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V2V System Congestion Control Validation and Performance

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***Abstract*—Major international automakers have considered the deployment of the 5.9 GHz Dedicated Short-Range Communications (DSRC) on their vehicle fleets for wireless connectivity. DSRC-enabled Vehicle-to-Vehicle (V2V) communication through broadcast of Basic Safety Messages (BSMs) enables safety applications for crash warning and avoidance. However, in dense traffic conditions as the V2V deployment scales up, the resultant channel load increases and leads to channel congestion and may adversely affect the performance of the safety applications. The Society of Automotive Engineers (SAE) J2945/1 standard that builds atop Institute of Electrical and Electronics Engineers (IEEE) 802.11p and IEEE 1609 standards provides the minimum performance requirements (MPR) for V2V safety communications. Specifically, it provides a Congestion Control (CC) protocol for transmission rate and power adaptations to achieve robust performance in dense vehicular networks. The primary contribution of this paper is that using a congestion generation testbed that emulates channel congestion including a large number of Remote Vehicles (RVs), we can validate and test any V2V equipped vehicle for compliance with the J2945/1 standard. Our paper also demonstrates that under heavy congestion, even with 600 ms of inter-transmit time (ITT), a moving vehicle can be tracked to lane-level accuracy.**

***Index Terms*—Dedicated Short Range Communications; V2V Scalability; Vehicular Ad Hoc Network; Vehicular Safety Communication.**

I. INTRODUCTION

Major U.S., European, and Japanese automakers such as General Motors, Volkswagen, and Toyota have recently either equipped some of their production vehicles with Dedicated Short Range Communications (DSRC) systems or plan to do so [1]–[3]. The U.S. Department of Transportation (USDOT) issued in January 2017 a Notice for Proposed Rule-Making (NPRM) with the eventual aim of mandating the deployment of Vehicle-to-Vehicle (V2V) safety communication based on DSRC on all new light vehicles sold in the United States. The DSRC-based V2V technology is an outcome of nearly 15 years of efforts of the industry, academia, and the government.

The DSRC-based V2V system builds atop several Institute of Electrical and Electronics Engineers (IEEE) and Society of Automotive Engineers (SAE) standards towards connected vehicles technology for safety and crash avoidance applications. Such safety applications are based on V2V safety communication that includes broadcast of vehicle status information through Basic Safety Messages (BSMs). The BSMs include core state information such as Global Navigation Satellite System (GNSS) location, speed, acceleration, brake status, and path history [4] [5], with communication ranges of 400-500 meters, or more. In particular, such V2V systems use the SAE J2945/1 standard [6] that is based on several IEEE and SAE standards:

- The Medium Access Control (MAC) and Physical Layer (PHY) protocol follow the IEEE 802.11p standard. The Federal Communications Commission (FCC) has dedicated 75 MHz of spectrum in the 5.9 GHz band for communication between vehicles (V2V) and between vehicles and roadside infrastructure (V2I).
- The BSMs follow the Wireless Access in Vehicular Environments (WAVE) Short Message (WSM) using the WAVE Short Message Protocol (WSMP) as defined in the IEEE 1609.3 standard.
- The BSM security is based upon compliance to the security certification as per the IEEE 1609.2 standard. It includes digital signatures along with security certificates or certificate digests to validate the sender's BSMs.
- The WAVE Provider Service ID (PSID) of the BSMs is defined as per the IEEE 1609.12 standard and is used to distinguish between DSRC messages.
- The message data dictionary, content and format of a BSM is as per the SAE J2735 standard.

The J2945/1 V2V standard, published in 2016, provides a set of minimum performance requirements (MPR) for V2V communication to support safety applications for crash warning and avoidance [7]. In particular, detailed performance requirements are specified to ensure the accuracy of GNSS position, speed, heading, acceleration, and yaw rate among other factors with respect to *ground truth*.

In a high traffic environment, where there is a high number of vehicles (transmitters), the channel suffers congestion due to rising interference and channel contention [8]. When it comes to channel capacity, [9] presented some fundamental limits especially as a wireless network scales. The conventional approach to handle interference in the IEEE 802.11p standard is to use Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) as the medium access protocol [10]. In CSMA/CA, when a node (or vehicle) has a packet to transmit it first listens to the channel. If the channel is deemed idle or unoccupied, it transmit the packet. Otherwise, the node waits for a random back-off time before transmitting the

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packet. While this mechanism reduces the chances of packet collisions, it does not avoid it entirely.

In large and dense V2V networks, the performance of safety applications may therefore unnecessarily suffer if all vehicles send their BSMs at the same high transmission rate and transmit power. The consequent high packet losses affect V2V situational awareness and make it difficult to predict a vehicle's movement or recognize an imminent crash in a timely manner. Hence, mitigating the channel congestion has been widely studied to address the challenge of scalability and to make the safety applications robust.

The authors in [11] have shown that communication and safety performance degrades significantly in a congested environment without a congestion control mechanism. For example, the authors have reported about 70% Packet Error Ratio (PER) with 360 transmitting nodes at a fixed 10 Hz transmission rate and 20 dBm transmit power. In [12], a congestion control algorithm is proposed that adapts the message rate of a vehicle according its motion dynamics so that neighboring vehicles can accurately track it. Additionally, the transmit power is adapted to maintain the channel load at a target level. In [13], a distributed transmit power control method is proposed, which reduces the power of safety message transmissions during congestion in order to control the load placed on the DSRC channel. In [14], a message rate control based approach is proposed to adapt the BSM transmission rate (frequency) based on a binary comparison between measured channel load and a target threshold. Binary message rate control is also the subject of [11], in which the authors propose using an Additive Increase Multiplicative Decrease (AIMD) message rate update mechanism for DSRC vehicular safety communication. They present results from prototype radio tests and computer simulations that illustrate effective message rate control for hundreds of emulated or simulated vehicles. The authors in [15] present simulation of two popular rate algorithms (ONOE and AARF) and compare the performance with different metrics. In [16], the authors propose an algorithm to minimize the average system information age in a congested environment. Through the simulations, they also show that simple contention window size adaptations (i.e. increasing or decreasing the window size) are unsuitable for reducing the information age. The authors in [13], propose a distributed transmit power control method which helps reduce BSM load and thus reserves bandwidth for emergency messages with higher priorities.

All these factors and considerations have been merged in the SAE J2945/1 standard which provides a congestion control (CC) protocol that adapts the transmit power and rate control of V2V BSM transmissions in order to achieve satisfactory safety performance. The CC protocol executes distributedly on each DSRC-equipped On-board Equipment (OBE) installed in a vehicle and adapts its radiated (transmit) power and the Inter-Transmit Time (ITT) based on the channel congestion levels the OBE experiences locally. The underlying algorithm is designed to be opportunistic to ensure channel utilization remains below the saturation level while V2V safety applications can have a good performance. The authors in [17] review the CC protocol presented in the J2945/1 standard and propose a testing methodology for its primary functions. In [18], this standard is also evaluated in a simulation environment in terms of packet error rate and information age.

A. Contributions

This paper presents on DSRC-based V2V system congestion control validation and performance through vehicle-level testing. The development was done under the V2V Systems Engineering Project conducted by the Crash Avoidance Metrics Partners (CAMP) LLC under a cooperative agreement with the National Highway Traffic Safety Administration (NHTSA). The CAMP VSC6 Consortium consists of Ford Motor Company, General Motors LLC, Honda R&D Americas Inc, Hyundai-Kia America Technical Center, Nissan Technical Center North America and Volkswagen Group of America.

We present the congestion control validation of a V2V DSRC-enabled OBE installed in a vehicle that complies with the J2945/1 standard. In our congestion control testbed, we use a DSRC-enabled Host Vehicle (HV) to wirelessly transmit BSMs, a Ground Truth Equipment (GTE) mounted on the HV to accurately capture its position and a DSRC sniffer to remotely capture the BSMs received over-the-air (OTA). Furthermore, we used a Congestion Generation Tool (CGT) that can emulate up to 160 Remote Vehicles (RVs) in our setup (which could be expanded) and up to 80% Channel Busy Percentage (CBP) (i.e., a measure of channel occupancy) by transmitting a mix of BSM and WSM packets.

We conducted multiple test runs where the HV was stationary or performed various kinds of dynamic maneuvers (such as sharp maneuvers or hard braking). The DSRC-enabled HV used a local GNSS unit for real-time positioning. Such tests were performed under specified congestion levels in the background to reproduce CBP and emulated RVs that are representative of actual traffic conditions.

Our tests validated that the DSRC-enabled vehicle can adapt its ITT and transmit power to real-world factors. Specifically, for a moving vehicle, we show that even with 600 ms between BSMs, an RV can track the HV to within 1.5m of its ground truth position. This result is particularly important as it shows that even with congestion in the background, vehicles can meet the J2945/1 position requirement for safety applications.

B. Article Outline

In Section II, we present the test setup that was used in this study. In Section III, we explain how the safety application of V2V communications depend on the ability of RVs to track an HV. In Section IV, we summarize the joint power-rate CC protocol that adapts to radio and vehicular environments. In Section V we provide the results which verifies while the congestion control algorithm decreases the transmission rate and power in the congested environment it still is able to meet the safety requirements of the the SAE J2945/1 standard. Finally, we provide conclusions of the paper in Section VI.

II. TEST SETUP

We conducted the congestion tests at FTTA Proving Ground at Fowlerville, MI under open-sky conditions. These conditions are defined as (i) no obstruction within 5^o above the mask

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angle, (ii) at least 7 healthy satellites used, (iii) with Horizontal and Vertical Dilution of Precision (HDOP/VDOP) reported at less than or equal to 1.5 and 3, respectively [6]. The complete set of equipment is shown in Fig. 1, where all devices were mounted on the HV except for the RT base station.

HV unit (OBE): The DSRC device of the HV unit broadcasts BSMs using inputs from its local GNSS for basic positioning (i.e., Coordinated Universal Time (UTC), latitude, longitude, elevation) and the vehicle's Controller Area Network (CAN) bus for additional inputs such as speed, longitudinal acceleration and yaw rate. The broadcast BSMs are secure BSMs as they are signed with certificate digests. Furthermore, in the absence of any congestion, the nominal (i.e., *baseline*) settings for the transmission frequency and the transmit power are 10 Hz (i.e., ITT of 100ms) and 20 dBm respectively [19]. With congestion control, the HV unit can detect the radio environment and adapt these parameters accordingly.

Ground Truth Equipment (GTE): The HV is also equipped with an Oxford System RT-3003 high precision localization and logging unit. This tool is able to capture highly accurate position and motion data of the HV in real-time at 100 Hz. Furthermore, the RT-3003 unit receives radio-based Real-Time Kinematic (RTK) corrections from an on-site surveyed GNSS RT base station. With these differential corrections, the ground truth position has a centimeter-level accuracy.

DSRC Sniffer: The Sniffer is a DSRC receiver operating on channel 172 that captures BSMs from the HV unit and creates a log of CBP and the received packets.

Congestion Generation Tool (CGT): This tool has several co-located GNSS/DSRC devices that can collectively transmit a large enough number of signed BSM and WSM packets on channel 172 to emulate multiple RVs and channel congestion in a repeatable manner. Since the CGT is mounted on the HV, all the virtual RVs appear within a designated range of the HV as it moves about. Specifically, the CGT can be configured to independently set the following variables:

- A target number of virtual or emulated RVs within a specified range (up to 160 RVs in our setup which could be increased).
- A target CBP (up to 80%) that indicates the percentage of time the channel is deemed occupied using Clear Channel Assessment (CCA) mechanism. In case the number of emulated RVs is small and the target CBP is high, additional WSM packets are generated by the CGT to achieve the desired CBP.
- A target channel quality indicator in terms of the PER (up to 30 %) from the emulated RVs. This PER is set by adjusting the message count in the BSMs of the emulated RVs.

Operator Test Tool: The DSRC Sniffer and the GTE are both streaming their recordings to a user-operated software test tool. The test tool processes the packet captures from the DSRC Sniffer and the GTE for congestion and ground position analysis. As the CGT changes its target congestion levels, the Sniffer is also able to record these changes and stream them to the test tool. In turn, the tool can correlate the congestion generated by the CGT with the rate and power adaptations of the HV unit to determine whether the latter complies with J2945/1.

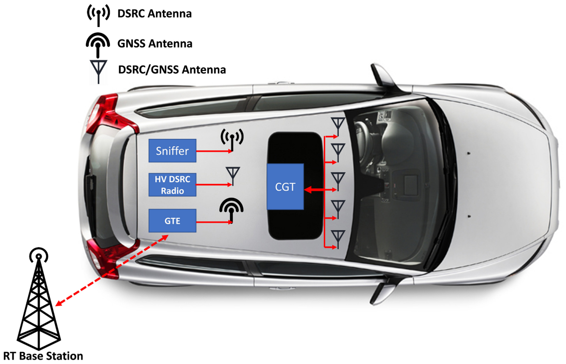


Fig. 1: The schematic of the equipment for validating the SAE J2945/1 congestion control protocol.

III. TRACKING ERROR AND ITS CHALLENGES IN CSMA/CA CHANNEL

In V2V safety communication, each vehicle continuously broadcasts its own status (e.g., position, speed, and heading) in BSMs. Each vehicle also tracks the movements of neighboring vehicles based on BSMs received from them. In intervals between BSMs from a moving vehicle, its current location has to be estimated. The accuracy of the vehicle's estimated position is measured in terms of distance from the ground truth. This displacement or distance error is a key consideration in crash avoidance applications.

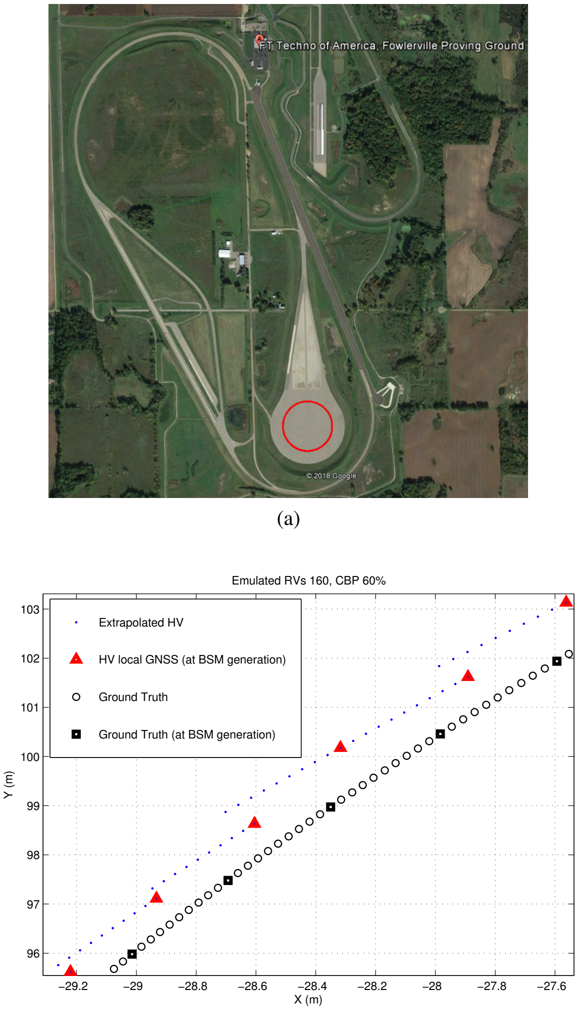
A. *Position Error vs. Tracking Error*

The position error represents the distance error from the ground truth and the HV's local GNSS position contained in a BSM. At the time instance t that the HV's BSM is generated, the position error $\rho_e(t)$ is defined as,

$$\rho_e(t) = \sqrt{(x_h(t) - x_g(t))^2 + (y_h(t) - y_g(t))^2}, \qquad \textit{(Eq. 1)}$$

where the Cartesian coordinates $(x_h(t), y_h(t))$ and $(x_g(t), y_g(t))$ are the vehicle's GNSS position (sent in BSM) and ground truth position (reported by GTE) at time instance t, respectively. Note that in (**??**), the Cartesian coordinates are derived from the latitudes and longitudes.

Since BSMs from the HV may be received intermittently by an RV, the latter can estimate the HV's current position in the intermediate time intervals. We define the tracking error τ_e of an HV as the distance between the ground truth (reported by GTE) and its position estimated remotely [6]. As per the SAE J2945/1 standard, a simple linear extrapolation that relies on the last known position, speed and heading in the latest received BSM is used to coast the HV's position. This coasting logic is implemented identically by all vehicles.



(a)

(b)

Fig. 2: (a) The Google Earth ⓒ satellite image of the test facility at Fowlerville, MI. The red path is the HV's circular track run to test dynamics-induced transmissions. (b) A segment from the run in (a) that compares the ground truth with the positions based on the HV's BSMs.

Given that Δt seconds have elapsed since the last received HV's BSM, the extrapolated Cartesian coordinates of the HV at time instant $t^{'} = t + \Delta t$ is given as,

$$\begin{aligned} \widetilde{x}_h(t^{'}) &= s_h(t)\Delta t cos(\theta_h(t)) + x_h(t) \\ \widetilde{y}_h(t^{'}) &= s_h(t)\Delta t sin(\theta_h(t)) + y_h(t). \end{aligned} \qquad (Eq.\ 2)$$

where the variables $s_h(t)$ and $\theta_h(t)$ are the HV's speed and heading at time instant t, respectively. Therefore, the tracking error at time instant $t^{'}$ is $\tau_e(t^{'})$ and is given as,

$$\tau_e(t^{'}) = \sqrt{(\widetilde{x}_h(t^{'}) - x_g(t^{'}))^2 + (\widetilde{y}_h(t^{'}) - y_g(t^{'}))^2}, \qquad (Eq.\ 3)$$

where the ground truth position is represented by $(x_g(t^{'}), y_g(t^{'}))$.

Figure 2(a) shows the circular path driven by the HV on the skidpad. Figure 2(b) shows a sample set of the HV's GNSS locations, coasted positions and the ground truth from the circular path. The ground truth samples are spaced by 10 ms (i.e. 100 Hz) and are much more frequent that the HV's local GNSS positions. In the intermediate intervals, the HV's position are extrapolated for each GTE time instant. The HV unit positions are derived from the captured BSMs at the Sniffer. The time-matched GTE positions that correspond to these HV unit positions are shown as black squares. For all GTE position samples between consecutive BSMs, the extrapolated positions based on (2) are also shown.

As the time since the last BSM received from HV increases, the tracking error at the RV may increase due to both an imperfect extrapolation (i.e., the HV may be turning or accelerating) and an initial position error. However, if the position errors are negligible, then after the reception of a new BSM from the HV, the tracking error at the RV resets to zero.

In reality, the HV does not actually know the tracking error since neither does it know if an RV received its latest BSM nor does it have knowledge of the position error (i.e., the GTE is only for validation purpose). To determine the tracking error from the perspective of RVs, the HV may use its own noisy GNSS position, speed and heading to coast to current time $t^{'}$. Thus, the HV makes an estimate of the tracking error, which we refer to as the *perceived tracking error* and it is defined as,

$$\tau_p(t^{'}) = \sqrt{(\widetilde{x}_h(t^{'}) - x_h(t^{'}))^2 + (\widetilde{y}_h(t^{'}) - y_h(t^{'}))^2}, \qquad (Eq.\ 4)$$

where $\left(x_h(t^{'}), y_h(t^{'})\right)$ is the Cartesian coordinate of the HV's GNSS position at time $t^{'}$. The perceived tracking error is the HV's estimate of its own displacement from where other RVs expect it to be.

Given the multi-access nature of the DSRC channel, the tracking error of an HV is affected by the number of neighboring RVs that share the channel. In a congested environment, with increasing packet losses and decreasing transmission rate, there are larger time intervals between BSMs from the HV, which consequently leads to increase in the tracking error.

IV. CONGESTION CONTROL ALGORITHM

In [9], a fundamental bound on the relationship between the communication rate and the corresponding range is presented, where as a network becomes dense, nodes need to throttle down the rate and transmission power so as to share the limited channel resources properly. Based on this principle, under an optimal protocol, the vehicles should adapt their rate and transmit power in such a way that minimizes the tracking error for better safety performance. The basic relationship between the congestion load (and vehicles contributing to the load) with transmission rate and power is shown in Fig 4.

The J2945/1 CC protocol is an adaptive joint rate-power control algorithm which lets vehicles adapt in a distributed manner using information available to the HV (i.e CBP and the number of RVs). The protocol is based on the following:

1) Rate control, which adapts the ITT and decides how frequently the HV should broadcast its own state information in the BSMs. The rate control is based primarily on the density of traffic within a certain range around

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the HV. Additional factors that impact the rate include critical events such as hard braking and sudden HV maneuvers.

2) Power control, which adapts the radiated (transmit) power and determine how far the HV's state information should be broadcast, and is mainly based on CBP. As with rate control, this adapts in response to critical events (e.g. hard braking, traction control loss etc.) and sharp HV maneuvers as well.

A. Rate Control

The default mode that determines the ITT is the average number of vehicles $N_s(t)$ within a range of $vPERRange$ meters from the HV at time t. A *smoothened* vehicle density over the past $vTxRateCntrlInt$ (ms) helps mitigate the ITT from changing too rapidly and is defined as

$$N_s(t) = \lambda N + (1-\lambda) N_s(t - vTxRateCntrlInt), \quad (\textit{Eq. 5})$$

where N is the unique number of RVs in range currently and $\lambda = vDensityWeightFactor$. The algorithm sets the maximum allowed ITT based on this smoothened vehicle density,

$$Max\_ITT(t) = \begin{cases} 100 & N_s(t) \leq B, \\ \dfrac{100 N_s(t)}{B} & B < N_s(t) < \dfrac{B \times vMax\_ITT}{100}, \\ vMax\_ITT & \dfrac{B \times vMax\_ITT}{100} \leq N_s(t), \end{cases} \quad (\textit{Eq. 6})$$

where $MaxITT(t)$ is the maximum BSM generation interval in milliseconds, B is the density coefficient, and $vMax\_ITT$ is the maximum threshold.

Specifically, using the SAE J2945/1 standard values in Table I, when the number of in-range RVs is fewer than 25, the BSMs are scheduled to be transmitted every 100 ms, which monotonically increases to a maximum of 600 ms when as this number ramps up to 150 or more (i.e., $100 \leq Max\_ITT(t) \leq 600$ ms). The number of RVs outside the $vPERRange$ (100 m) distance from the HV do no affect the ITT.

However, there are two exceptions in the rate control which may not follow Eq. (6) which are explained as follows:

1) Critical Event: When the HV experiences critical events such as traction loss, ABS activation, or hard braking (i.e., more than $0.4G$ of deceleration, where $G = 9.8\ m/s^2$), a BSM is transmitted immediately. If the event persists, the ITT for subsequent BSMs is set at 100 ms.

2) High Tracking Error: The HV may transmit the next BSM before the $Max\_ITT(t)$ elapses due to sudden or sharp maneuvers. The HV makes this decision based on its perceived tracking error so that the neighboring RVs have an accurate estimate of its current location. The HV uses an average PER (i.e., a channel quality indicator) from all RVs within $vPERRange$ distance to infer whether they received its latest BSM or not. The coasting time (Δt) to determine $\tau_p(t)$ starts from the last BSM that was inferred to have been received by the neighboring RVs. The conditional transmission probability based on the perceived tracking error is performed every 100 ms as follows,

$$p(t) = \begin{cases} 0 & \tau_p(t) < T_{\min}, \\ 1 - \exp(-\alpha \left|\tau_p(t) - T_{\min}\right|^2) & T_{\min} \leq \tau_p(k) < T_{\max}, \\ 1 & T_{\max} \leq \tau_p(t), \end{cases} \quad (\textit{Eq. 7})$$

where $T_{\min}$ is a minimum tracking error threshold, α is the error sensitivity, and $T_{\max}$ is a tracking error saturation value. Thus, an HV's transmission probability monotonically increases when its tracking error increases. If $\tau_p(t) < T_{\min}$ (low tracking error), the next BSM transmission remains scheduled after Max_ITT ms. However, if the tracking error becomes large, then there is a probability of an earlier transmission.

TABLE I: System Parameters.

J2945/1 Parameters	**Mode/Value**
Data Channel Frequency	$5855 - 5865$ MHz (ITS channel 172)
Receiver Power Sensitivity	-92 dBm
OFDM Data Rate	6 Mbs
$vMax\_ITT$	600 ms
$vPERRange$	100 m
$vTxRateCntrlInt$	100 ms
$vDensityWeightFactor$	0.05
α	75
T_{min}	0.2 m
T_{max}	0.5 m
vRP_{min}	10 dBm
vRP_{max}	20 dBm
$vMinCBP$	50%
$vMaxCBP$	80%
$vSUPRAGain$	0.5
B	25

B. Power Control

When an HV transmits a BSM based on a critical event or due to high tracking error as in (7), the transmit or radiated power (RP)[1] is set to the maximum $vRPMax$. Otherwise, the radiated power of outgoing BSMs are based on the Channel Busy Percentage (CBP). The RP is set as follows,

$$RP(t) = \begin{cases} RP(t-t_0) + vSUPRAGain \times (f(CBP) - RP(t-t_0)) & \text{Default} \\ vRPMax & \text{Otherwise.} \end{cases} \quad (\textit{Eq. 8})$$

$RP(t-t_0)$ is the RP in the previous iteration t_o and $vSUPRAGain$ is the Stateful Utilization-based Power Adaptation (SUPRA) gain. The initial RP is $RP(0) = 15$ dBm and where $f(CBP)$ is,

$$f(CBP) = \begin{cases} vRPMax & CBP \leq vMinCBP \\ vRPMax - \left(\dfrac{vPRMax - vPRMin}{vMaxCBP - vMinCBP}\right)(CBP - vMinCBP) & vMinCBP < CBP < vMaxCBP \\ vRPMin & CBP \geq vMaxCBP. \end{cases} \quad (\textit{Eq. 9})$$

As specified under SAE J2945/1, an HV decreases its calculated radiated power (or simply RP) from a maximum of 20 dBm (when the CBP is lower than 50%) to a minimum of 10 dBm (when the CBP is 80% or higher).

Table I provides the list of values of each of the variables in the CC protocol.

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[1] For simplicity, we ignore the cable loss and antenna gain and treat RP as the transmit power.

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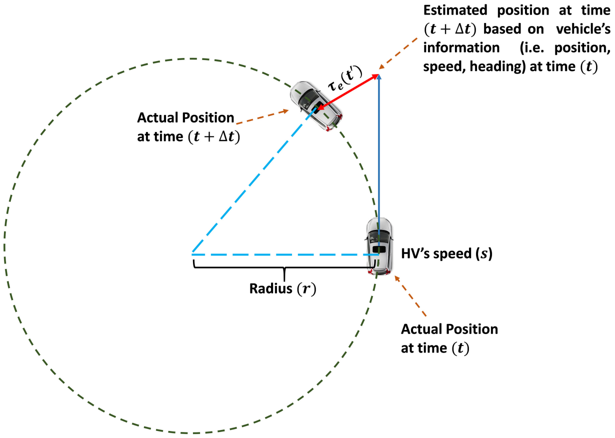


Fig. 3: On an ideal circular track, the HV's tracking error is the displacement between the straight (extrapolated) and the actual turned paths.

C. Example: Circular Track

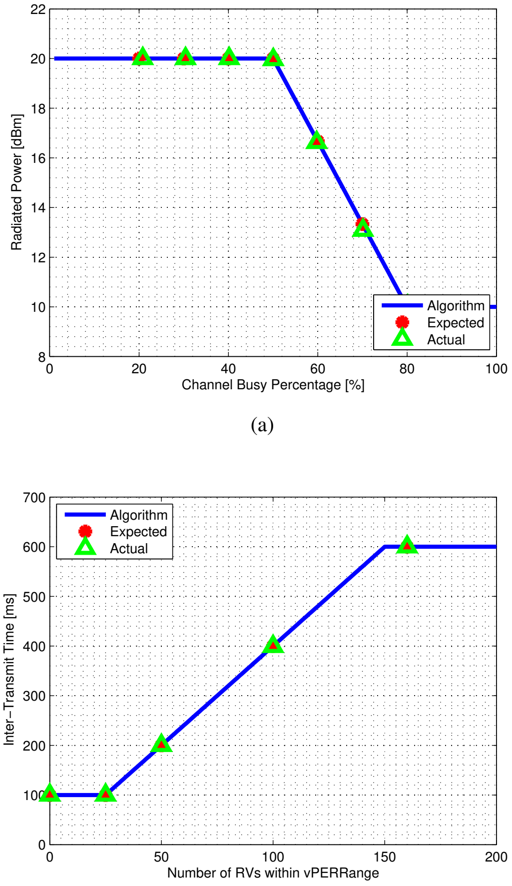
Consider an HV moving at constant speed s (ms^{-1}) on a circular track with radius r (m) as depicted in Fig. 3. If the last received BSM by an RV is generated at time t, then tracking error at time $t' = t + \Delta t$ from the RV's perspective can be defined as a function of time delay $(\Delta t = t' - t)$ from the last BSM such as,

$$\tau_e(t') = \sqrt{\left(s\Delta t - rsin\left(\frac{s\Delta t}{r}\right)\right)^2 + \left(r\left[1 - cos\left(\frac{s\Delta t}{r}\right)\right]\right)^2}. \qquad (Eq.\ 10)$$

With 160 RVs within 100 m of a stationary HV and 60% CBP, the default ITT and RP are 600 ms and 16.67 dBm as per (6) and (8), respectively. However, when the HV moves at $s = 15.56$ ms^{-1} (55 Kph) on a $r = 100$ m circular track, then at time intervals $\Delta t = \{100, 200, 300, 400, 500, 600\}$ ms since the last successfully received BSM, the tracking errors are $\tau_e(\Delta t) = \{0.01, 0.05, 0.11, 0.2, 0.31, 0.44\}$ m as per (10). The corresponding conditional probabilities that a BSM is sent at each of the intervals are $P(\Delta t) = \{0, 0, 0, 0, 0.57, 0.99\}$ as per (7). Thus, the HV is likely to transmit by the 500 ms interval at a 20 dBm radiated power.

V. VALIDATION & CC RESULTS

We have validated and tested a light vehicle HV OBE in different congestion scenarios, where the vehicle is (i) stationary, (ii) cruising on a circular track at constant speed and (iii) moving at a high speed followed by a sharp deceleration with hard braking. In both moving tests in (ii) and (iii), a constant congestion load is set, where the target CBP is 60% with 160 emulated RVs. The CGT tool achieves this through the execution of an adaptive transmission of a mix of emulated BSMs and WSMs, while listening to the channel so that the load remains at the target level. The corresponding default Max_ITT is 600 ms and the default RP is 16.67 dBm. The HV DSRC radio may only be able to transmit in fixed power increments of half or one dBm. Thus, it may not be able to exactly generate the RP calculated under the protocol. J2945/1 standard provides a 1 dBm tolerance margin for such limitations.



(a)

(b)

Fig. 4: The ITT and RP values for various congestion thresholds for a stationary vehicle setting are shown as blue lines above. The specific tested thresholds (red) match well with the actual field results (green marks).

The operator test tool is receiving input from the HV and the CGT through the DSRC Sniffer. It compares the number of emulated RVs within 100 m range of the HV to the ITT of the HV's BSMs to check if the SAE J2945/1 standard is being obeyed. Furthermore, the RP value set by the HV unit is transmitted in the WSM header of its BSMs in the transmit power field and is then recorded by the test tool. Since the Sniffer antenna is co-located with the HV DSRC and CGT antennas, it experiences the same CBP as the HV. This allows the test tool to match the HV's RP with the CBP. A large number of tests were conducted to collect the data from which a sample set is shown below.

Stationary Vehicle Validation: We ran the CGT to emulate a target combination of in-range number of RVs and target CBP while the HV is parked, where each combination is run for 60 seconds. As per the CC protocol, the ITT is dependent only on the number of the emulated RVs, whereas the RP is affected only by the CBP.

In Fig. 4(a), the corresponding RP is plotted against target CBP, whereas, in Fig. 4(b), we plot the average ITT against the number of emulated RVs. Note that the legend 'Algorithm'

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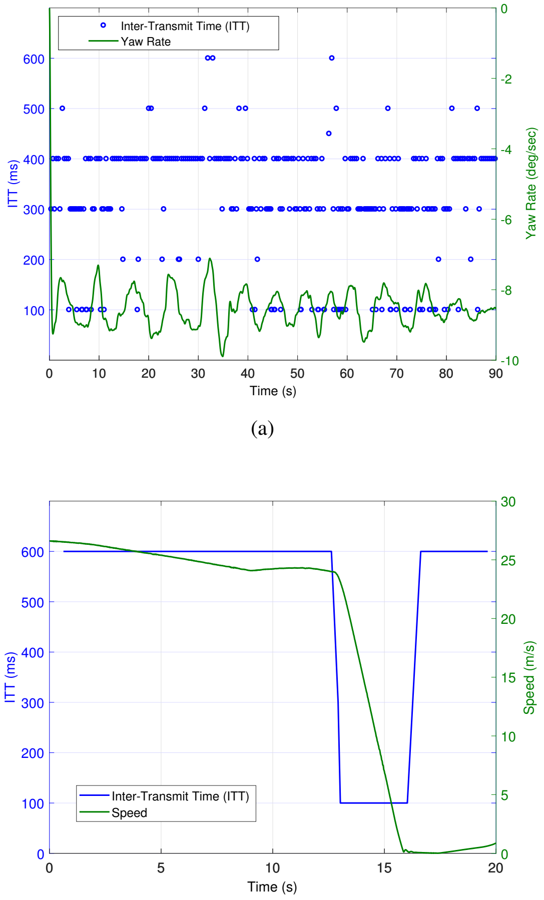
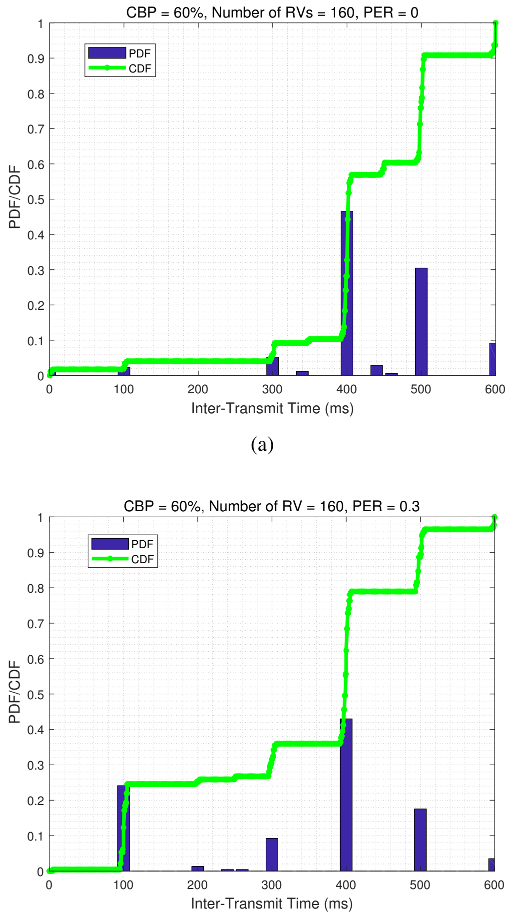


(a)

(b)

Fig. 5: The ITT drops from 600 ms to lower values in both moving tests, where the HV is either turning (a) or decelerating (b).



(a)

(b)

Fig. 6: On a circular track, the ITTs values fall much below 600 ms, where, in contrast to 0% PER in (a), with a lower channel quality (i.e. 30% PER) in (b), many more ITT samples are at 100 ms.

represents the nominal relationship defined by the J2945/1 for a range of CBPs and number of RVs as per (6) and (8) with ITT and RP, respectively. The legend ‘Expected’ represents those specific pairs of target CBP and number of RVs that the CGT generated during the test. Finally, legend ‘Actual’ represents the actual results of the HV unit. The HV passed this test since the average ITTs are within 10 ms, whereas the average RPs are within 1 dBm tolerance margin of the expected values.

Moving Vehicle Validation: In this test, the HV is moving around a circular track of radius $r = 100$ m at cruise speed of 55 Kph on the skidpad (see Fig. 2(a)). Furthermore, the CGT sets two channel quality levels at 0% PER and 30% PER with 90 seconds for each threshold. The CGT controls the PER level by appropriately adjusting the message count in the BSMs to emulate packet losses.

Fig 5a plots the HV’s ITT and the yaw rate over time. Due to vehicle dynamics, a high tracking error is induced which leads to more frequent BSM transmissions from the HV. (i.e. the ITT samples fluctuate between 100 and 600 ms). Recall that if the HV is stationary, the ITT and RP should be constant at 600 ms and 16.67 dBm, respectively.

In Figs. 6(a) and (b), we plot the corresponding Probability and Cumulative Density Functions (PDFs/CDFs) of the ITT for this test. We confirm that the majority of ITT values are distributed between 100 and 500 ms as per the CC protocol. Furthermore, as the PERs increases, the CC protocol does allow for more frequent transmissions since the HV unit perceives a lower channel quality. At 30 % PER, which is the J2945/1 saturation threshold for a deteriorated channel quality, a large proportion of ITT samples are at 100 ms intervals. While not shown, nearly all BSMs are transmitted at RP values of 20 dBm.

Safety Application Aspects: We also plot the CDF of the position error and the (actual) tracking error in Fig. 7 for this test. To reiterate, the former represents the distance between the ground truth and HV unit in terms of ground position when a BSM is transmitted. The latter, however, represents the distance between the ground truth and the extrapolated position of the HV using the last known BSM. We can observe that both the position error and the tracking error are well with 1.5 m most of the time in a high congestion environment for both channel quality (PER) levels.

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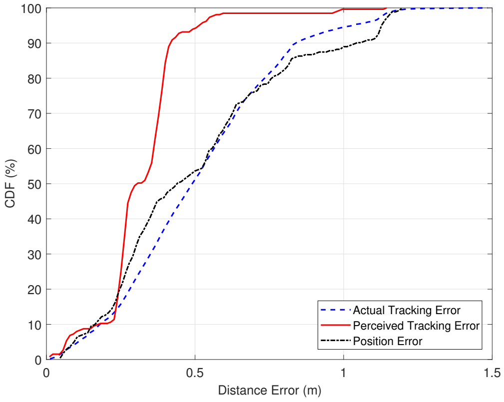
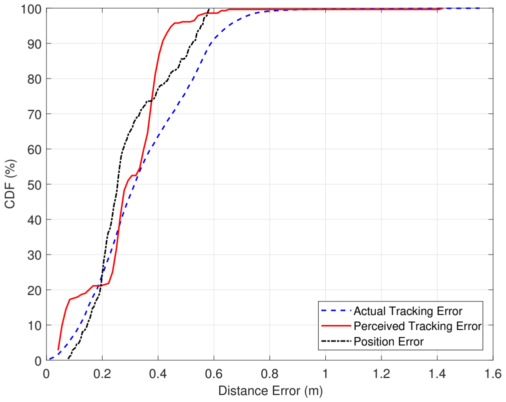
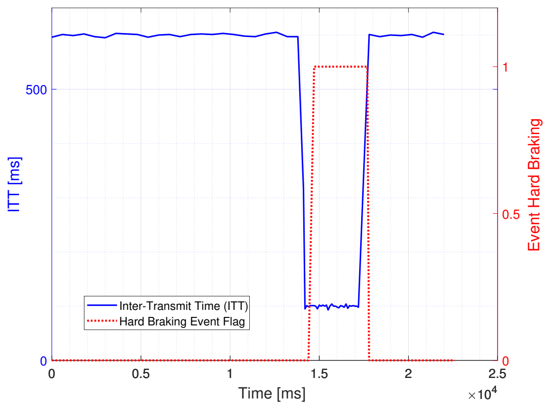


(a) PER = 0

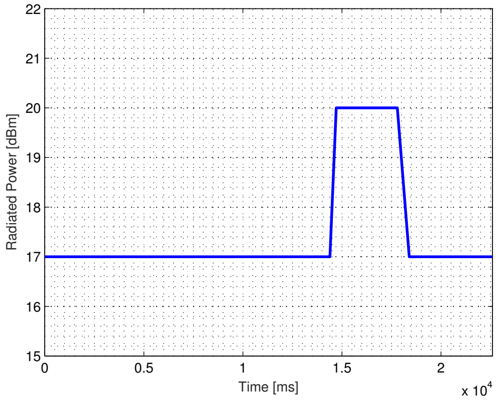


(b) PER = 0.3

Fig. 7: Number of RVs = 160, CBP = 60%. The CDFs of position error and tracking error are well within 1.5 m under the CC algorithm, thus meeting the safety application criterion in congestion environments for two PER thresholds.



(a)



(b)

Fig. 8: (a) In a critical event, shown as a binary event (i.e. 0 or 1), the ITT values fall from 600 ms to 100 ms. In (b) the corresponding RP increases to the maximum of 20 dBm.

To reiterate, in contrast to the actual tracking error, the perceived tracking error does not account for the HV's GNSS position error. The HV transmits with probability of 1 if its perceived tracking error exceeds 0.5 m. We observe from the plots that almost 95 percentile of the perceived tracking error is within 0.5 m at both PER thresholds.

Critical Events Validation: We next consider the results for a critical event condition such as hard braking. Under the test, the HV drives on a straight path constantly at 90 Kph (or 26 ms^{-1}) for a brief interval followed by a sharp deceleration, as depicted in Fig. 5b. The hard braking critical event flag is set when the vehicle rapidly decelerates from 90 Kph, as shown in Fig. 8a. The HV's ITT correspondingly drops from 600 ms to 100 ms and the RP goes to the maximum 20 dBm as shown in Fig. 8b.

VI. CONCLUSIONS

We have presented field test results on DSRC-based V2V system in a congestion environment, which complied with the SAE J2945/1 standard for V2V minimum performance requirements. Our tests provide vehicle-level validation for the congestion control protocol and also demonstrate that the GNSS position of a vehicle can be tracked to within 1.5m of ground truth position even with ITTs of 600 ms. Our results demonstrate the readiness of DSRC-based V2V systems for active safety and crash avoidance.

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