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Investigating Communications Performance for Automated Vehicle-based Intersection Control under Connected Vehicle Environment

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Abstract— **This paper investigates the wireless communications performance of Cooperative Vehicle Intersection Control (CVIC) powered by the Connected Vehicle (CV) environment. Considering the CV communication standards defined in IEEE 802.11p, IEEE 1609, and SAE J2735, the performances of CV communications were examined under several external factors including the number of On-Board Units (OBUs) and the distance between transceivers by using an off-line simulation framework integrating NCTUns, a wireless communications network simulator, for DSRC communications and VISSIM for vehicular movements. Unlike perfect communications assumptions made in most CV studies in the transportation literature, a case study implementing the simulations of the CVIC algorithm showed that no perfect packet deliveries were observed, resulting in about 48% packet drops at most.**

I. INTRODUCTION

Vehicular Ad-hoc Network (VANET) [1] technology has received great attention throughout the world. In particular, the United States has established Connected Vehicle (CV) Research [2]. After the U.S Federal Communication Commission (FCC) assigned 75 MHz of dedicated short-range communication (DSRC) bandwidths at 5.9GHz to CV, the U.S. Federal Highway Administration (FHWA) initiated the investigation of the potential benefits of CV for various applications, such as traffic safety, management, and operations [2].

Numerous state-of-the-art CV applications focusing on the improvements of safety and mobility have been proposed, and some of them have demonstrated promising benefits. Such applications include: i) traffic safety [3, 4], ii) traffic monitoring [5, 6], iii) ramp metering [7], iv) route guidance [8], and v) Cooperative Vehicle Intersection Control (CVIC) for automated vehicles [9, 10]. However, those studies assumed the presence of perfect communications connections between vehicles and infrastructures that resulted in no information loss: unfortunately, this is not the case in the real world. In general, wireless communications are frequently interrupted by various external factors such as distance between transmitters and receivers; the amount of data packets to be transmitted; and topologies such as tunnels, buildings, or trees. These factors would affect the quality of communication as well as the potential benefits of the safety critical CV applications.

This paper explores the communication performances of automated vehicle-based intersection control algorithm that was proposed by [9,10]. To this end, this paper facilitated an off-line simulation-based framework inherited from the previous research proposed in [11]. The simulation framework couples two different simulation models: i) VISSIM [12] for vehicular movements, and ii) NCTUns [13], a wireless communications network simulator, for the simulation of CV communications standards such as IEEE 802.11p [14], IEEE 1609 [15-18], and SAE J2735 [19].

The remainder of this paper is organized as follows. The next section summarizes previous research highlights on the evaluations of VANET-based wireless communications performance. A simulation-based framework for investigating the CV communications performance is discussed in Section III. Section IV provides a brief review on the CVIC algorithm followed by evaluation results in Section V. Finally, findings from this study and conclusions are addressed in Section VI.

II. LITERATURE REVIEW

Numerous studies have attempted to ascertain the behavior of wireless communications in the Vehicular Ad-hoc Network (VANET) environment. This section summarizes some of the key efforts.

Artimy et al. [20] 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 that affects the connectivity. However, the 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 error.

Stibor et al. [21] developed an event-driven stochastic network simulator for VANET, namely Wireless Access Radio Protocol 2 (WARP2), based on the WAVE/DSRC standards ruled by Federal Communication Committee(FCC), to investigate the performance of communication range of CV. The research also measured packet delivery rates as a performance indicator for various communicating distances and discovered that the delivery rates decrease as the distance between two communicating vehicles increase. However, the research did not clearly describe about the vehicles' mobility model.

Sommer et al. [22] proposed a real-time simulation framework by coupling a microscopic traffic simulator, SUMO [23], for realistic vehicle movements, and a

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communications network simulator, OMNeT++[24], to pursue a truly interactive simulation environment for VANET. While this coupling effort sound ideal, a scalability issue, most likely making the simulation framework impractical, still remains. In addition, the wireless communication standard they applied for the study was a Wi-Fi, utilizing existing IEEE 802.11a/b/g standards [25] because OMNeT++ does not support the WAVE/DSRC communication standard.

To overcome such a scalability issue in the integrated model, Assemacher et al. [27] proposed a hybrid simulation approach incorporating a small scale propagation model and a microscopic traffic simulator. The authors estimated the propagation model based on the Nakagami-m distribution by using a network simulator, NS-2 [27]. Then the model was embedded into VISSIM as a part of the external module that determines the probability of packet receptions. With communications range and transmitter power as independent variables for the propagation model, the authors estimated the performance of a variable speed limit (VSL) strategy under varying market penetration rates and congestion conditions. As a result, given 100% and 50% of market penetration rates, the research discovered 26%, and 10% of total travel time savings, respectively.

Lee and Park [28] also developed a VISSIM-based hybrid simulation framework enabling a unique channel operation scheme defined in WAVE/DSRC communication standards, namely multi-channel operation, by employing NCTUns. Through a case study focusing on an actual freeway merging section in Virginia, the authors investigated the service channel-based Vehicle to Infrastructure (V2I) communication performances of CV standards by using packet drop rates and transmission delays under both various traffic conditions and communication environment variables such as bandwidth and packet sizes. As a result, it was discovered that i) the number of on-board equipment (OBE) vehicles was the most crucial component in communication delays, but ii) the impacts of OBE speeds and distances between OBE and roadside equipment(RSE) are insignificant as long as the OBEs are located within the RSE communication range. Although their research came closer to actual CV communication standards, the message set they applied was not ruled by SAE J2735 standards.

Park et al [11] enhanced the simulation framework of Lee and Park [28] by developing a real-time integrated CV simulation environment that fully satisfies all the standards defined in IEEE 802.11p, 1609, and SAE J2735. While [28] focused on the communication performances of service channel messages, [11] investigated the communication behaviors of control channel messages, which are designed for the data exchange of safety-critical applications such as collision avoidance, or freeway merging control systems. A case study applied to an CV-based freeway merging control application in [7] showed that communication delays do not have significant impacts in control channel messages. Whereas no perfect packet delivery rates were observed and such rates varied depending on the number of OBE and distances between OBE and RSE.

In summary, there have been several VANET-based research efforts to identify the characteristics of the CV communications performances as reviewed in this section. However, neither the multi-channel operations defined in IEEE standards, nor the CV applications-dedicated message sets defined in the SAE J2735 were precisely taken into consideration in the previous research except for a few studies. In addition, the mobility models in the previous VANET research were insufficient to address the realistic movements of individual vehicles. Obviously, in order for CV performance investigations to be reliable, such critical components must be taken into account.

III. Simulation Framework for CV Communications Performance Investigation

A. Overall Architecture

This paper proposed an easy-to-implement off-line simulation framework, which is a spin-off version of the CV simulation environment proposed by Park et al. [11]. The major component of the simulation environment is the integration of two heterogeneous simulators: i) a traffic simulator and ii) a wireless communications simulator.

While almost all traffic simulators are time-based, wireless communications simulators are event-driven. Thus, an inconsistency exists in exchanging data between the two simulators. In this paper, as shown in Figure 1, two additional elements, a traffic simulator agent and a communications network simulator agent, are developed to run both simulators simultaneously. Details of each element in the simulation environment are presented in the following sections.

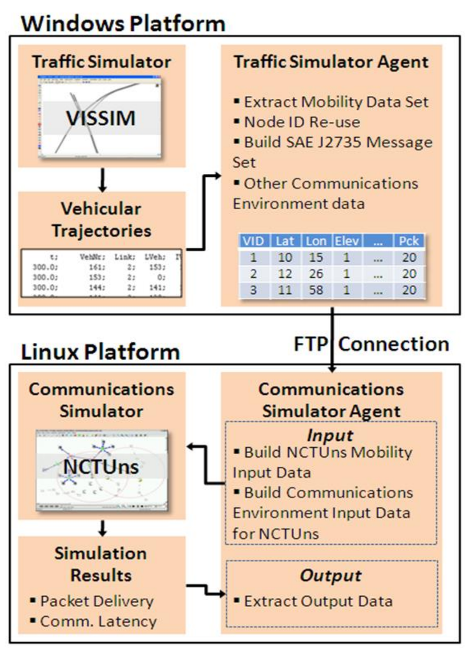


Figure 1. *Proposed Integrated Simulation Framework*

B. Microscopic Traffic Simulator

The role of a microscopic traffic simulator in this integrated simulation environment is two-fold: i) implementing CV applications such as a lane-changing advisory system or collision avoidance system and ii) producing corresponding vehicular movements under such applications. To satisfy the latter, any existing simulators such as VISSIM, AIMSUN [29], and PARAMICS [30] could be used as they are capable of producing the vehicular trajectories. In this paper, VISSIM was selected due to authors' hands-on experience of using it. The VISSIM program produces the vehicular movement information of every vehicle in the network at every simulation update interval (i.e., 0.1 seconds).

C. Communications Network Simulator

To properly simulate the CV communication environment, a communications network simulator must be able to perform multi-channel operations defined in the WAVE/DSRC communication standard. There exist everal communications network simulators including NS-2/3, GlomoSim [31], SUMO[23], and NCTUns[13]. In this paper, we enhanced NCTUns, an open-source network simulator that runs on Linux developed by Wang and Lin [32] to simulate VANET-type environment, including CV. The enhanced NCTUns features include i) SAE J2735-based message disseminations, ii) real-time vehicular trajectory data, and iii) Nakagami fading model [33] for the small scale fading effect.

SAE J2735 standards define four different types of message disseminations for CV communications: i) V2X Basic Safety Message (BSM) broadcast, ii) I2X A-La Carte Message (ACM) broadcast, iii) V2X ACM unicast, and iv) I2X ACM unicast. Since the NCTUns program supports only broadcastings for both BSM and ACM disseminations, it was necessary to add the unicast feature into the original program. To this end, this paper facilitated a SAE J2735-enhanced NCTUns program modified by the Center for Transportation Studies (CTS) at the University of Virginia.

Many communications network simulators including NCTUns adopt historical trajectory-based mobility model which might be unsuitable for on-line implementations. To overcome this issue, a research team at the Center for Transportation Studies (CTS) at the University of Virginia enhanced the original NCTUns program to enable it to obtain real-time trajectory data from traffic simulators.

To deal with stochastic natures of radio signal fading effects, the NCTUns program supports two fading models: i) Rayleigh fading model and ii) Rician fading model. Since both the Rayleigh and Rician fading models are based on mathematical probability theories, it is known that these models often result in serious misfits with obtained field data. In order to overcome such misfits, an empirical model, namely the Nakagami fading model, has been proposed by Nakagami [33]. The Nakagami fading model is known as a practically useful fading model to be used for generic fading effects. The NCTUns 6.0 program does not support the Nakagami fading model. Therefore, a research team at the Center for Transportation Studies (CTS) at the University of Virginia added the Nakagami fading model into the original NCTUns program. In this paper, the Nakagami fading model was employed to obtain realistic fading effects for CV applications.

D. Traffic Simulator Agent

Datasets obtained from the VISSIM program were not directly accessible for the implementation of NCTUns due to following reasons: i) NCTUns runs on a Linux platform, whereas VISSIM runs on a Windows platform, ii) NCTUns uses its own data format for both mobility data and communications environment data, iii) the number of vehicles in NCTUns is unchangeable once defined, and iv) NCTUns uses a pre-defined message dissemination schedule. Thus, in order to overcome these limitations, and to effectively manage the data organization, a traffic simulator agent (TSA) was developed.

With vehicular trajectories obtained from the VISSIM program, TSA i) extracts instant mobility data of every vehicle such as its latitude, longitude, speed, and acceleration rates to be used for the mobility input dataset of NCTUns, and ii) creates a proper message set that would be either a BSM or an ACM depending on who the sender is (i.e., if the senders are multiple vehicles, for example, the message set must be the BSM). Obviously, such senders are dynamically determined while the CV application is being implemented. In addition, TSA archives the message sets in the respective database according to the types of message set, in order to keep the data in chronological order for potential future use.

E. Communications Network Simulator Agent

In order to execute the NCTUns program, a dataset should be properly prepared. The majority of such a dataset includes: i) message dissemination schedules, ii) individual vehicular trajectories information, and iii) communications models' parameters. To perform these tasks, a network simulator agent (NSA) was developed.

Like almost all existing communications network simulators, NCTUns is incapable of automatically creating message dissemination schedules. Rather, it allows the specification of the start time of the message dissemination, thereby requiring that the schedule be manually generated before the NCTUns program starts. Given the vehicular trajectories transferred from the traffic simulator agent through the FTP connection shown in Figure 1, the NSA assigns each vehicle a message dissemination time, randomly generated within the control channel period (i.e., 0~50 ms).

The NSA also creates an input dataset for NCTUns, including the message dissemination schedule, vehicular trajectories, and other communication-environment parameters such as bandwidths, transmitter powers, etc. Based on the dataset, NCTUns is invoked and produces raw-level communications-performance results including packet drops and transmission latencies by the message types (i.e., BSM or ACM). Once the NSA gathers the performance results, it stores them into an output database to be used for analysis

IV. Intersection Control Algorithm For Automated Vehicles

The intersection control algorithm for automated vehicles is based on optimizing individual vehicles' predictive trajectories to avoid any potential collisions. This section briefly addresses the core of the algorithm; one can refer to the original research efforts from [9,10] for more details.

The control algorithm seeks the optimal trajectories utilizing non-linear constraint optimization techniques, which are designed to solve an optimization problem given the Equations 1 through 4. With optimal acceleration/deceleration rate for each vehicle approaching to the intersection, the overlapping trajectory for each vehicle is adjusted to safely cross the intersection without stops or the need for a traffic signal. In case no feasible solutions are found, however, the CVIC algorithm runs in a recovery mode, a traffic signal-based special period designed to be quickly returned to normal optimization-based control mode [9, 10]. During the recovery mode, all the vehicles approaching to the intersection are controlled by both the CVIC system and a regular traffic signal system.

$$Min\ TL = \sum_{i=1}^{P}\sum_{k=1}^{L_i}\sum_{m=1}^{N_{ik}}\sum_{j=1}^{P}\sum_{l=1}^{L_j}\sum_{n=1}^{N_{jl}}\int_p^q \sqrt{1+x'_{ikm}(w)^2\,dw} \qquad (1)$$

such that,

$$a_{ikm} \geq \max\left(a_{\min}, \frac{-v_{ikm}^2}{2x_{ikm}(0)}, \frac{u_{\min}^2 - v_{ikm}^2}{2(x_{ikm}(0)-x_{ikm}(t))}\right) \ \forall i,k,m \qquad (2)$$

$$a_{ikm} \leq \min\left(a_{\max}, \frac{u_{\max}^2 - v_{ikm}^2}{2(x_{ikm}(0)-x_{ikm}(t))}\right) \quad \forall i,k,m \qquad (3)$$

$$S\big(0.5(a_{i,k,m} - a_{i+1,k,m}\big)R^2 - (a_{i,k,m}h - v_{i,k,m} + v_{i+1,k,m})R + S > 0 \ \forall i,k \ and \ m = 1,2,\ldots N_{i,k}-1 \qquad (4)$$

where,

P : Total signal phase numbers

i, j : Signal phase number indices (1 if phases are conflicted, 0 otherwise)

k, l: Lane identifier

m, n: Vehicle identifier

L_i, L_j: Total number of lanes of signal phase i,j, respectively

N_{ik}, N_{jl}: Total number vehicles on lane k and l of signal phase i and j respectively.

p: Arrival time at the beginning of intersection

$(= \max\left(t_{i,k,m}(o), t_{j,l,n}(o)\right))$

q: Arrival time at the end of intersection

$(= \min\left(t_{i,k,m}(d), t_{j,l,n}(d)\right))$

$t_{i,k,m}(o)$, $t_{j,l,n}(o)$: Arrival times at the beginning of the intersection of vehicle m(n) on lane k(l) in signal phase i(j)

$t_{i,k,m}(d)$, $tl_{j,l,n}(d)$: Arrival times at the end of the intersection of vehicle m(n) on lane k(l) in signal phase i(j)

$$S = 0.5a_{i,k,m}h^2 - v_{i,k,m}h - x_{i,k,m}(0) + x_{i+1,k,m}(0)$$

$$R = a_{i+1,k,m}^{-1}\left(-v_{i+1,k,m} + \sqrt{v_{i+1,k,m}^2 + 2a_{i,k,m}x_{i+1,k,m}(0)}\right)$$

For the implementation of the CVIC algorithm, this paper assumed that there is an intersection controller especially designed both to gather individual vehicular information and to provide optimal maneuvers to the vehicles crossing an intersection. The controller equipped with Roadside Equipment (RSE) periodically broadcasts beaconing messages every 100 ms through the control channel (CCH) as defined in the CV communications standards, and then the vehicles equipped with On-Board Equipment (OBE) listen to the beaconing messages and answer them. If a new OBE vehicle enters the RSE's communication range, which is assumed to be set to 1000 m in this study, the vehicle is registered as a node in the VANET.

Assuming a perfect wireless communications condition and a 100% market penetration rate, the performance of the CVIC algorithm was evaluated on a hypothetical isolated intersection with varying traffic congestion conditions by using a simulation test-bed [9]. The overall performances of the CVIC algorithm compared to an actuated control (AC) are summarized in Table 1.

Table 1 Summary of the overall gains of CVIC algorithm

Measure (Unit)	CVIC	AC	Gain
Average total stop delay time (Hour)	0.1	12.1	99%
Average total travel time (Hour)	25.1	37.2	33%
Carbon Dioxide (CO_2) (ton)	263.7	471.0	44%
Fuel Consumption (Liter)	120.9	215.2	44%

V. EVALUATION

The intersection controller is assumed to perform an optimization process to find the optimal maneuvers. To this end, the controller would need the latest driving information from every individual vehicle approaching to the intersection. Given the CV environment, such driving information was assumed to be disseminated by the basic BSM and thus, the controller would have the driving state information of each individual vehicle at every 100 ms as the dissemination period of the BSM is defined as 100 ms in SAE J2735.

Assuming that the computation to obtain the optimal solutions can be completed in 100 ms, once the BSM is gathered from every vehicle, the controller disseminates the optimal solutions via the ACM at every 100 ms, which is the dissemination interval of ACM defined in SAE J2735.

However, it would not be necessary to gather the vehicular information and disseminate the optimal solutions at every 100 ms under the CVIC algorithm. That is, once optimal maneuvers are given to vehicles, they maintain their maneuvers until new updates are given. The new maneuvers would be updated either whenever new vehicles enter into the system or at a given fixed interval (e.g., 500 ms, 1 second, or 2 seconds). In this paper, 1-second fixed interval was adopted to update the vehicles' maneuvers.

With respect to a communication environment, it was assumed that each vehicle in the network was equipped with a communication device, i.e., OBE. RSE was assumed to be located in the middle of the intersection area by hanging on a mast arm installed at a curb side of the intersection, and to be connected to an intersection controller via a wired or wireless link to act as a service provider.

While the free-space shadowing model was used to properly simulate the effects of large scale radio propagation behaviors, the Nakagami fading model was employed to take into consideration the small scale fading effects. Parameters used in both models and other parameters for the operation of RSE and OBEs in NCTUns are summarized in Table 2.

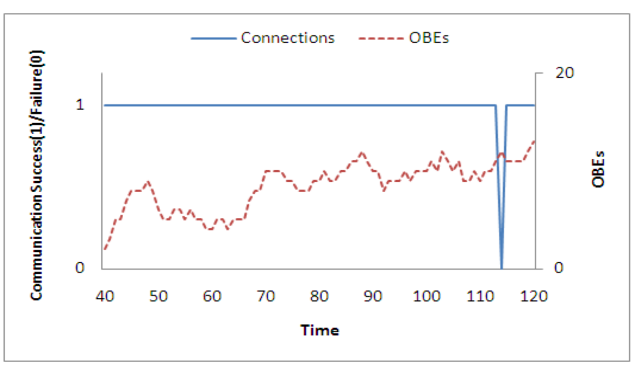
Table 2 Parameters for network models

Parameter	Value
Propagation model	Free-space shadowing model
Fading model	Nakagami fading model
Path Loss exponent	2.0
System loss	1.0
Antenna height	1.5m
Data rate	6 Mbps
Transmitter power	33.0 dbm
Receiver sensitivity	-82 dbm
Close-in distance	1m

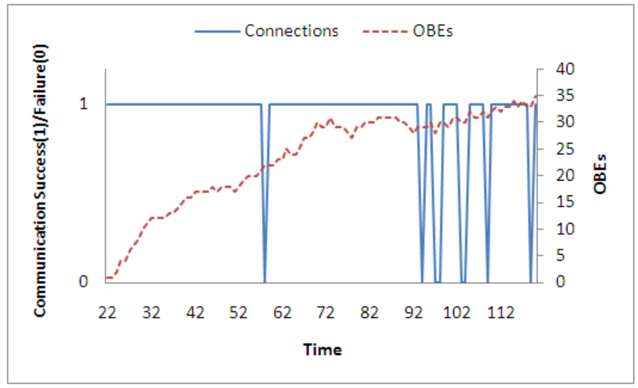
To investigate the quality of communications, this paper employed the packet drop rate measure. Figure 2 shows the frequency of both communication packet drops (i.e., 0 on the y-axis) and success (i.e., 1 on the y-axis), monitored for 120 seconds. The packet drops were examined under i) three different distance ranges between OBEs and the controller (i.e., up to 150-meter, 300-meter, and 450-meter as shown in Figure 2(a), (b) and (c)) and the number of OBEs with each distance range. Note that the distance range refers to an effective distance in which the controller actually takes into consideration vehicles within the range for the optimal maneuvers to let them cross the intersection.

With the 150-meter range case, a single packet drop was observed for the monitoring period, resulting in approximately 0.01% of packet drop rates. While the 300-meter range case showed similar communication connection performance as that of the 150-meter case, resulting in about 0.06% drop rates, the communication success rate of 450-meter case was about 48% as shown in Figure 2 (c). More seriously, consecutive packet drops were more frequently observed than the 300-meter case, which potentially require the implementation of the recovery modes of the CVIC algorithm.

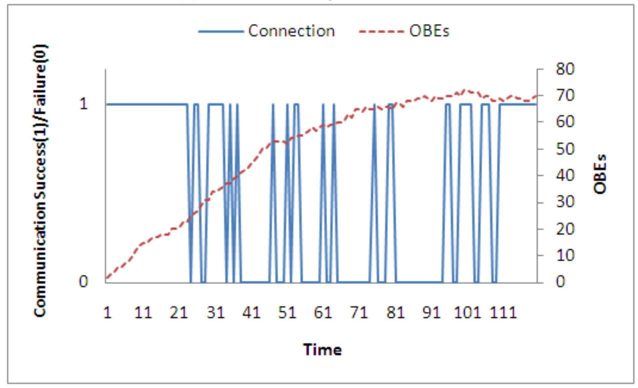
In addition to the impact of distances, the number of OBEs also affected the packet drops. As shown in Figures 2 (b) and (c), the seamless communication successes were observed when OBEs within each range were approximately 30 or less. Thus, even though the control range of the CVIC was optimally set (e.g., 150-meter), the packet drops would occur if OBEs were more than 30, which would eventually undermine the operability of the CVIC algorithm.



(a) 150-meter range from the RSE



(b) 300-meter range from the RSE



(c) 450-meter range from the RSE

Figure 2 Packet drops under different communications ranges

VI. Conclusions

This paper identified the characteristics of the CV's communications performances that have not been explicitly considered in the evaluations of CV applications. Followed by the specifications for message sets defined in the SAE J2735, the behavior of communication performances were examined by two types of communication channels and their proper message sets such as BSM and ACM for CVIC system.

With the performance measure capturing the packet drops of both V2I-I2V communications proposed in this paper, the performance of communications for the CVIC system were examined: while insignificant communications drops, i.e., 0.01%, were observed when about 30 or less vehicles are traveling within a short communication range, i.e., 150 meters, such drop frequencies dramatically increased as both the number of OBEs and communications ranges increase, resulting in 48% of packet drops with more than 30 vehicles within the 450 meters of communication ranges.

The proposed simulation framework has been successfully applied for the examination of CV's communications performances. It is expected that the framework used for an urban intersection scenario can certainly be implemented for other CV applications such as freeway merging control, route guidance system, traffic monitoring, and any other entertainment/information related applications. Consequently, this framework can enhance the quality of evaluation studies of the CV applications.

As demonstrated by the simulation results, perfect wireless communication conditions expected by traditional algorithms are nearly impossible to achieve. Therefore, it is vital to establish an additional module to explicitly consider such imperfect communications when developing and evaluating algorithms for safety-critical CV applications.

It is worth noting that the frequency of the packet drops would be improved by adjusting the communication environment to be dedicated to the implementation of the CVIC algorithm. Such adjustments would include: i) allowing service channel for the dissemination of safety critical messages, ii) multi-hop connections between transceivers, and iii) deploying a new wireless communication technology dedicated for the CVIC algorithm. The first two bullets are available adjustments as they are defined in the CV communication standards. In addition, as long as the CVIC algorithm guarantees promising benefits for the aspects of safety, mobility, and sustainability, the dedicated wireless technology for the CVIC mentioned in the third bullets would be feasible in a near future.

VII. ACKNOWLEDGEMENTS

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