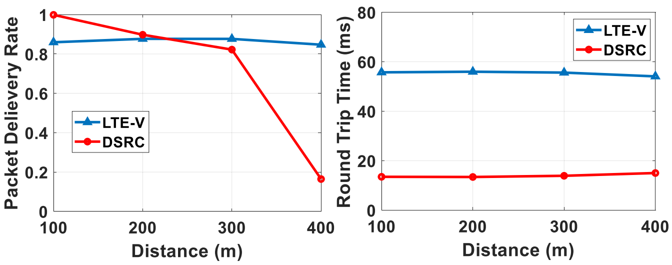


Fig. 4. Test conducted in the static and open environment.

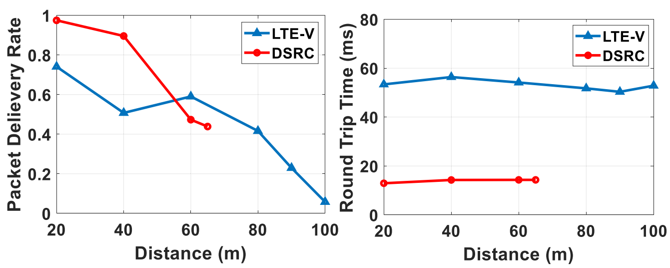


Fig. 5. Test conducted in the environment with shelters (trees).

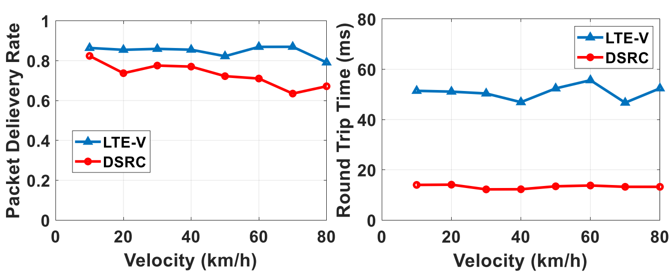


Fig. 6. Test in the driving, open environment.

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.

TABLE I
PDF FITTING OF COMMUNICATION DELAY IN DIFFERENT SCENARIOS, USING DSRC EQUIPMENT

Test Case	Closest PDF
rtt_dsrc_open100	Gamma
rtt_dsrc_open200	Nakagami
rtt_dsrc_open300	Gamma
rtt_dsrc_open400	Gamma
rtt_dsrc_tree20	Nakagami
rtt_dsrc_tree40	Gamma
rtt_dsrc_tree60	Nakagami
rtt_dsrc_tree65	Gamma
rtt_dsrc_10km/h	Nakagami
rtt_dsrc_20km/h	Gamma
rtt_dsrc_30km/h	Gamma
rtt_dsrc_40km/h	Nakagami
rtt_dsrc_50km/h	Nakagami
rtt_dsrc_60km/h	Nakagami
rtt_dsrc_70km/h	Gamma
rtt_dsrc_80km/h	Nakagami

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.

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.

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

TABLE II
PDF FITTING OF COMMUNICATION DELAY IN DIFFERENT SCENARIOS, USING LTE-V EQUIPMENT

Test Case	Closest PDF
rtt_lte-v_open100	Gamma
rtt_lte-v_open200	Gamma
rtt_lte-v_open300	Gamma
rtt_lte-v_open400	Gamma
rtt_lte-v_tree20	Nakagami
rtt_lte-v_tree40	Rician
rtt_lte-v_tree60	Nakagami
rtt_lte-v_tree80	Rician
rtt_lte-v_tree90	Rician
rtt_lte-v_tree100	Normal
rtt_lte-v_10km/h	Gamma
rtt_lte-v_20km/h	Gamma
rtt_lte-v_30km/h	Gamma
rtt_lte-v_40km/h	Gamma
rtt_lte-v_50km/h	Gamma
rtt_lte-v_60km/h	Gamma
rtt_lte-v_70km/h	Gamma
rtt_lte-v_80km/h	Nakagami

environment than others, whether it is DSRC equipment or the LTE-V equipment. In the environment with many trees, Rician distribution seems to be more proper than others to fit the V2I 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 $[-5,\ 5]\text{m/s}^2$), 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., $p_i^f = 400$m, considering the

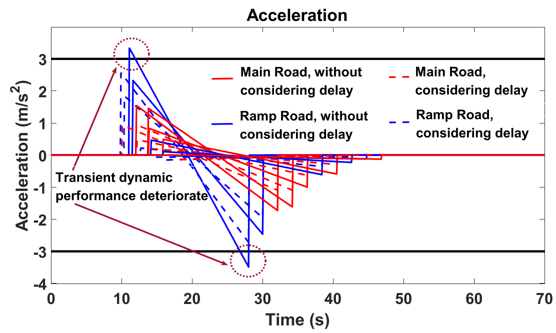


Fig. 7. Control inputs (acceleration) of the vehicles, Case 1.

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 $v_i(t_i^0) \sim N(15, 0.5^2)$, and all vehicles are expected to pass the merging area with $v_m = 13.4$m/s (i.e., $v_i^f = 13.4$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 τ as an normal distributed random variable, where $\tau \sim N(25, 12^2)$ (the unit is millisecond. 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 $M/v_m = 2.24$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 ($[-5,\ 5]\text{m/s}^2$), 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 τ as a normal distributed random variable, where $\tau \sim N$ $(500,\ 20^2)$ (the

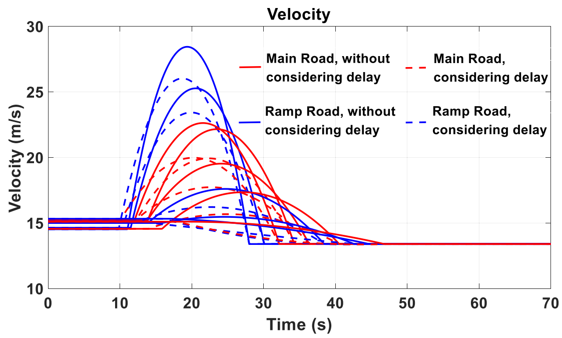


Fig. 8. Velocity profiles of the vehicles, Case 1.

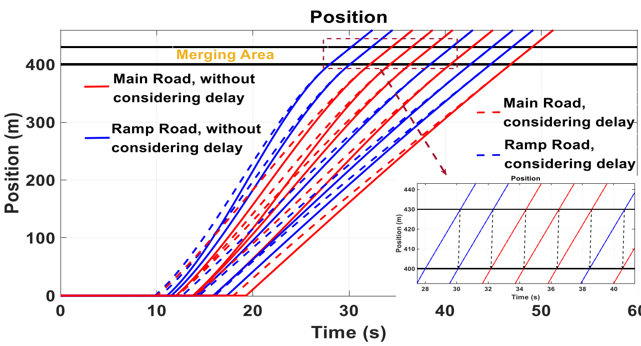


Fig. 9. Position trajectories of the vehicles, Case 1.

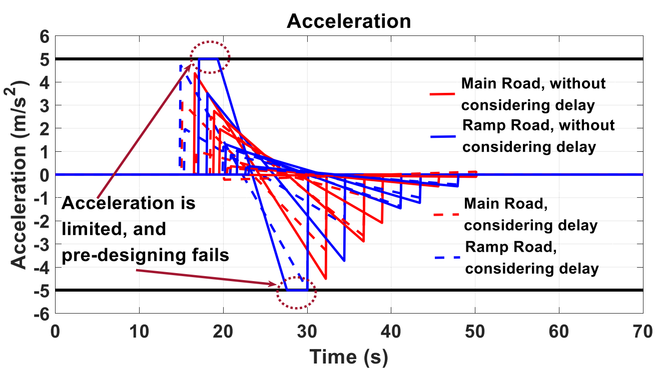


Fig. 10. Control inputs (acceleration) of the vehicles, case 2.

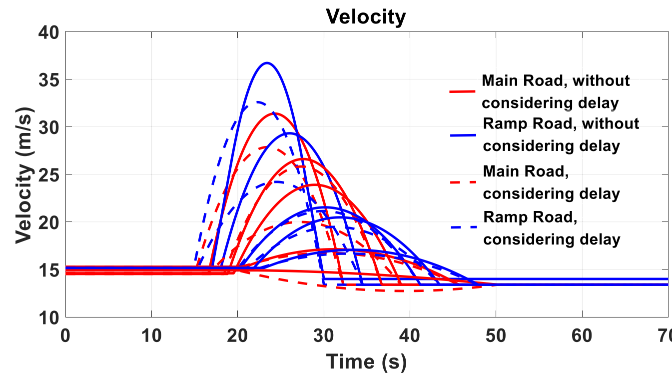


Fig. 11. Velocity profiles of the vehicles, case 2.

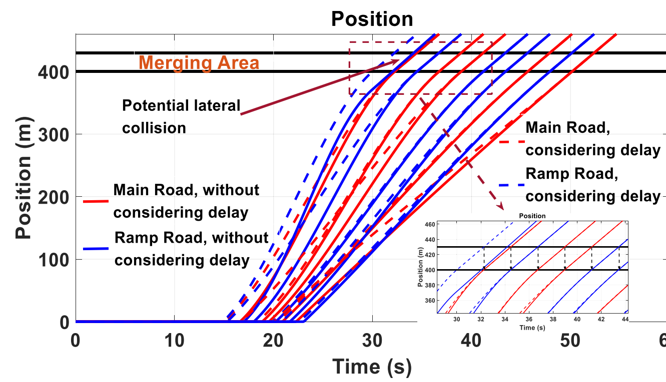


Fig. 12. Position trajectories of the vehicles, case 2.

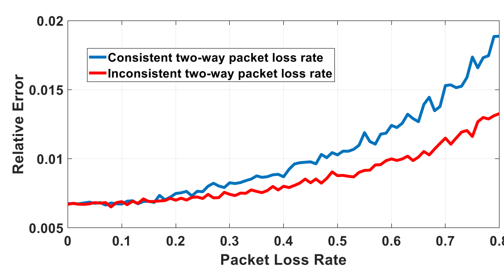


Fig. 13. Relative error change with packet loss rate (fix the packet loss rate for one of the receivers as 0.1).

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 τ_V and τ_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

Relative error		Sample size of the vehicle sender						
		10	50	100	500	1000	5000	10000
Sample size of the controller sender	10	0.12837	0.125398	0.14106	0.062615	0.095144	0.076689	0.108573
	50	0.061102	0.085573	0.039555	0.035922	0.032915	0.069751	0.04906
	100	0.116506	0.054712	0.037182	0.023306	0.023938	0.018356	0.02584
	500	0.121518	0.076703	0.020107	0.01372	0.015802	0.00988	0.011872
	1000	0.084223	0.030147	0.026576	0.01442	0.009725	0.009149	0.00867
	5000	0.081073	0.044235	0.048143	0.009611	0.009374	0.004512	0.005346
	10000	0.087842	0.063533	0.023385	0.021613	0.024451	0.004324	0.002845

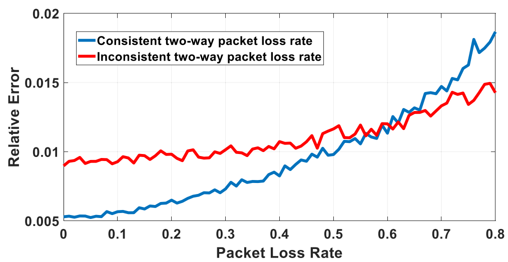


Fig. 14. Relative error change with packet loss rate (fix the packet loss rate for one of the receivers as 0.6).

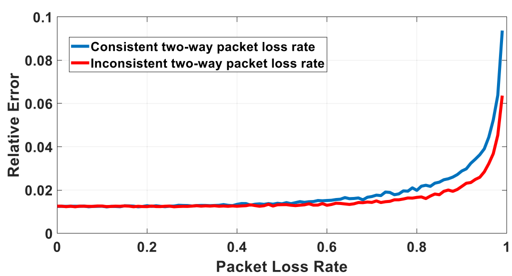


Fig. 15. Relative error with packet loss rate close to 1 (fix the packet loss rate for one of the receivers as 0.1).

than zero, the random variable would be regenerated until it is greater than 0). Firstly, we explore the relative error rate under different packet loss rate and divide the packet loss rate with step length 0.01 from 0 to 0.8. Both the vehicle and the controller will send 1000 packets in each step, and we simulate sending and receiving packets containing timestamp for 1000 times and use the statistical mean value as the estimation of the communication delay under the given packet loss rate. Fig. 13-15 show the simulation results. For all of these three figures, the solid blue line represents the change of relative error where packet loss rate of the receiver for both the vehicle and the controller consistently changes, while, for the solid red line, we fix the packet loss rate for one of the receivers to observe the relative error change.

We can conclude form Fig. 13 and Fig. 14 that the accuracy of communication delay estimation depends on the receiver with higher packet loss rate. In other words, the receiver with worse performance dominates the estimation accuracy. However, reducing the packet loss rate can improve the 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.

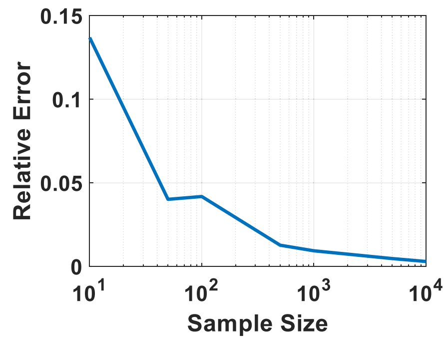


Fig. 16. Relative error change with sample size (sample size for both receivers is the same).

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

TABLE IV
STATISTICS OF THE DSRC EQUIPMENT IN DIFFERENT SCENARIOS

Scenario	Tx Size	Rx Size	PDR	RTT_avg (ms)	RTT_std
open100	1042	1041	0.9990	13.4801	4.8827
open200	1057	949	0.8978	13.4056	5.0200
open300	1035	851	0.8222	13.8911	5.4062
open400	1040	171	0.1644	15.0046	5.5861
tree20	1039	1013	0.9750	12.9233	4.7354
tree40	1036	928	0.8958	14.2676	5.3928
tree60	1028	450	0.4733	14.3126	4.9159
tree65	2075	910	0.4386	14.3071	4.9944
10km/h	1295	1067	0.8239	14.0054	5.3516
20km/h	841	620	0.7372	14.0991	5.3420
30km/h	824	639	0.7755	12.2252	4.1370
40km/h	831	640	0.7702	12.2761	4.1399
50km/h	821	593	0.7223	13.4436	5.0540
60km/h	618	439	0.7104	13.7706	5.0268
70km/h	545	346	0.6349	13.2466	4.5669
80km/h	475	319	0.6716	13.2396	4.7054

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 has 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 imbedded 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 CAV 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.

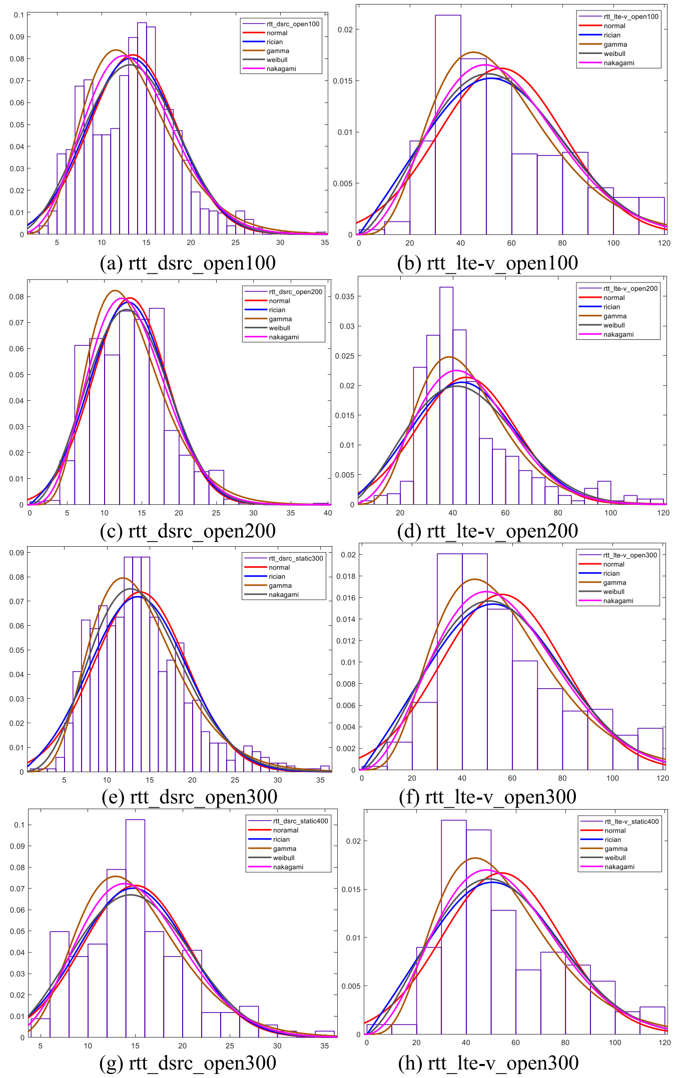


Fig. 17. PDF of the V2I communication delay in open environment.

TABLE V
STATISTICS OF THE LTE-V EQUIPMENT IN DIFFERENT SCENARIOS

Scenario	Tx Size	Rx Size	PDR	RTT_avg (ms)	RTT_std
open100	1068	918	0.8596	55.7170	24.6076
open200	1049	920	0.8770	55.9671	23.7382
open300	1047	918	0.8768	55.6096	24.6462
open400	1080	915	0.8472	54.0814	23.9952
tree20	1085	804	0.7410	53.3772	21.6741
tree40	1127	572	0.5075	56.3859	26.4726
tree60	1162	686	0.5904	54.1461	24.0210
tree80	1105	460	0.4163	51.7576	22.2675
tree90	1982	455	0.2296	50.3370	24.0119
tree100	3872	225	0.0581	52.8556	24.5918
10km/h	1190	1028	0.8639	51.4184	22.1982
20km/h	1203	1028	0.8545	51.0965	21.6861
30km/h	1066	916	0.8593	50.3598	21.5901
40km/h	1070	915	0.8551	46.9035	21.0326
50km/h	1115	917	0.8224	52.3798	23.6272
60km/h	1056	918	0.8693	55.6409	25.1167
70km/h	1058	920	0.8696	46.7002	21.3281
80km/h	1158	916	0.7910	52.4093	23.1278

VI. CONCLUSION

In this paper, we studied the scenario of on-ramp merging for CAVs considering the communication delay of the V2I

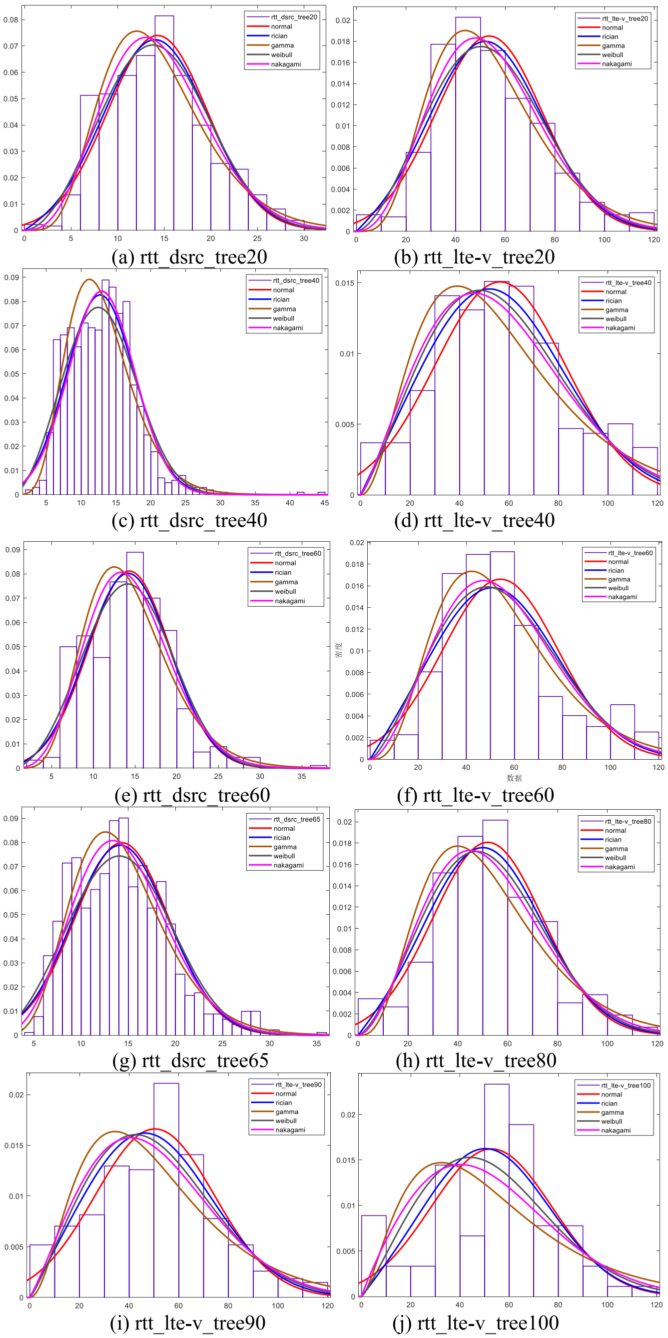


Fig. 18. PDF of the V2I communication delay in the environment with shelters (trees in this experiment).

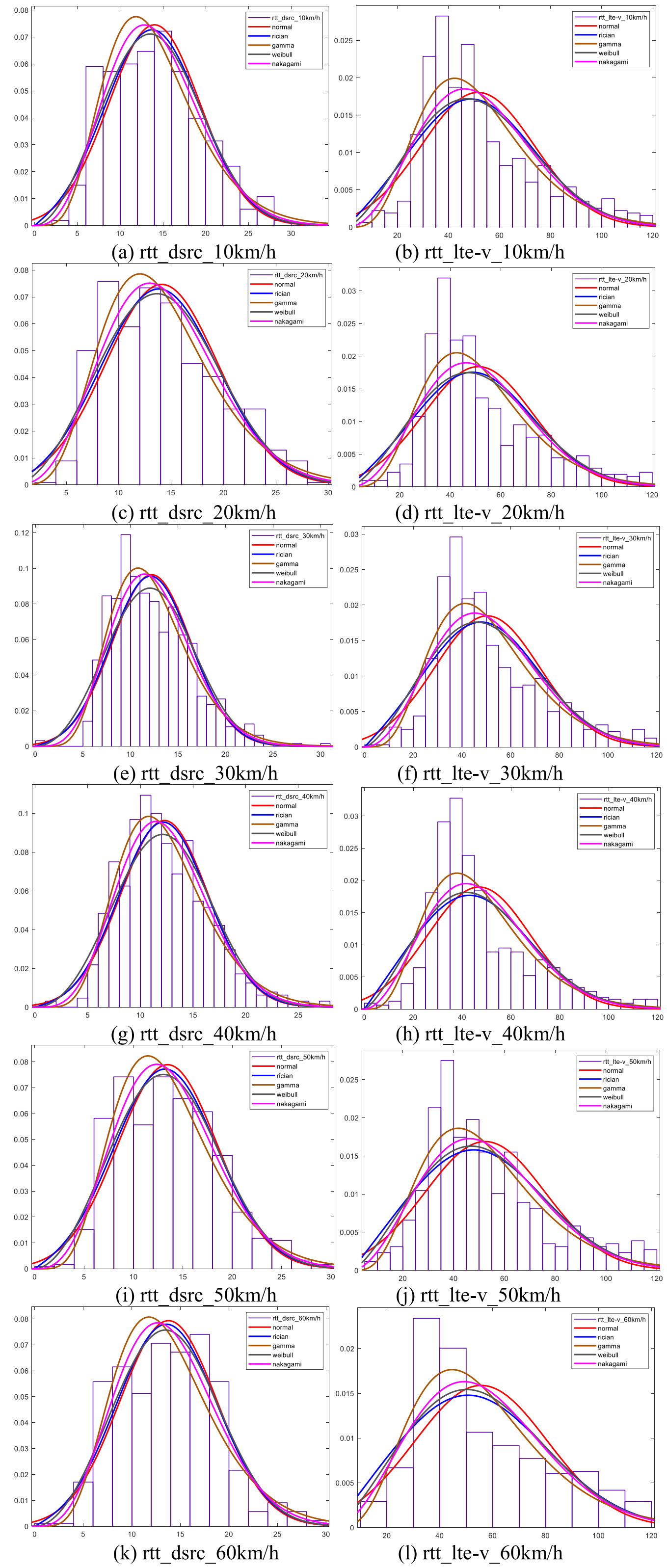
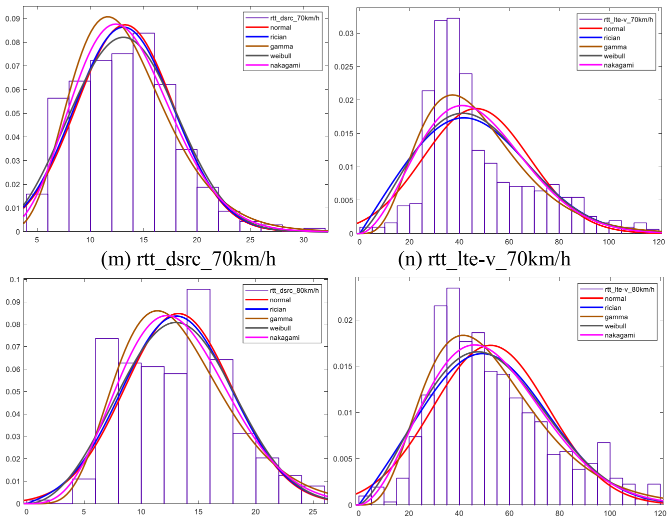


Fig. 19. PDF of the V2I communication delay in the driving environment (open environment).

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 ensure 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 was explored. Then, we proposed a communication delay



(m) rtt_dsrc_70km/h (n) rtt_lte-v_70km/h

(o) rtt_dsrc_80km/h (p) rtt_lte-v_80km/h

Fig. 19. *(Continued.)* PDF of the V2I communication delay in the driving environment (open environment).

TABLE VI

LOG LIKELIHOOD OF EACH FITTING PDF FOR DSRC EQUIPMENT IN DIFFERENT SCENARIOS

Scenario	Normal Log Likelihood	Rician Log Likelihood	Gamma Log Likelihood	Weibull Log Likelihood	Nakagami Log Likelihood	Closet PDF
open100	-3201.16	-3185.01	-3137.12	-3189.61	-3153.28	Gamma
open200	-2874.19	-2864.74	-2855.00	-2860.29	-2850.72	Nakagami
open300	-2643.11	-2629.98	-2591.62	-2623.49	-2604.23	Gamma
open400	-536.31	-534.40	-529.09	-533.57	-530.29	Gamma
tree20	-3012.16	-3001.57	-2967.93	-3002.40	-3012.16	Gamma
tree40	-2876.92	-2868.23	-2871.18	-2863.50	-2860.14	Nakagami
tree60	-1354.64	-1352.10	-1353.16	-1352.99	-1347.55	Nakagami
tree65	-2754.31	-2747.01	-2715.85	-2745.42	-2724.06	Gamma
10km/h	-3303.30	-3290.77	-3277.55	-3281.32	-3274.03	Nakagami
20km/h	-1918.12	-1910.79	-1895.78	-1904.27	-1897.71	Gamma
30km/h	-1813.56	-1809.86	-1796.77	-1813.42	-1797.87	Gamma
40km/h	-1816.15	-1813.71	-1810.70	-1873.83	-1806.48	Nakagami
50km/h	-1801.70	-1795.31	-1785.78	-1790.26	-1785.01	Nakagami
60km/h	-1331.31	-1327.96	-1330.49	-1325.62	-1324.87	Nakagami
70km/h	-1015.97	-1013.69	-1007.29	-1012.79	-1007.50	Gamma
80km/h	-946.18	-944.27	-946.30	-942.87	-942.14	Nakagami

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

TABLE VII

LOG LIKELIHOOD OF EACH FITTING PDF FOR LTE-V EQUIPMENT IN DIFFERENT SCENARIOS

Scenario	Normal Log Likelihood	Rician Log Likelihood	Gamma Log Likelihood	Weibull Log Likelihood	Nakagami Log Likelihood	Closet PDF
open100	-2939.09	-2918.68	-2893.55	-2909.71	-2902.91	Gamma
open200	-2902.57	-2885.00	-2812.71	-2874.34	-2847.86	Gamma
open300	-2875.84	-2857.59	-2837.01	-2849.71	-2843.32	Gamma
open400	-2760.12	-2741.73	-2719.41	-2733.70	-2727.03	Gamma
tree20	-2280.43	-2273.61	-2275.90	-2272.18	-2269.22	Nakagami
tree40	-1398.62	-1395.99	-1415.90	-1398.39	-1399.68	Rician
tree60	-1824.85	-1816.01	-1817.49	-1813.82	-1812.25	Nakagami
tree80	-1186.56	-1183.99	-1198.78	-1185.84	-1187.58	Rician
tree90	-1240.82	-1237.29	-1255.82	-1240.03	-1241.09	Rician
tree100	-415.42	-417.57	-429.26	-420.35	-420.60	Normal
10km/h	-2844.24	-2826.84	-2793.00	-2817.67	-2806.52	Gamma
20km/h	-2840.73	-2823.81	-2782.56	-2813.87	-2800.18	Gamma
30km/h	-2882.83	-2866.21	-2836.69	-2857.71	-2847.26	Gamma
40km/h	-2915.15	-2893.19	-2858.03	-2883.43	-2872.67	Gamma
50km/h	-2363.47	-2345.06	-2323.95	-2338.31	-2332.30	Gamma
60km/h	-2223.24	-2204.86	-2182.99	-2197.93	-2192.65	Gamma
70km/h	-2807.81	-2784.45	-2756.75	-2775.99	-2768.05	Gamma
80km/h	-2840.36	-2824.48	-2816.48	-2818.93	-2814.76	Nakagami

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 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.

References

[1] Y. Chung and W. W. Recker, "Spatiotemporal analysis of traffic congestion caused by rubbernecking at freeway accidents," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 3, pp. 1416–1422, Sep. 2013.

[2] G. R. Iordanidou, C. Roncoli, I. Papamichail, and M. Papageorgiou, "Feedback-based mainstream traffic flow control for multiple bottlenecks on motorways," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 610–621, Apr. 2015.

[3] E. Moradi-Pari, H. N. Mahjoub, H. Kazemi, A. Tahmasbi-Sarvestani, and Y. P. Fallah, "Utilizing model-based communication and control for cooperative automated vehicle applications," *IEEE Trans. Intell. Veh.*, vol. 2, no. 1, pp. 38–51, Mar. 2017.

[4] S. E. Li *et al.*, "Dynamical modeling and distributed control of connected and automated vehicles: Challenges and opportunities," *IEEE Intell. Transp. Syst. Mag.*, vol. 9, no. 3, pp. 46–58, Jul. 2017.

[5] C. M. Filho, M. H. Terra, and D. F. Wolf, "Safe optimization of highway traffic with robust model predictive control-based cooperative adaptive cruise control," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 11, pp. 3193–3203, Nov. 2017.

[6] O. Altan, G. Wu, M. J. Barth, K. Boriboonsomsin, and J. Stark, "GlidePath: Eco-friendly automated approach and departure at signalized intersections," *IEEE Trans. Intell. Vehicles*, vol. 2, no. 4, pp. 266–277, Nov. 2017.

[7] S. Jing, F. Hui, X. Zhao, J. Rios-Torres, and A. J. Khattak, "Cooperative game approach to optimal merging sequence and on-ramp merging control of connected and automated vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 11, pp. 4234–4244, Nov. 2019.

[8] D. Jia and D. Ngoduy, "Enhanced cooperative car-following traffic model with the combination of V2V and V2I communication," *Transp. Res. B, Methodol.*, vol. 90, pp. 172–191, Aug. 2016.

[9] I. Kabashkin, "Reliable V2X communications for safety-critical intelligent transport systems," in *Proc. Adv. Wireless Opt. Commun. (RTUWO)*, Nov. 2017, pp. 251–255.

[10] S. Biswas, R. Tatchikou, and F. Dion, "Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety," *IEEE Commun. Mag.*, vol. 44, no. 1, pp. 74–82, Jan. 2006.

[11] H. Min, Y. Fang, R. Wang, X. Li, Z. Xu, and X. Zhao, "A novel on-ramp merging strategy for connected and automated vehicles based on game theory," *J. Adv. Transp.*, vol. 2020, pp. 1–11, Jul. 2020.

[12] J. Rios-Torres and A. A. Malikopoulos, "Automated and cooperative vehicle merging at highway on-ramps," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 4, pp. 780–789, Apr. 2017.

[13] L. Chen and C. Englund, "Cooperative intersection management: A survey," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 2, pp. 570–586, Feb. 2016.

[14] H. Min, Y. Fang, X. Wu, G. Wu, and X. Zhao, "On-ramp merging strategy for connected and automated vehicles based on complete information static game," *J. Traffic Transp. Eng.*, vol. 8, no. 4, pp. 582–595, Aug. 2021.

[15] N. Chen, B. van Arem, T. Alkim, and M. Wang, "A Hierarchical model-based optimization control approach for cooperative merging by connected automated vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 12, pp. 7712–7725, Dec. 2021.

[16] Y. Wang, E. Wenjuan, W. Tang, D. Tian, G. Lu, and G. Yu, "Automated on-ramp merging control algorithm based on internet-connected vehicles," *IET Intell. Transp. Syst.*, vol. 7, no. 4, pp. 371–379, Dec. 2013.

[17] L. Xu, J. Lu, B. Ran, F. Yang, and J. Zhang, "Cooperative merging strategy for connected vehicles at highway on-ramps," *J. Transp. Eng. A, Syst.*, vol. 145, no. 6, Jun. 2019, Art. no. 04019022.

[18] G. Raravi, V. Shingde, K. Ramamritham, and J. Bharadia, "Merge algorithms for intelligent vehicles," in *Next Generation Design and Verification Methodologies for Distributed Embedded Control Systems*, 2007th ed. Dordrecht, The Netherlands: Springer, Aug. 2007, pp. 51–65.

[19] T. Awal, L. Kulik, and K. Ramamohanrao, "Optimal traffic merging strategy for communication- and sensor-enabled vehicles," in *Proc. 16th Int. ITSC*, Oct. 2013, pp. 1468–1474.

[20] W. Cao, M. Mukai, T. Kawabe, H. Nishira, and N. Fujiki, "Cooperative vehicle path generation during merging using model predictive control with real-time optimization," *Control Eng. Pract.*, vol. 34, pp. 98–105, Jan. 2015.

[21] W. Cao, M. Mukai, T. Kawabe, H. Nishira, and N. Fujiki, "Gap selection and path generation during merging maneuver of automobile using real-time optimization," *SICE J. Control, Meas., Syst. Integr.*, vol. 7, no. 4, pp. 227–236, Jul. 2014.

[22] J. Rios-Torres and A. A. Malikopoulos, "A survey on the coordination of connected and automated vehicles at intersections and merging at highway on-ramps," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 5, pp. 1066–1077, May 2017.

[23] J. Liu, W. Zhao, and C. Xu, "An efficient on-ramp merging strategy for connected and automated vehicles in multi-lane traffic," *IEEE Trans. Intell. Transp. Syst.*, early access, Jan. 8, 2021, doi: 10.1109/TITS.2020.3046643.

[24] S. Triest, A. Villaflor, and J. M. Dolan, "Learning highway ramp merging via reinforcement learning with temporally-extended actions," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Las Vegas, NV, USA, Oct. 2020, pp. 1595–1600.

[25] Z. E. A. Kherroubi, S. Aknine, and R. Bacha, "Novel decision-making strategy for connected and autonomous vehicles in highway on-ramp merging," *IEEE Trans. Intell. Transp. Syst.*, early access, Oct. 4, 2021, doi: 10.1109/TITS.2021.3114983.

[26] S. Aradi, "Survey of deep reinforcement learning for motion planning of autonomous vehicles," 2020, *arXiv:2001.11231*.

[27] Y. Hu, A. Nakhaei, M. Tomizuka, and K. Fujimura, "Interaction-aware decision making with adaptive strategies under merging scenarios," 2019, *arXiv:1904.06025*.

[28] Y. Lin, J. McPhee, and N. L. Azad, "Anti-jerk on-ramp merging using deep reinforcement learning," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Las Vegas, NV, USA, Oct. 2020, pp. 7–14.

[29] S. G. Hu, H. Y. Wen, L. Xu, and H. Fu, "Stability of platoon of adaptive cruise control vehicles with time delay," *Transp. Lett.*, vol. 11, no. 9, pp. 506–515, Oct. 2019.

[30] M. Wang, "Infrastructure assisted adaptive driving to stabilise heterogeneous vehicle strings," *Transp. Res. C, Emerg. Technol.*, vol. 91, pp. 276–295, Jun. 2018.

[31] Z. Wang, "Motion estimation of connected and automated vehicles under communication delay and packet loss of V2X communications," SAE Tech. Paper 2021-01-0107, 2021.

[32] Y. Shui *et al.*, "Vehicle-to-vehicle radio channel characteristics for congestion scenario in dense urban region at 5.9 GHz," *Int. J. Antennas Propag.*, vol. 2018, pp. 1–14, Jan. 2018.

[33] Y. Ni, J. He, L. Cai, and Y. Bo, "Delay analysis and message delivery strategy in hybrid V2I/V2V networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6.

[34] D. Č. Pavlović, N. M. Sekulović, G. V. Milovanović, A. S. Panajotović, M. Č. Stefanović, and Z. J. Popović, "Statistics for ratios of Rayleigh, Rician, Nakagami-*m*, and Weibull distributed random variables," *Math. Problems Eng.*, vol. 2013, pp. 1–10, Jan. 2013.

[35] R. Protzmann, "V2X communication in heterogeneous networks," Ph.D. dissertation, Dept. Electron. Inf., Tech. Univ. Berlin, Berlin, Germany, 2018.

[36] L. Cao, H. Yin, J. Hu, and L. Zhang, "Performance analysis and improvement on DSRC application for V2V communication," in *Proc. IEEE 92nd Veh. Technol. Conf. (VTC-Fall)*, Nov. 2020, pp. 1–6.

[37] N. Vivek, S. V. Srikanth, P. Saurabh, T. P. Vamsi, and K. Raju, "On field performance analysis of IEEE 802.11p and WAVE protocol stack for V2V & V2I communication," in *Proc. Int. Conf. Inf. Commun. Embedded Syst. (ICICES)*, Feb. 2014, pp. 1–6.

[38] M. A. Al-Absi, A. A. Al-Absi, and H. J. Lee, "Performance analysis for city, highway, and rural area in vehicle-to-vehicle network," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2018, pp. 639–644.

[39] G. T. Pitsiladis, D. Papanikolaou, A. D. Panagopoulos, and C. Antoniou, "Vehicle-to-vehicle communication: End-to-end performance evaluation in dense propagation environments," in *Proc. 9th Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2015, pp. 1–5.

[40] Z. Liu, Z. Liu, Z. Meng, X. Yang, L. Pu, and L. Zhang, "Implementation and performance measurement of a V2X communication system for vehicle and pedestrian safety," *Int. J. Distrib. Sensor Netw.*, vol. 12, no. 9, Sep. 2016, Art. no. 155014771667126.

[41] S. Ramyar and A. Homaifar, "Impact of unreliable communication on string stability of cooperative adaptive cruise control," in *Proc. IEEE Int. Conf. Syst., Man Cybern. (SMC)*, Bari, Italy, Oct. 2019, pp. 4263–4268.

[42] M. A. Hoque, J. Rios-Torres, R. Arvin, A. Khattak, and S. Ahmed, "The extent of reliability for vehicle-to-vehicle communication in safety critical applications: An experimental study," *J. Intell. Transp. Syst.*, vol. 24, no. 3, pp. 264–278, Feb. 2020.

[43] L. S. Pontryagin, *Mathematical Theory of Optimal Processes*. Boca Raton, FL, USA: CRC Press, 1987.

[44] J. J. Sijbers, A. J. den Dekker, P. Scheunders, and D. Van Dyck, "Maximum-likelihood estimation of Rician distribution parameters," *IEEE Trans. Med. Imag.*, vol. 17, no. 3, pp. 357–361, Mar. 1998.

[45] D. DeRiggi, "A central limit theorem for correlated variables with limited normal or gamma distributions," *Commun. Statist.-Theory Methods*, vol. 48, no. 21, pp. 1–10, 2019.

[46] H. Chang, K. Huang, and C. Wu, "Determination of sample size in using central limit theorem for Weibull distribution," *Int. J. Inf. Manage. Sci.*, vol. 17, no. 3, p. 31, 2006.

[47] G. K. Karagiannidis, N. C. Sagias, and P. T. Mathiopoulos, "N*Nakagami: A novel stochastic model for cascaded fading channels," *IEEE Trans. Commun.*, vol. 55, no. 8, pp. 1453–1458, Aug. 2007.

[48] S. A. Alghamdi, "Emperor based resource allocation for D2D communication and QoF based routing over cellular V2X in urban environment (ERA-D^2Q)," *Wireless Netw.*, vol. 26, no. 5, pp. 3419–3437, Jul. 2020.

[49] Y. A. Harfouch, S. Yuan, and S. Baldi, "An adaptive switched control approach to heterogeneous platooning with intervehicle communication losses," *IEEE Trans. Control Netw. Syst.*, vol. 5, no. 3, pp. 1434–1444, Sep. 2018.

[50] T. Huang and Z. Sun, "Cooperative ramp merging for mixed traffic with connected automated vehicles and human-operated vehicles," *IFAC-PapersOnLine*, vol. 52, no. 24, pp. 76–81, 2019.

[51] X. Liao *et al.*, "A game theory based ramp merging strategy for connected and automated vehicles in the mixed traffic: A unity-SUMO integrated platform," 2021, *arXiv:2101.11237*.

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