Evaluation Framework of Cyber Physical Systems for Transportation

Byungkyu "Brian" Park · Joyoung Lee

This paper presents a development of Cyber Physical System for Transportation (CPS-T) evaluation framework and a case study application of freeway merge. The integrated CPS-T evaluation framework is one of kind approach that explicitly and realistically simulates individual vehicles, traffic control devices and wireless communication data packets. To demonstrate an effectiveness of the proposed integrated framework, a microscopic traffic simulator, VISSIM and a wireless communications simulator, NCTUns were integrated and the communications latencies were assessed through a freeway merge application. The case study results indicated that the proposed framework should be used for assessing any safety critical CPS-T applications including the freeway merge.

Keywords: Cyber Physical System for Transportation (CPS-T), Communications simulator, Microscopic traffic simulator, Intelligent transportation, VISSIM, NCTUns

I. INTRODUCTION

Transportation is a vital element for sustaining economic growth and for ensuring quality of life. Past few decades, transportation infrastructure growth (i.e., building roadway) has been much slower than the growth of vehicle miles traveled. This obviously resulted in congestions and wasted fuel and emissions. A recent Texas Transportation Institute Urban Mobility report noted that Americans spent 5.5 billion hours of extra time and 2.9 billion gallons of extra gas due to congestion in 2011 [1]. Nationwide, the United States wasted about 121 billion dollars and 56 billion pounds of additional Carbon Dioxide greenhouse gas released due to congestion [1]. In addition, 32,367 people were killed and more than 2.2 million people were injured due to crashes in 2011 [2]. This is a traffic safety statistics that remains challenge.

To address these challenges, Intelligent Transportation System (ITS) has been deployed to improve transportation mobility, safety and environment by embracing advances in information technology. While ITS has been fairly successful, its potential has not been fully realized mainly due to lack of widely deployed sensors and communications capabilities. An answer to additional sensors and communications capabilities is about to be realized through Cyber Physical System for Transportation (a.k.a., connected vehicle technology initiative) led by US Department of Transportation, National Science Foundation, and CPS-T related research community. The purpose of this paper was to describe and apply an integrated framework that explicitly and realistically considers individual vehicular movements, traffic control devices and impact of wireless communications within CPS-T applications. The remainder of this paper is organized as follows. Section II summarizes existing research efforts evaluating CPS-T applications in transportation domain that assumes perfect communications within a predefined range, and

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communications domain research that assumes a simple vehicular movements without considering car following and lane changing maneuvers. Section III describes an integrated framework that explicitly and realistically considers traffic maneuvers and communications impact simultaneously. Section IV presents a case study of freeway merge demonstrating the importance of explicitly considering communications impact in developing and evaluating CPS-T algorithms and applications.

II. CPS-T PERFORMANCE EVALUATIONS

Existing studies mainly focused on the evaluations of Intelligent Transportation System (ITS) applications and algorithms under Cyber Physical Systems environment. In order to evaluate the performance of the proposed Cyber Physical System for Transportation (CPS-T) applications and/or algorithms, researchers in transportation relied on traffic simulators without explicitly considering communications impact while researchers in electrical or computer engineering used communications simulators without utilizing realistic vehicular maneuvers. Little attempts were made to consider both traffic and communications simulators at the level adequate to be realistic conditions.

1. Traffic Simulator-based Performance Investigations

Cyber Physical System for Transportation (a.k.a., Connected Vehicle) research primarily focused on the use of test-beds using traffic simulations. For example, Tanikella et al. [3], [4] developed CPS-T simulation test-beds to quantify benefits of traffic monitoring application using AIMSUN [5] and a ramp metering application using PARAMICS [6]. These simulation test-beds consist of a microscopic traffic simulation model and a simplified CPS-T layer that filters vehicle snapshots and generates CPS-T data. A key assumption was perfect communications: for example, no communication delays or packet drops among vehicles or between vehicles and infrastructure as long as vehicles are within a predefined communication zone. In real world, transmission delays and packet drops exist during radio communications. Even though the assumption of the CPS-T layer is reasonable for traffic monitoring applications, they might be invalid for safety or traffic control related applications such as freeway merge and collision avoidance system.

2. Communications Network Simulator-based Performance Investigations

Researchers in electrical engineering have tried to investigate the performance of a vehicular wireless communications for CPS-T applications.

Artimy et al. [7] investigated the connectivity performance of an inter-VANET through the integration of a cellular automata-based traffic simulation model and a Mobile Ad-Hoc Network (MANET)-based wireless communication model. Their study discovered that the distance between two communicating vehicles is the most significant factor affecting the connectivity. However, their study employed a MANET-type model for a VANET-type application and did not clearly indicate the utilized communication standards. Note that VANET is fundamentally different from MANET in that (i) VANET s network topology rapidly changes due to high speed mobile nodes, and (ii) no power losses are considered for VANET. Thus, it may not be adequate to apply MANET for VANET studies. In addition, the study did not consider such issues as delay and transmission errors.

Yousefi et al. [8] addressed the performance of beacon message dissemination in VANET. According to the DSRC standard [9], the beacon message refers to a data packet that is periodically (i.e., 50 ms) broadcasted to and monitored by every receiver in the communications range. Therefore, beacon messages are used not only for the dissemination of safety data such as individual vehicles' instantaneous locations or velocities but also for non-safety data establishing a mobile network. By employing GloMoSim [10], a communication simulation model, they investigated the packet delivery rates and delays under free flow traffic conditions. However, their study employed a simplified mobility model that was derived from the flow-density relationship, resulting in a constant speed for every vehicle and an original Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as a Medium Access Control (MAC) layer protocol in IEEE 802.11 standard, which differs from the up-to-date connected vehicle technology standard, Enhanced Distributed Channel Access (EDCA), an enhanced version of the CSMA/CA [11].

Stibor et al. [12] evaluated the maximum communication range of broadcast messages in VANET. To this end, they developed their own event-driven stochastic network simulation program named Wireless Access Radio Protocol 2 (WARP2) based on connected vehicle technology standards set by the Federal Communications Commission (FCC). While the WARP2 follows

WAVE/DSRC standards ruled by FCC, its vehicle mobility model must be specifically described. This study showed the packet delivery rates as a performance indicator for various communicating distances, but the authors did not address any delays or latency issues at the MAC layer.

Wang and Chou [13] evaluated a Wi-Fi-based wireless vehicular communication network by using NCTUns [14]. Unlike [8], they implemented a kinematic car-following model to improve vehicular movement behaviors. However, their car following model was inadequate to represent actual vehicular movements such as the lane changing or merging behaviors.

3. Integrated Simulators-based Performance Evaluations

It is clear that either a traffic simulator or a communications simulator alone is not adequate to assess the performance of CPS-T algorithms and/or applications. A group of researchers proposed integrated simulation approaches by integrating the traffic and communications simulators.

Sommer et al. [15] integrated SUMO [16], a microscopic traffic simulation model, and OMNeT++ [17], an open-source network simulation model to allow an interactive simulation environment. Thus, the traffic simulator's individual vehicular data including locations and speeds are sent to the network simulator such that the communication performance was evaluated. This is to allow proper driving behavior in traffic simulator when a packet drop or a communication delay affecting drivers' behaviors happens. While their integration appears to be successful, it is not clear their approach is scalable. In addition, they utilized Wi-Fi, instead of DSRC, based on IEEE 802.11a/b/g standards [18].

Assemacher et al. [19] proposed a hybrid simulation to address the scalability challenge. A microscopic traffic simulation program VISSIM [20] created vehicular trajectories that was fed into a network simulator NS-2 [21]. A probability model based on Nakagami m distribution [18] was derived from NS-2 simulation results. This probability model as a function of communications distance and transmitter power was embedded into VISSIM to determine the packet reception probability. They evaluated the performance of a Variable Speed Limit (VSL) strategy on an actual freeway section in Frankfurt, Germany. However, Connected Vehicle technology protocols were not used as the NS-2 did not support the communication protocols of WAVE/DSRC.

In summary, even with notable attempts by many researchers none of studies fully integrated traffic simulator and communications simulator realizing connected vehicle technology.

III. INTEGRATED FRAMEWORK

1. General Framework

As noted, it is crucial to integrate both traffic simulator and communications simulator so that the impacts of traffic (i.e., driver's) behavior as well as communications latencies are explicitly considered in the development and evaluation of Cyber Physical System for Transportation (CPS-T) applications and their control algorithms. This section describes an integrated framework developed in Lee [21] and applied in Park et al. [22].

The integrated framework ensures that the program (i) replicates precise vehicular movements, (ii) incorporates CPS-T (i.e., Connected Vehicle wireless communications) based on the WAVE/DSRC protocols, and (iii) simulates message sets defined in the SAE J2735 standard. An overall framework of the CPS-T (a.k.a., Connected Vehicle) simulation environment is shown in Figure 1.

The major focus of the simulation environment is the integration of two heterogeneous simulators: (i) a microscopic traffic simulator and (ii) a wireless communications simulator. Given that almost all traffic simulators are time-based and wireless communications simulators are event-driven, an inconsistency exists in exchanging data between the two simulators. To address this, a traffic simulator agent and a communications network simulator agent were introduced.

2. Microscopic Traffic Simulator: VISSIM

A microscopic traffic simulator used in this framework provided two functions: (i) implementing CPS-T (i.e., Connected Vehicle) applications such as ramp metering or lane changing advisory applications, collision avoidance system, etc., and (ii) producing corresponding vehicular movements under CPS-T applications. Any existing microscopic traffic simulators including CORSIM [23], VISSIM [20], AIMSUN [5], and PARAMICS [6] can be used as they are all capable of generating vehicular trajectories. However, modeling CPS-T applications require an interface allowing advanced requirements such as real-time communications with external programs and the manipulations of infrastructure components in a traffic

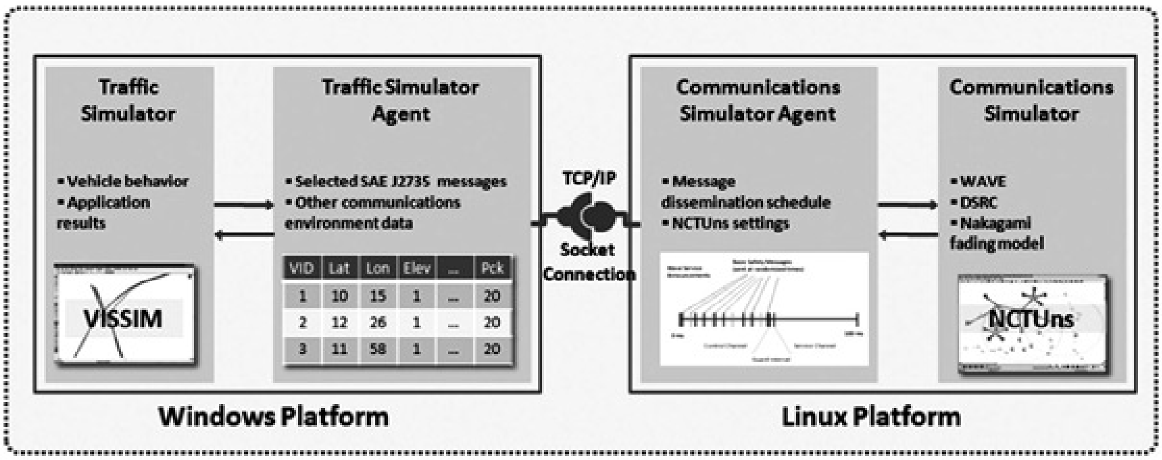

Figure 1. CPS-T(i.e., Connected Vehicle) Simulation Environment[22]

network. Given such requirements, VISSIM, AIMSUN, and PARAMICS providing an Application Programming Interface (API) are applicable. In this paper, VISSIM was selected for demonstration purpose. It is noted that VISSIM does satisfy the transmission/generation requirements of all the messages defined in the SAE J2735 standard.

3. Communications Network Simulator: Modified NCTUns 6.0

To properly simulate CPS-T communications environment, a communications network simulator must be able to perform multi-channel operations defined in the WAVE/DSRC standards. Of existing commercial and non-commercial communications-network simulators such as NS-2, OPNET, GlomoSim, NCTUns, etc., NCTUns is a simulator providing such standards.

NCTUns, developed by Wang et al. at the National Chiao Tung University in Taiwan, is an open-source network simulator designed to run on a Linux platform [14]. The most unique feature of NCTUns is its capability of modeling the Connected Vehicle communications standards (i.e., the IEEE 802.11p and IEEE 1609 family). Furthermore, unlike NS-2 requiring a Tool Command Language (TCL), NCTUns provides an easy-to-use Graphical User Interface (GUI) to create or edit communications network modules.

Despite these features of NCTUns, NCTUns does not seem to meet the requirements of the SAE J2735 standard defining four specific message dissemination techniques: V2V (or V2I) broadcast, V2V (or V2I) unicast, I2V broadcast, and I2V unicast. Since the latest NCTUns version supports only broadcasting for both BSM and ACM disseminations, it is necessary to add unicasting features to NCTUns code. To this end, the original NCTUns program was modified.

4. Traffic Simulator Agent

The traffic simulator agent (i) gathers the trajectory of every vehicle from a microscopic traffic simulator and (ii) creates a proper message set as defined in SAE J2735, e.g. a Basic Safety Message, a Probe Vehicle Data, an A La Carte Message, etc., required by a CPS-T application under consideration.

The traffic simulator agent sends vehicular trajectory information to NCTUns and receives communication performance results from NCTUns. This communication is accomplished through Transmission Control Protocol and Internet Protocol (TCP/IP) socket connection. As noted, the NCTUns program runs on a Linux platform, while VISSIM runs on a Windows platform. TCP/IP socket communication provides flexible means for inter-process communications when the communicating processes run on more than one operating system.

5. Communications Simulator Agent

The communication simulator agent receives messages from the traffic simulator agent and generates an input dataset for the NCTUns. The dataset consists of (i) message dissemination schedule, (ii) individual vehicular trajectory and (iii) communications parameters including

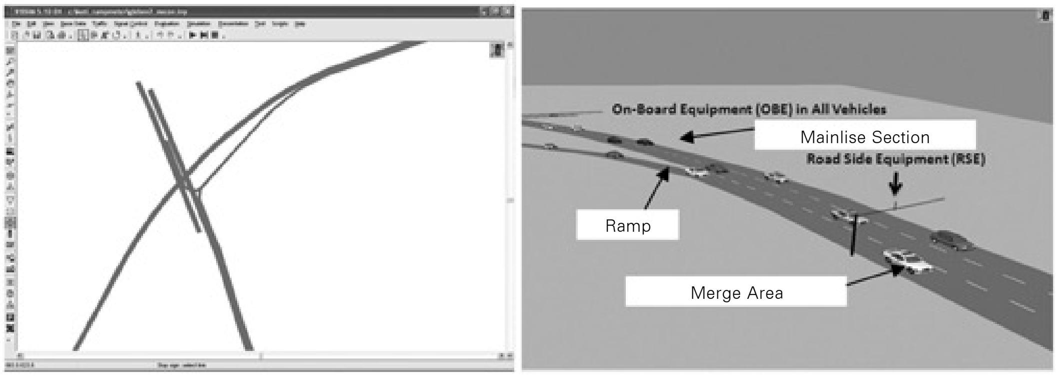

Figure 2. Test network: geometry of the site (left) and the locations of OBEs and RSE (right) [22]

transmission rate and transmitter power.

The communications simulator agent assigns each of the messages a dissemination time that is randomly generated for transmission on an appropriate channel based on the vehicular trajectories from the traffic simulator agent. Then, NCTUns produces raw communications performance results such as packet drops and transmission latencies for the messages. The results are sent back to the traffic simulator agent via TCP/IP socket.

IV. FREEWAY MERGE APPLICATION

A case study implementing a freeway merge under Cyber Physical System for Transportation (CPS-T, a.k.a., connected vehicle) environment was conducted, and the results are shown in this section.

1. Study Description

This case study was motivated from a freeway merge assistance project supported by the FHWA's Exploratory Advanced Research (EAR) program and the IT-based Smart Highway Project funded by the Korea Transport Institute. The freeway merge assistance project envisioned CPS-T enabled freeway merge control strategies including (i) Dynamic lane control, (ii) Gap-responsive ramp metering and (iii) Merge control that should be implemented within CPS-T environment. As such it is necessary to explicitly consider the impact of wireless communications for realistic evaluations.

The purpose of this case study was to demonstrate an applicability of the integrated framework using a CPS-T enabled freeway merge application. To this end, a well-calibrated simulation network of an actual freeway merge area on the Interstate Highway 66 in Virginia was selected to build vehicular trajectories [24]. A set of calibration parameters including desired speed distributions of freeway and arterial roads, look ahead distance, car following model, etc. was adjusted through an optimization approach against the observed traffic volumes and travel times. Detailed description on the calibration can be found [24]. A snapshot of the study network is displayed in Figure 2. The mainline section has 2 lanes, and about 600 ft of the merge section has 3 lanes. Traffic volumes at the entrance of the mainline and the ramp are 2,774 vph and 613 vph, respectively.

2. Simulation Scenario Setting

Each vehicle in the network was equipped with a communication device, i.e., On-Board Equipment (OBE). Road-Side Equipment (RSE) was located near the beginning of the merge area. Acting as a service provider, the RSE was connected to a traffic management center via wired or wireless link. The RSE periodically broadcasted beaconing messages every 50 ms through the control channel. The OBE vehicles within the RSE's communications range, which was set to 800 ft for this case study, listened to the beaconing message and answered it. Once a new OBE vehicle successfully received the beaconing message and answered to the RSE, the vehicle was registered as a node in the VANET. In the VANET, IP addresses were assigned to all OBEs. Thus, all units including the RSE were communicated each other via unicasts through the IP-based VANET.

The RSE broadcasts not only the periodical beaconing messages but also non-periodical messages, which are

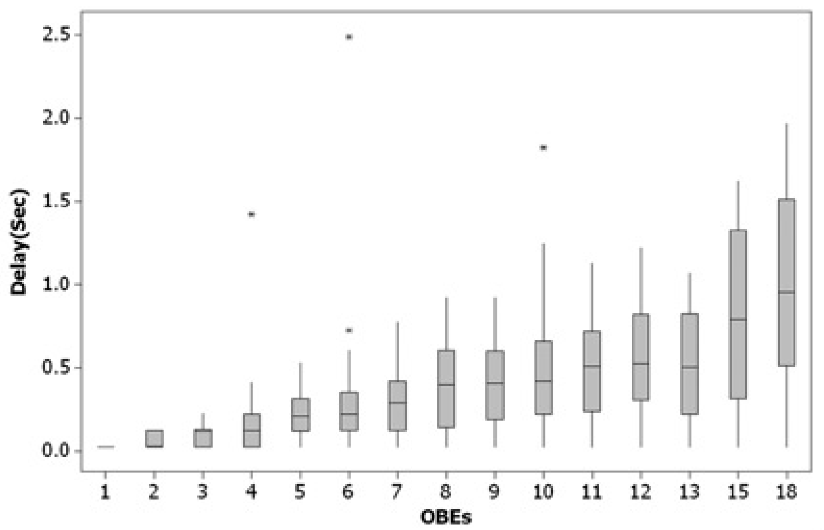

Figure 3. Delays affected by the number of OBEs

Table 1. Parameters for communications network models

Model	Parameter	Selected model/value
Channel Model	Propagation model (Unitless)	Two-ray ground model
	Path Loss exponent (Unitless)	2.0
	Antenna height (m)	1.5
PHY Model	Data rate (Mbps)	6
	Transmitter power (dbm)	18.8
	Receiver sensitivity (dbm)	-82
MAC Model	Request to send (RTS) thereshold (byte)	3000
Routing Model	Address resolution protocol	Built-in routing table

disseminated through a service channel when a certain event happens. In this case study, the non-periodical messages were broadcasted from the RSE when a vehicle entered the ramp assuming that the traffic management center provided all vehicles within the RSE range with advisory information, like do a lane change to the left or decelerate to make safe merge gap. Since considering vehicles that were already located in the merge area might be unnecessary, only vehicles that were traveling on the mainline section and approaching the ramp reacted to the advisory messages. Thus, after each of such vehicles receives the advisory message and completes any required actions (i.e., running corresponding applications), each of them unicasts a UDP-type answer messages (i.e., message confirms) to the RSE through the same service channel that the RSE used. The delay times to the RSE were measured at this moment. In addition, the setting for the operation of RSE and OBEs are summarized in Table 1. A propagation model simulating the behavior of radio signal propagations and a two-ray ground model simulating the effects of ground reflections for the radio propagations were used.

A total of 88 mobile nodes were simulated in the NCTUns after applying the node reuse scheme, and the simulation duration of a 900-second period was replicated 5 times. In addition, no topological obstacles that likely prevent the radio communications were considered, such as barriers, buildings, or trees.

3. Delay Results

A delay refers to the duration required for a data packet to complete its travel from the sender's MAC layer to the receiver s MAC layer. The delays presented in this

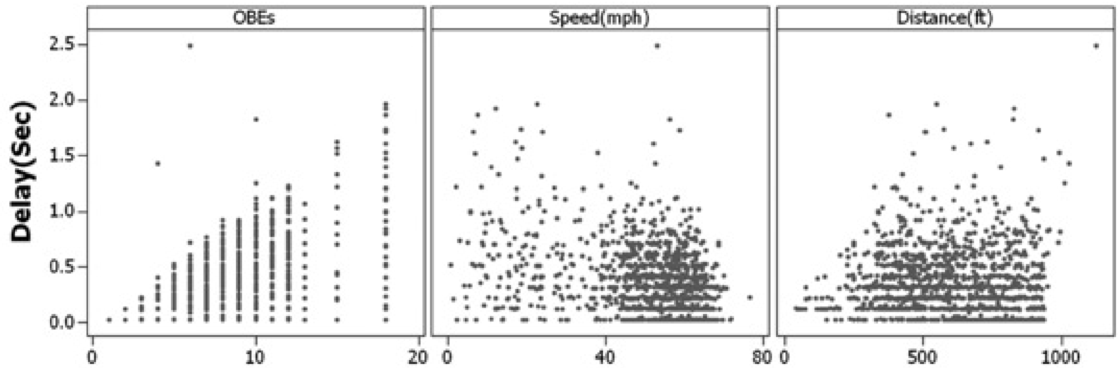

Figure 4 . Communication delays measured

section refer to the duration from each OBE to the RSE. In addition, the characteristics of the delays were investigated based on the following three factors: distance to the RSE, the velocities of the vehicles, and the number of OBEs within the range of the RSE coverage.

As demonstrated in Figure 3, the delays were likely to increase as the number of OBEs within the RSE coverage increases. Excluding statistically identified outliers indicated as asterisks in Figure 3, the maximum delay time of 2.01 seconds was observed with 18 vehicles within the RSU coverage. The median delay time over the entire OBE number ranges was slightly less than 1.0 second. It was also observed that the variances became larger as the number of OBEs increases. This clearly indicates the communications reliability could be an issue when the number of OBEs within the RSE coverage increases.

Considering the fact that the queue time at the receiver's MAC layer increased as the number of received messages increased, such observation might be obvious. However, the number of OBEs might be more important. That is, considering the deployment of the CPS-T applications, understanding how many vehicles can maintain reliable and seamless connections is extremely crucial for safety critical applications.

On the other hand, it appears that the impact of speed and distance is not clear. Regarding the impact of the speed as depicted in the middle of Figure 4, delays appear to be evenly dispersed even though they seem to be denser in the high speed area (i.e., over 40 mph) than the low speed area. In addition, the impact of communications distance appears to be intuitive as the longer distance results in the increased delay time as shown in the right side of Figure 4. However, it was discovered that the impacts of these two factors were statistically not significant on the delay time: the Pearson correlation coefficients of the speed and the distance were -0.342 (p=0.000) and -0.016 (p=0.550), respectively. This finding is also visually supported by the plots shown in Figure 5.

V. CONCLUSIONS AND FUTURE RESEARCH

This paper described an integrated framework that explicitly and realistically considers vehicular movements and communications packets. Thus, the integrated framework models characteristics of the communication delays/latencies under CPS-T that have not been explicitly considered in the evaluations of CPS-T applications under WAVE/DSRC standards. The characteristics of communications delays were examined with three factors including (i) the number of OBEs under the RSE coverage, (ii) the distance between each OBE and the RSE, and (iii) the speed of each individual OBE.

The integrated framework-based simulation experiment on a freeway merge application suggested that the number of OBEs was the most crucial component in communications delays: the delay and its variance became worse as the number of OBEs within the RSE communications coverage was increased. While the maximum observed delay was less than 200 ms until the number of OBEs reached 3, those delays became over 1.5 seconds when 10 or more OBEs were present within the RSE coverage. It was also observed that the communicating distances and vehicle speed did not significantly affect the communication delays.

The delays obtained from this paper clearly indicates challenges to deploy safety-critical CPS-T applications such as freeway merge control and/or traffic signalized

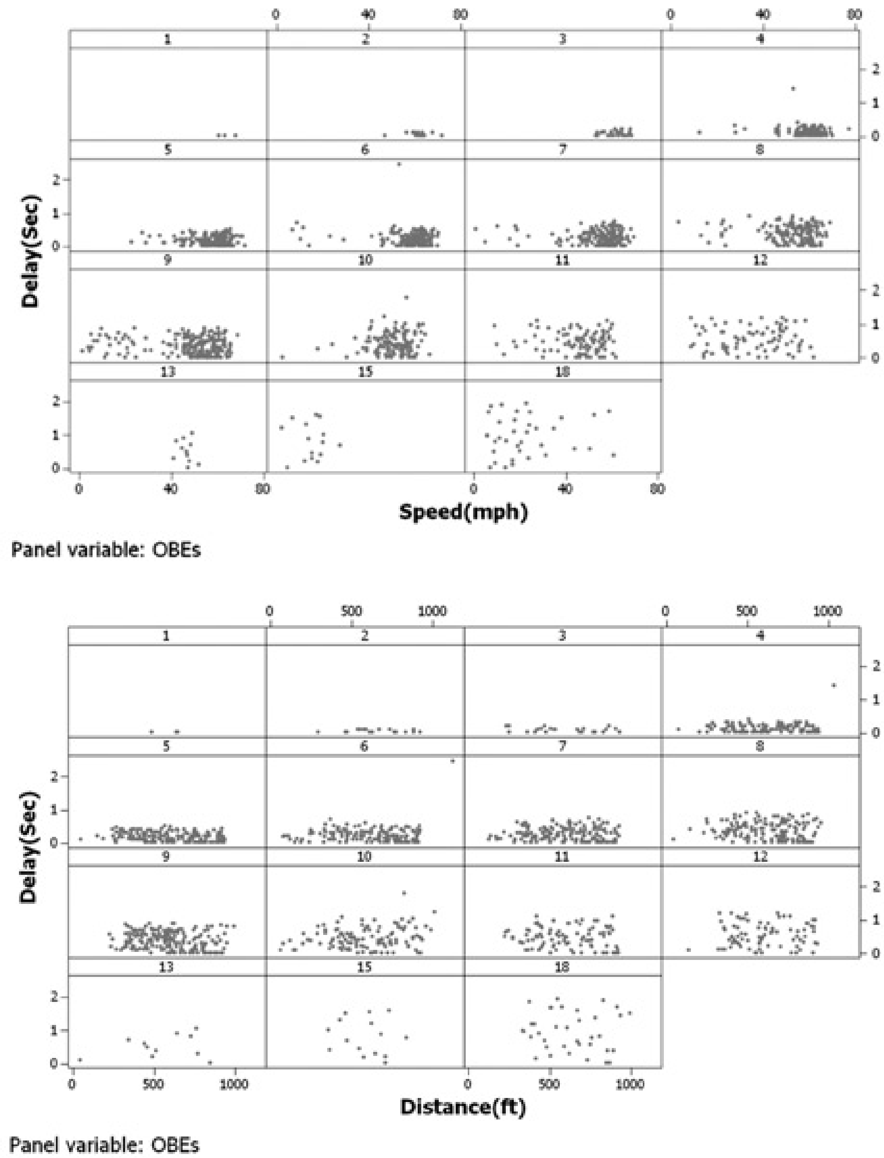

Figure 5. The impacts of speed (top) and distance (bottom)

intersection control that are sensitive to drivers' perception/reaction times. If the delay time is short enough (i.e., 50 ms), for instance, the deployments of such applications would not be an issue because the communications would be completed before drivers become aware of it. However, it would be unlikely to maintain such a condition that the number of vehicles within the RSE coverage to be less than 3 or so in real world. Therefore, it is necessary to establish an additional module to take into consideration the communications delay issue when developing algorithms for such applications. In addition, as pointed out in the proof of concept report [25], the CSMA/CA protocol parameters such as back-off durations or service-control channel change intervals in the MAC layer which most likely affects the delay time needs to be optimized for CPS-T applications, especially those safety critical ones.

Obviously, the integrated CPS-T evaluation framework needs further enhancements. For example, calibration of each simulation modeling component should not be overlooked. Some efforts given in the traffic simulation modeling calibration can be found in [26]~[29], and communications simulation modeling calibration is in [30]. Computation time required to complete the integrated framework for a large scale network having a large number of vehicles within the simulation would make the evaluation impractical - a cloud computing or cloud sourcing would be a suitable approach. A recent emphasis on sustainability calls for development and evaluation of CPS-T algorithms and applications that would save fuel consumption and emissions, and improve safety. Some studies in saving fuel consumption can be found in [31]~[36] and safety in [37].

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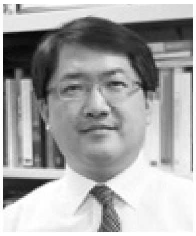

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