A Digital Twin Paradigm: Vehicle-to-Cloud Based Advanced Driver Assistance Systems

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***Abstract*—Digital twin, an emerging representation of cyber-physical systems, has attracted increasing attentions very recently. It opens the way to real-time monitoring and synchronization of real-world activities with the virtual counterparts. In this study, we develop a digital twin paradigm using an advanced driver assistance system (ADAS) for connected vehicles. By leveraging vehicle-to-cloud (V2C) communication, on-board devices can upload the data to the server through cellular network. The server creates a virtual world based on the received data, processes them with the proposed models, and sends them back to the connected vehicles. Drivers can benefit from this V2C based ADAS, even if all computations are conducted on the cloud. The cooperative ramp merging case study is conducted, and the field implementation results show the proposed digital twin framework can benefit the transportation systems regarding mobility and environmental sustainability with acceptable communication delays and packet losses.**

I. Introduction

Recent development of the Internet of Things (IoT) brings forward numerous novel technologies, where the application scenarios are not only limited to the user level (e.g., individual consumer or private company), but can also be applied to the system level (e.g., commercial or industrial sector). Digital twin, an emerging representation of IoT, has attracted more and more attentions very recently. Digital twin was ranked as one of the top 10 strategic technology trends for 2019, among the others including autonomous things (e.g., autonomous vehicles), immersive technologies (e.g., virtual reality and augmented reality), and quantum computing [1]. Digital twin is widely adopted by the industry, and will play an important role in the fully connected, prototype "Woven City" that Toyota is going to build at the base of Mt. Fuji in Japan [2].

Although the definition of digital twin varies in different previous publications such as [3]–[5], the basic ideas are very similar: A digital twin is a digital replica in cyber world of an entity in physical world. Digital twin technology opens the way to real-time monitoring and synchronization of the real-world activities with the virtual counterparts thanks to the physical-cyber connection and the Cyber-Physical Systems (CPS) elements [5]. The digital twin concept was first born in the aerospace field when the United States' National Aeronautics and Space Administration (NASA) adopted that as a key element in its 2010 technology roadmap. Along its rapid development in different fields during the past decade, including aeronautics and space [3], [6]–[9], robotics [10], [11], manufacturing [12]–[14], and informatics [15], digital twin also has a huge potential in the transportation field.

The digital twin concept has been loosely defined and adopted in the automotive industry since its emergence during the past decade, partly due to its similarity and connection with other technologies, such as CPS and IoT. However, many previous efforts related to CPS and IoT in the automotive domain envision the development of the digital twin, since the majority of those proposed methodologies and/or algorithms were developed on the systems with a physical entity (i.e., vehicle) and its digital replica (simulation model/environment). Sharma and George explored the role of the digital twin in addressing the current challenges in the automotive industry, especially with regards to vehicle product design, manufacturing, sales, and service [16]. Alam and Saddik developed a digital twin architecture reference model for the cloud based CPS (C2PS), where a telematics based driving assistance application for the vehicular CPS described in the study mainly consists of three parts: 1) computation, 2) control, 3) and sensors and services fusion [17]. However, these existing literature are written with a broad scope without diving into the details of digital twin in the automotive domain, so it is still unknown what kind of transportation/vehicle use cases can benefit from the digital twin.

In this study, we propose a digital twin framework for connected vehicles using vehicle-to-cloud (V2C) communication. A paradigm of digital twin is developed for an advanced driver assistance system (ADAS), where the advisory speed calculated by the cloud server is shown on the vehicle on-board driver-vehicle interface (DVI) device, so the driver can control the vehicle in a more intelligent manner. A case study of cooperative ramp merging is conducted, where a field implementation in real-world traffic on three passenger vehicles validates the effectiveness of the proposed digital twin framework.

The remainder of this paper is organized as follows: Section II proposes the general framework of the digital twin system for connected vehicles. Section III looks into the details of the paradigm of digital twin, where the architecture of V2C based ADAS is developed. The case study of cooperative ramp merging is conducted in section IV, where the methodology and the field implementation using real passenger vehicles are introduced. Section V draws the conclusion of this study, and raises some potential work in the future.

II. Digital Twin Framework for Connected Vehicles

As can be seen from Fig. 1, we develop the digital twin system for connected vehicles with a two-layer framework. The lower layer stands for the physical world, while the upper layer represents the cyber world. Additionally, the communication module plays a crucial role in this system framework as a nexus to tightly connect two layers together. In this study, we refer to the cellular communication as the communication module.

The physical layer of the digital twin framework, defined on a world coordinate over the time, may contain all the physical entities and their interactions, including vehicles & components, drivers & passengers, roadway infrastructure, me-

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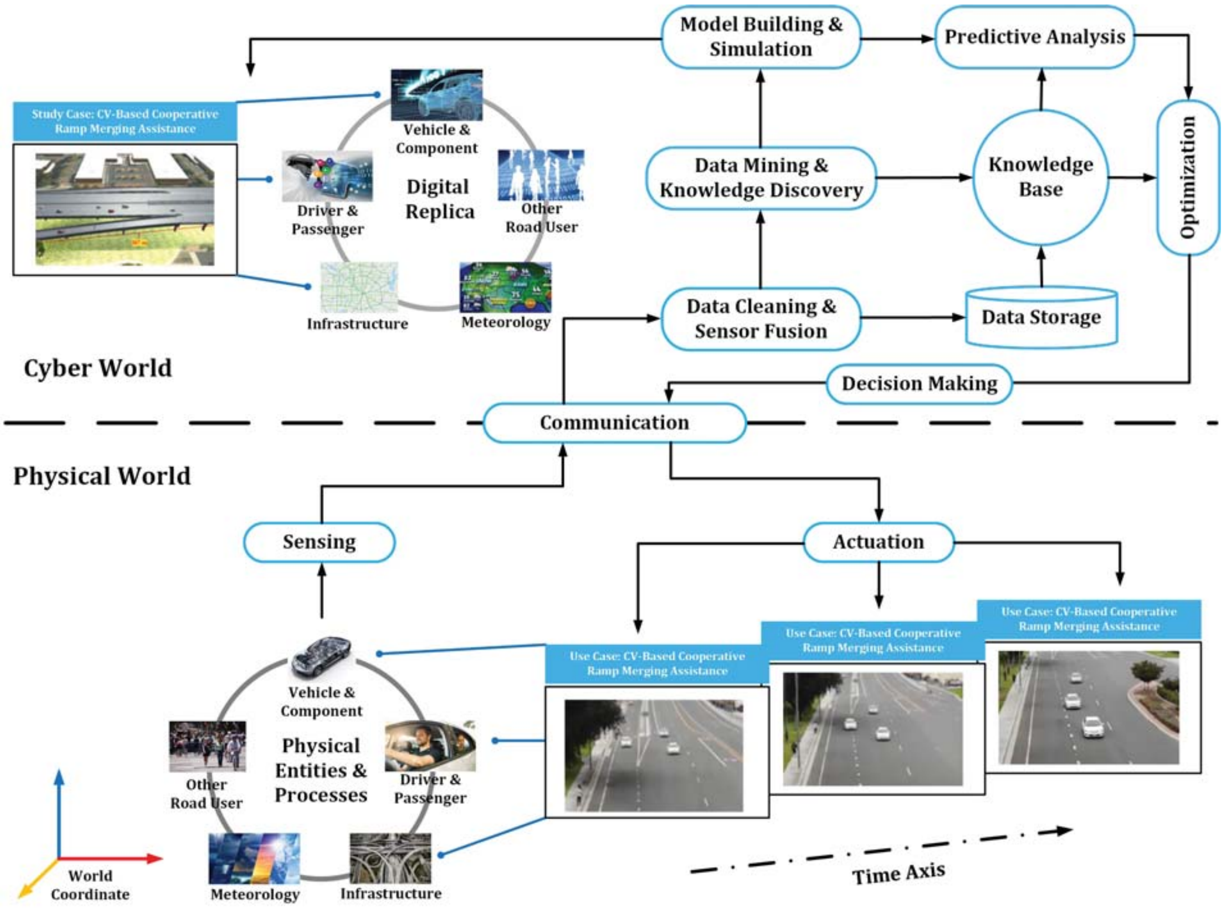


Fig. 1: General framework of the digital twin system for connected vehicles

teorology, other road users, etc. Two key modules residing in this layer are sensors and actuators. The sensors may detect the dynamic states of physical entities, changes in operating process, or event occurrences, such as vehicle speed, driver's gaze, and traffic light status, and aggregate the measurements under different resolutions. The information is transmitted to the cyber world via the communication module for further processing.

On the other hand, the processed results from the cyber world are received (again via the communication module) and serve as the actuation guidance for the entities or processes in the physical world. The connected vehicles in the physical world can be partially or fully automated (i.e., as connected and automated vehicles), or be driven by human drivers with some ADAS features. The actuation guidance sent from the cyber world will advise the automatic controller or human driver of connected vehicles to conduct cooperative/intelligent maneuvers, and in turn benefits transportation systems with respect to safety, mobility, and/or environment sustainability.

The cyber world within the digital twin frame handles all of the computational efforts in this two-layer framework. It not only consists of an abstract of the physical world (i.e., the digital replicas of physical entities and processes), but also performs a few key functions. Firstly, sensed data from the physical world are cleaned (such as outlier detection and removal, missing data imputation) and fused (including time synchronization). Then, the pre-processed data may be stored in the database (e.g., for digital traceability) or be sent to the data mining & knowledge discovery module for further exploration with advanced computational techniques (such as machine learning). The extracted information from the data mining & knowledge discovery module is utilized to either contribute to the knowledge base or construct the model of the physical world. For the visualization purpose, simulation tools (such as vehicle simulator, driving simulator, and traffic simulator) may be integrated into the modeling module. Located at the heart of the cyber world, the knowledge base is built on top of historical information and keeps updated as new information flows in. The knowledge can be drawn to perform predictive analyses (with the combination of modeling/simulation tools) and find optimal strategies to support decision making processes. The cogitative actions are transmitted (via the communication module) back to the actuators in the physical world to improve the overall system performance.

III. Vehicle-to-Cloud Based Advanced Driver Assistance Systems

In this section, we develop a paradigm of the digital twin, which demonstrates how the digital twin framework exactly works for connected vehicles. Specifically, an ADAS based on V2C communication is developed within the digital twin framework, which aims to provide the advisory speed information to the drivers of equipped vehicles. Different from the general system framework shown in Fig. 1, a system architecture diagram particularly for this ADAS is shown in Fig. 2. The features of different components in this V2C based ADAS are discussed below.

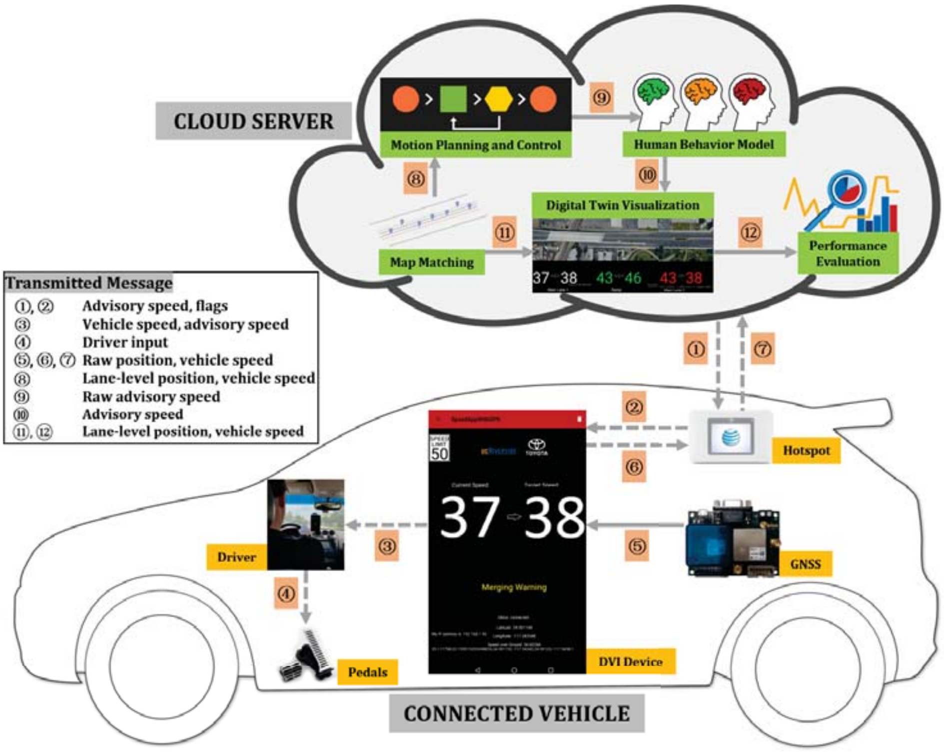


Fig. 2: Architecture of the V2C based ADAS with the digital twin framework

A. *Physical World*

In the physical world, a connected vehicle consists of cellular hotspot (optional), global navigation satellite system (GNSS), DVI device, and a human driver. Since the calculated speed guidance is sent from the cyber world through V2C communication, on-board computer is not necessary in the physical world.

1) Cellular hotspot: This module provides cellular access to the DVI device, and therefore enables V2C communication in this digital twin model. The Wi-Fi hotspot may be equipped with a 4G LTE (potentially 5G) sim card and has the "share hotspot" feature. However, if the DVI device (such as a mobile phone or tablet) is already equipped with a sim card, this cellular hotspot is not a necessity.

2) GNSS: This module is equipped on the vehicle to measure its real-time raw position (latitude and longitude) and speed information, and sends it to the DVI device through a micro USB cable.

3) DVI device: This module shows the advisory information (via V2C communication) to the driver to conduct cooperative/intelligent maneuvers. The information displayed on the DVI (an example is shown in Fig. 2) may include current speed (the left number), advisory speed (the right number) and some other additional messages (e.g., verbal guidance, latitude and longitude, IP address).

4) Driver: The driver of the equipped vehicle adjusts the vehicle speed according to the DVI by pressing the accelerate/brake pedal. Since it is impossible for the driver to perfectly track the advisory speed, a human behavior model is running on the cloud server to predict the tracking errors and compensate for the guidance in real time to improve system performance.

B. *Cyber World*

All computations of this V2C based ADAS are conducted on the cloud server, where digital replicas of the physical entities (e.g., vehicles, drivers, roadways) and the relevant functional modules are created in the cyber world. A breakdown of the major cyber modules for the ADAS are listed below:

1) Map matching: For the map matching module, a pre-built map of the testing field is available on the cloud server, with information such as the road type, road length, road ID and direction, road speed limit, merging zone, and influence zone. The main functions of the map matching module are position synchronization and geo-fencing. For position synchronization, vehicles' coordinates (i.e., longitude, latitude, and altitude) received from the GNSS can be matched to the pre-built map by the proposed map matching algorithm to update their current position in the cyber world. For geo-fencing, flags are defined to check the positions and conditions of the vehicles in each time step, so associated actions can be conducted accordingly.

2) Motion planning and control: This module generates the raw advisory speed of the ego vehicle. The inputs of this module are the speed and lane-level position of all relevant vehicles, where the motion planner generates the desired motion of the ego vehicle, while the motion controller calculates the reference speed to achieve that desired motion.

3) Human behavior model: This module predicts the speed tracking error generated by the driver, and compensates for the raw advisory speed in real time. The output of this model is the advisory speed sent to the physical world, which already considers the speed error generated by the driver.

4) Digital twin visualization: This module demonstrates the digital replica of vehicles in the cyber world. It receives advisory speed from the human behavior model, and also the position and vehicle speed from the map matching module. The interface displays the real-time movements of all vehicles on the pre-built map based on their positions measured by the GNSS module. It also displays some additional information, such as server IP address, latitude and longitude of vehicles, and/or a simplified version of the DVI in the equipped vehicle.

5) Performance evaluation: The performance evaluation module analyzes the data in real time. The speed, acceleration, energy consumption, criteria pollutant emissions and many other performance indices of interest can be analyzed on the cloud server, and their results can be sent back to the physical world or displayed on the DVI.

IV. Case Study: Cooperative Ramp Merging

A. Problem Formulation & Methodology

In order to demonstrate the real-world effectiveness of the digital twin framework in terms of ADAS, we conduct a case study of cooperative ramp merging. The proposed methodology is illustrated as Fig. 3, where every merging vehicle is assumed to be enabled with V2C communication and driven by a human driver. The merging maneuver between any two vehicles is simplified into a car-following problem, where a "virtual vehicle" idea is adopted from our previous research [18]: A virtual vehicle of the real vehicle will be created on the other merging lane, which shares the same longitudinal speed and distance to merge as the real vehicle.

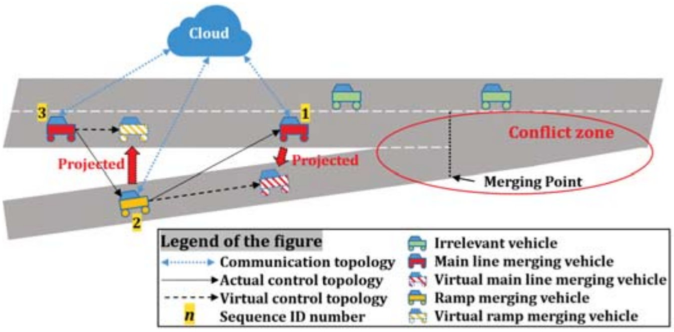


Fig. 3: System framework of digital twin model for the cooperative ramp merging use case

Based on the current speed and the distance to merge, an estimated time to merge value can be calculated by the motion planner on the cloud server [18]. The merging sequences of all relevant vehicles can then be determined by sorting all those values of estimated time to merge. As can be seen from Fig. 3, the virtual vehicles are projected on the other merging lane, so that their following vehicles (with one larger sequence ID number) can conduct a car-following maneuver based on the motion controller on the cloud server.

The lookup table based consensus algorithm is adopted for the motion controller based on our previous research [19]. Basically, the ego vehicle i retrieves information of its (virtual) leading vehicle j ($j = i - 1$) from the cloud server, including its length l_j, longitudinal speed v_j and distance to merge r_j. Then, the proposed consensus algorithm takes those inputs as well as the vehicle dynamics data from the ego vehicle i, and computes a reference acceleration a_{ref} for the ego vehicle i by the following algorithm:

$$a_{ref}(t+\delta t) = -\alpha_{ij}k_{ij} \cdot \Bigg[\Big(r_i(t) - r_j\big(t-\tau_{ij}(t)\big) + l_j + v_i(t) \cdot \big(t_{ij}^{g}(t) + \tau_{ij}(t)\big)\Big) + \gamma_i \cdot \Big(v_i(t) - v_j\big(t-\tau_{ij}(t)\big)\Big)\Bigg] \quad (1)$$

where δt is the length of each time step, α_{ij} denotes the value of adjacency matrix, k_{ij} and γ_i are control gains, $\tau_{ij}(t)$ denotes the time-variant communication delay between two vehicles, $t_{ij}^{g}(t)$ is the time-variant desired time gap between two vehicles. Specifically, the value of the control gain γ_i is set based on a lookup table, which is built offline based on safety, efficiency, and comfort constraints [19]. The raw advisory speed at the next time step can then be calculated as:

$$v_i(t+\delta t) = v_i(t) + a_{ref}(t+\delta t) \cdot \delta t \quad (2)$$

where $v_i(t)$ is the current speed of the ego vehicle.

Due to the presence of speed tracking error generated by the human driver at each time step, the human behavior model trains a nonlinear autoregressive (NAR) neural network to predict the error at the next time step [20]:

$$\hat{y}(t+\delta t) = f\big(y(t), (y(t-\delta t), y(t-2\delta t), ..., y(t-p\delta t)\big) \quad (3)$$

where the value of the predicted speed tracking error y at time $t + \delta t$ is calculated based on a function of its $p + 1$ past values in the time series. The raw advisory speed can then be compensated by this predicted error as:

$$\hat{v}_i(t+\delta t) = v_i(t+\delta t) + \hat{y}(t+\delta t) \quad (4)$$

where $\hat{v}_i(t+\delta t)$ is the advisory speed being sent to the physical world and displayed on the DVI device.

B. Field Implementation

A field implementation is conducted along Columbia Ave. (from Chicago Ave to Iowa Ave) in Riverside, CA, USA to validate the benefits of the proposed digital twin framework. The segment length along the main line is 780 m, and the length of the ramp is 322 m. The speed limit is around 20 m/s (precisely 45 mph) on both lanes. Towards the conflict zone, the main line is coming from an elevated bridge while the ramp is under the bridge. It is impossible to observe the traffic information on the other lane due to different elevations, which makes this testbed suitable to conduct cooperative merging implementation and show its benefits.

The proposed V2C based ADAS has been integrated into three production Toyota Corollas, which are originally equipped with no ADAS at all. All the system algorithms and models are running on a Dell R630 server located at the server room of University of California, Riverside. This server is equipped with two Intel Xeon 2.4 GHz 6-core processors, 64GB RAM, 14 TB storage, and operated by Windows Server 2012 and Linux OS with Python 3. Dedicated Netgear Unite 770S 4G LTE mobile Wi-Fi hotspot is adopted for the cellular hotspot. U-Blox NEO-M8P-2 real-time kinematic (RTK) application board package is adopted for the GNSS module. Google Nexus 7 tablet is adopted for the DVI device on the vehicle, which connects with the U-Blox GNSS module with a micro USB cable.

Fig. 4 shows the visualization of the digital twin in the cyber world, where digital replicas of all three vehicles are moving in the virtual map with real-time position updates from the physical world. The advisory speeds calculated in the cyber world are also shown here, and they are sent to all three vehicles in the physical world through V2C communication. The in-cabin view of the ramp vehicle is shown as Fig. 5, where the driver is tracking the advisory speed shown on the DVI tablet (when he/she has no line-of-sight of the two coming mainline vehicles).

Fig. 4: Digital twin visualization in the cyber world (speed unit is mph)

Fig. 5: Driver of the ramp vehicle is tracking the advisory speed shown on the DVI (speed unit is mph)

(a)

(b)

(c)

(d)

Fig. 6: Key steps of the cooperative ramp merging process

The cooperative ramp merging process of these three vehicles are shown through four snapshots in Fig. 6[1]. In Fig. 6 (a), two mainline vehicles come down the bridge with relatively short gap, while the ramp vehicle just starts to accelerate on the ramp. In Fig. 6 (b), the following mainline vehicle already receives the "merging warning" from the cloud server and is creating the gap for the ramp vehicle to merge in. In Fig. 6 (c), since the mainline vehicle and the ramp vehicle already adjust their longitudinal speed and position (by the drivers tracking the advisory speeds), the ramp vehicle can conduct a simple lane change without further adjustments. In Fig. 6 (d), the cooperative ramp merging maneuver has been successfully conducted by all three vehicles.

C. Performance Evaluation

The data from all three vehicles (mainly speeds and distance to merge) are analyzed by the performance evaluation module on the cloud server in real-time, and are shown as Fig. 7. As can be seen from Fig. 7 (a), the ramp vehicle accelerates during 0-15 second to close its gap with respect to the (virtual) mainline vehicle 1. The two mainline vehicles maintain a constant speed for the initial 8 seconds, when the mainline vehicle 2 considers mainline vehicle 1 as its leading vehicle to follow. Starting from 8 second, the leading vehicle of mainline vehicle 2 switches from the mainline vehicle 1 to the (virtual) ramp vehicle based on the value change of the defined switching flag. During 8-15 second, the mainline vehicle 2 decelerates to create the gap for ramp vehicle to merge. During 15-20 second, both the ramp vehicle and the mainline vehicle 2 converge their speeds to mainline vehicle 1's speed, so that they can be travelled in a three-vehicle string after the merge.

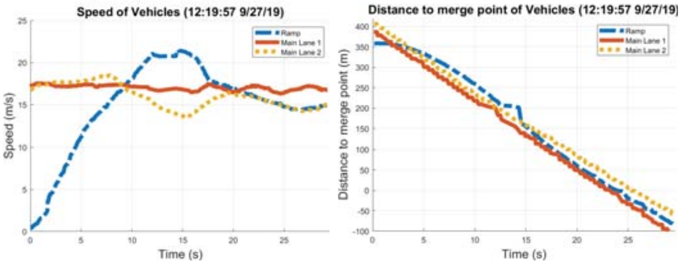
The distance to merge point trajectories can be seen from Fig. 7 (b), which coincides with the speed trajectories. Note that, the packet losses of V2C communication can be seen when the distance trajectory is flat within a short period (the distance value is not updated), such as 11-12 second for the mainline vehicle 1, 12-14 second and 23-24 second for the ramp vehicle.

The fuel and emissions results of the same trip are analyzed by the performance evaluation in the cyber world as well, which inform the driver regarding his/her environmental impact in real time. As shown in Fig. 8, the ramp vehicle is shown to consume more fuel and produce more pollutant emissions than the two mainline vehicles due to its drastic speed changes. Mainline vehicle 1 and 2 are shown to consume similar amount of fuel and produce similar amount of pollutant emissions in the results.

We also conduct a comprehensive test to measure the communication delay of V2C communication. A total of 1707 communication delay samples are recorded during the field implementation from five different trips, recording the time differences between a message is sent from one vehicle and

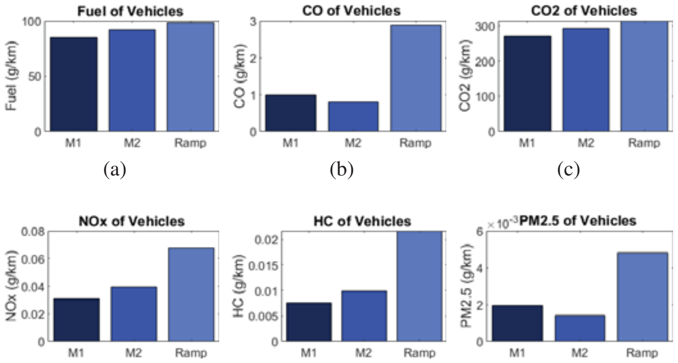
[1]The full video can be watched online at https://youtu.be/WZlzYP_u4hs or https://v.youku.com/v_show/id_XNDUwOTcxNzgzMg==.html

received by another vehicle (where the message already goes through the cloud server). The average of the communication delay is 88 ms, and the maximum is 854 ms.



(a) (b)

Fig. 7: Vehicle dynamics results of the cooperative ramp merging case study



(a) (b) (c)

(d) (e) (f)

Fig. 8: Fuel and emissions results of the cooperative ramp merging case study

V. Conclusion and Future Work

In this study, a digital twin framework is proposed for connected vehicles, which consists of a physical layer and a cyber layer with various modules. As a paradigm of this framework, an advisory speed based ADAS is presented using V2C communication. To show the effectiveness of the digital twin framework in the real-world traffic environment, a case study of cooperative ramp merging is conducted using three passenger vehicles, and the results show the digital twin can benefit the transportation systems regarding mobility and environmental sustainability with acceptable communication delays and packet losses.

A major future step of this study is to apply this digital twin paradigm to other transportation/vehicle use cases, such as the mixed traffic scenario where not all vehicles have V2C connections, and to validate the effectiveness of the proposed digital twin framework. Also, more service modules need to be proposed and implemented within this digital twin framework to maximize the advantages of V2C communication compared to other communication methods.

Acknowledgment

This research was funded by InfoTech Labs, Toyota Motor North America. The contents of this paper only reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of Toyota Motor North America.

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