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Cooperative Perception using Cellular V2X in Mixed Traffic Scenario

Muhammad Rony Hidayatullah, Jyh-Ching Juang, Zhao-Shun Zheng
Department of Electrical Engineering
National Cheng Kung University
Tainan, Taiwan
n28087010@gs.ncku.edu.tw
juang@mail.ncku.edu.tw
e14051148@gs.ncku.edu.tw

Wei-Hsuan Chang
Information and Communication Technology Group
Automotive Research and Testing Center
Changhua, Taiwan
brant.chang@artc.org.tw

***Abstract*—The ultimate goal of connected autonomous vehicles (CAVs) is to provide traffic accident-free, road capacity, and mobility service. The CAVs are supported by vehicle-to-everything (V2X) communication to achieve those goals. The 3rd Generation Partnership Project (3GPP) standardizes the V2X called cellular V2X (C-V2X). In the real application, the CAVs should deal with mixed traffic scenarios during its penetration in the highways. The term mixed traffic refers to the traffic that consisted of human driving and CAVs. This paper considers that human driving is an unconnected vehicle and has a jerky driving behavior. Hence, when the CAVs interacted with human driving vehicles, CAVs required large spacing between vehicles to provide safety and comfortable driving. It will sacrifice the road capacity where the spacing between vehicles is large. This paper proposes the cooperative perception strategy using C-V2X to mitigate the adverse effect of unconnected vehicles without sacrificing safety and comfortable driving. The errors during transmission such as propagation error, half-duplex error, packet sensing ratio error, and message collision are considered. The effectiveness of our cooperative strategy is demonstrated by a joint simulation of Matlab/Simulink and PreScan.**

Keywords—Cellular V2X, connected autonomous vehicles, cooperative perception, mixed traffic, road capacity, vehicle-to-everything.

I. INTRODUCTION

Today, autonomous driving is starting to penetrate highways and is expected to mitigate traffic accidents. Autonomous driving is now equipped with several onboard sensors (radar, lidar, camera, GNSS, IMU) to support its abilities, such as lane-keeping, lane changing, adaptive cruise control (ACC), automatic parking [1]. Currently, autonomous driving with wireless communication sensors, called connected autonomous vehicles (CAVs), is able to enhance vehicle's awareness with an extensive range [2-5]. For instance, the vehicle can sense a blind spot area covered by objects such as a vehicle or building with communicating with infrastructures, pedestrians, or other vehicles, which the onboard sensor cannot handle. Hence, wireless communication is essential for the vehicle and is known with the term vehicle-to-everything (V2X) communication. The V2X in vehicle applications is standardized by IEEE 802.11p and the 3rd Generation Partnership Project (3GPP). IEEE 802.11p is used with different names and applications on the different spectrums such as Intelligent Transport System @5.9GHz (ITS-G5A/B/D) in Europe and dedicated short-range communication (DSRC) in the United States (US). On the other hand, 3GPP defined cellular V2X (C-V2X) used in this paper.

In 2015, Release 12, the C-V2X introduced device-to-device (D2D) communication with mode 1 (scheduled) and mode 2 (autonomous) as part of proximity service (ProSe) based on long-term evolution (LTE) systems [6]. However, D2D communication fail to fulfil vehicle safety requirement due to lack of reliability and efficiency such as large latency and packet loss [7]. In 2016, Release 14, the C-V2X introduced mode 3 (scheduled) and mode 4 (autonomous) as enhancement of previous mode in D2D communication to support V2X communication [8]. Mode 3 utilized the cellular network or LTE base station (eNB) to manage the vehicle's radio resource for communication and communicated through LTE-Uu interface. Mode 4 utilized several methods such as sensing-based semi-persistent scheduling (SB-SPS) to manage the radio resource for vehicle communication without assisting by the cellular network and communicated through LTE-PC5 interface [9]. In simple words, mode 4 will use when the vehicle is out of the coverage area of mode 3. In Release 15, the range and reliability are improved with feature ultra-reliable and low latency communication (URLLC) and introduced 5G new radio (NR) [10]. Release 16 introduced new use cases such as sensor measurement sharing with 5G NR and communicated backward and forward with Release 14 and Release 15 [11].

In vehicle application, the V2X messages, such as basic safety message (BSM), cooperative awareness message (CAM), or decentralized environmental notification message (DENM), are periodically transmitted by the vehicle in order to provide the information to others. The information can be varied such as road information, vehicle information, and even sensor measurements. The sharing local sensor measurements with other vehicles or better known as cooperative perception is one of the use cases C-V2X as mentioned in [11]. Most of the existing paper discusses cooperative perception concern to pedestrian safety solutions [12], crash warning system [13], localization [14], map merger [15], and decision making and planning [16]. This paper *addresses the cooperative perception via C-V2X to reduce the spacing between vehicles in mixed traffic scenarios without sacrificing safe and comfortable driving*. We believe that during penetration on the highways, the CAVs should interact with human driving. The vehicle with a human driver is an unconnected vehicle (without a communication device), and its behaviors are complex and uncertain. Need to be underlined, for the next, the term unconnected vehicle refers to the vehicle with a human driver. The traffic consisted of human driving and CAVs called mixed traffic. If the CAVs are behind the unconnected vehicle, it requires more spacing between vehicles to provide safe driving. However, it sacrifices the road capacity. Moreover, there are possibilities that the unconnected vehicle has poorly driving behavior, leading to crash and uncomfortable driving. To mitigate those adverse effects, we utilized a cooperative perception strategy through C-V2X with considering packet loss on C-V2X.

This paper is organized as follows. Section II discusses the C-V2X. The cooperative perception strategy is given in Section III. Then, simulation and discussion are presented in Section IV. Finally, Section V gives the conclusion and future works.

II. CELLULAR V2X

A. Physical layer

C-V2X mode 4 employed single-carrier frequency division multiple access (SC-FDMA). It supported to have channels bandwidth as big as 10 MHz and 20 MHz. C-V2X channels can be separated as three parts namely, resource block (RBs), sub-frames, and sub-channel. The sub-channels are in the domain frequency while the sub-frames are in the time domain. The number of RBs in sub-channels can be varied and have wide 180 kHz or 12 sub-carriers of 15 kHz. Sub-frames or transmission time interval (TTI) has long 1ms for message scheduling. A group of RBs in the same sub-frames are called sub-channels. It is divided as two parts namely data and side link control information (SCI). SCI consisted critical information such as modulation and coding scheme (MCS) that used to transmit data. The data will transmit by transport blocks (TBs) using QPSK, 16-QAM, or turbo coding. Specifically, TBs contained CAM, BSM, and/or DENM messages. SCI and data will transmit together that used two RBs. When the vehicles received the data then it decoded by using information from SCI. In practice, incorrect reception of SCI will lead to packet loss.

B. Sensing-Based Semi-Persistent Scheduling

SB-SPS mechanism on the CV2X mode 4 can be summarized from [17] in the following steps.

Step 1: Suppose the reselection counter is zero and the sensing window is set up as long as 1000ms (1000 sub-frames). The user equipment (UE) will monitor the sub-frames, decode the SCI+TB, and check the received signal strength indicator (RSSI) within resource sensing window.

Step 2: When the message is coming from the upper layer then reselection counter is activated at time *k*. The candidate single-subframe resources or candidate resources from $k + n_1$ until $k + n_2$ will be checked. The time duration from $k + n_1$ until $k + n_2$ should be less than or equal with 100ms, 50ms, or 20ms based on [8] for the communication rate 10Hz, 20Hz, or 50Hz. This time duration is called selection window. The candidate resources consist of a group SCI+TB (messages).

Step 3: A candidate resources will be thrown away if its meet with the following condition: (a) a candidate resources were not monitored in the sensing window (the last 1000ms); (b) the candidate resources have RSSI lower than the power threshold. The threshold is based on the priority of the message. This priority is determined by upper layers according to the uses cases such as platooning, forward collision warning and so forth.

Step 4: After Step 3 is executed, the available candidate resources should be more than 20% in the selection window. If not, the power threshold is increased by 3dB repeatedly until candidate resource 20%.

Step 5: The UE will reserve the selected candidate resource. The number of the reselection counter for the selected candidate resource is randomly selected based on their selection window. For selection window 100ms, 50ms, or 20ms are selected in range of 5 and 15, 10 and 30, or 25 and 75. Whenever UE need to reserve a new resource, it will randomly select those values.

Step 6: After UE transmitted or received messages, the reselection counter is decreased by one. When it reached to zero, the UE will select new resource with probability 20% and 80% to keep same resource.

C. Transmission Error

During operation, the vehicle with C-V2X suffers from transmission errors. Several errors are taking account in this paper based on [17] as explained in the following.

1) Half-duplex error: This error occurred when the vehicle is transmitting the CAM messages in the same sub-frame as receiving the CAM messages from other vehicles. Hence, the CAM messages failed to receive. This error is not influenced by the distance between transmitter and receiver. However, it mostly influenced by the number of packets transmitted per vehicle per second and the number of sub-frames per second.

2) Packet sensing ratio error: The CAM message will fail to decode if received signal power less than the signal power threshold. The vehicle received low signal power due to several factors such as transmission power, setting power threshold, shadowing, propagation effect, and distance between transmitter and receiver. The standard sensitivity power level at the receiver is -90.4 dBm the maximum transmit power is 23 dBm [8].

3) Propagation error: The propagation error occurred due to signal-to-noise ratio (SNR) is low. It depends on the PHY layer performance of the receiver.

4) Message collision: The message collision occurred due to signal to interference and noise ratio (SINR) is low. Suppose the vehicle v_t is transmitting CAM messages in the urban environment to the vehicle v_r. At same time, the vehicle v_i is also transmitting to the vehicle v_r on the same sub-frame and sub-channel as vehicle v_t. As result, the interference cannot be avoided. Hence, the receiver received incorrect packet. Its phenomena frequently arised in the highways. This error strongly relied on the distance between transmitter and receiver, the distance between v_t, v_i, and v_r, SB-SPS performance, and traffic density.

Remark 1. The error model of CV2X used in this paper is following the error model on [17]. It have been compared with Veins simulator where the error between error model in [17] and Veins simulator less than 1%. For more details, the readers are invited to read [17].

D. Use Cases

The use cases of C-V2X are focused on safety, road capacity, and mobility service. The requirement for use cases is described by European telecommunications standards institute (ETSI). The use cases will use the CAM or DENM message type with communication rate 10 Hz. Table I show the performance requirement for several use cases of CV2X. The latency in Table I refers to the end-to-end latency.

TABLE I. PERFORMANCE REQUIREMENT FOR DIFFERENT CV2X USE CASES [11]

Use cases	Latency*	Reliability	Communication Range*
Cooperative maneuver	3ms-100ms	> 99%	200m-500m
Cooperative awareness	100ms-1s	90%-95%	200m-500m
Cooperative perception	3ms-1s	> 95%	< 200m
Traffic Efficiency	> 1s	< 90%	> 500m
Vulnerable Road User	100ms-1s	95%	< 200m

*Units details are explained in the following. ms = millisecond, s = second, m = meter.

III. COOPERATIVE PERCEPTION STRATEGY

First of all, we clarify that the CAVs is equipped with onboard sensor and communication device. Expressly, the range sensors are provided by PreScan, namely technology-independent sensor (TIS) [18]. TIS operated with following the principle of active scanning sensors such as radar and lidar. As a result, the CAVs are capable to perform ACC and cooperative-ACC (CACC) driving mode. Next, the CAVs will share the local range sensor measurements to other CAVs. The range sensor provided measurements such as relative distance and velocity between vehicles.

There are many ways to reduce the spacing between vehicles, one of them taking advantage of the spacing policy. The spacing policy plays a critical role in improving road capacity and reducing traffic oscillation [19]. It determined how large the spacing between vehicles during operation. The popular spacing policies used in CAVs are the constant time gap (CTG) and constant distance gap (CDG). CTG defined the spacing between vehicles as a function of velocity following human driver's principle. Given a proper time gap, it only requires the information from its preceding vehicle to avoid traffic oscillation [19]. However, in the road capacity overview, CTG cannot significantly improve the road capacity because the spacing between vehicles is proportional with vehicle's velocity. On the other hand, CDG works with a fixed distance between vehicles and independent from the vehicle's velocity [19]. As a result, it can significantly improve road capacity. However, it requires at least two information from its neighbor to avoid traffic oscillation, its leader and preceding vehicles. Suppose there are *N*-th vehicles and $\Delta d_{N,N-1}$ is defined as the safe distance between vehicle *N*-th and vehicle (*N*-1)-th then CTG and CDG spacing policy is defined in (1).

$$\Delta d_{N,N-1} = \begin{cases} \delta_0 \text{ for CDG} \\ \delta_0 + t_{g,N} v_{x,N} \text{ for CTG} \end{cases} \quad (1)$$

where δ_0, t_g, v_x are the minimum distance between vehicles, time gap between, and vehicle's longitudinal velocity.

Fig. 1a show the group of CAVs in ideal traffic which only consist of CAVs. We can observe that vehicle 1, as a group leader, is driving with ACC mode. Next, the spacing policy between vehicle 2 and vehicle 1 is CTG due to vehicle 2 only obtain information from vehicle 1. The spacing policy for other CAVs are CDG due to obtain more than one information. Further, we inserted the unconnected vehicle as shown in Fig. 1b which then figure out the mixed traffic situation. We can observe the negative effect after we insert an unconnected vehicle as a leader group. Vehicle 2 should change its driving mode to ACC which then requires larger time gap. It is necessary due to vehicle 1 is unconnected vehicle. In addition, the spacing policy between vehicle 3 and vehicle 2 must change to CTG in order to avoid traffic oscillation. As mentioned before, the CDG requires two information from its neighbor, its leader and preceding vehicles. For vehicle 4 and the rest vehicles used CDG as long as there is not unconnected vehicle between vehicles. The

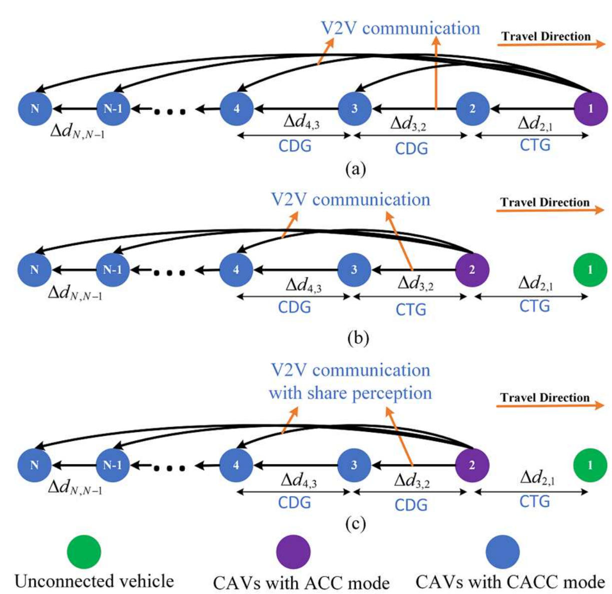

Fig. 1. Traffic scenario. (a) ideal traffic; (b) mixed traffic; (c) mixed traffic with cooperative perception strategy.

changed driving mode in vehicle 2 and spacing policy between vehicle 3 and vehicle 2 instantly lead to reduce road capacity comparing with ideal traffic as shown in Fig. 1a.

To solve the issue in mixed traffic, we proposed cooperative perception strategy in order to improve road capacity and avoid traffic oscillation. Similar to Fig. 1b, we inserted unconnected vehicle as a group leader in Fig. 1c. As mentioned before, in cooperative perception, the CAVs will share their local range sensor measurements. This feature made significant difference between Fig. 1b and Fig. 1c. We can observe in Fig. 1c that spacing policy between vehicle 3 and vehicle 2 back to CDG similar to ideal traffic as shown in Fig. 1a. The cooperative perception opens the possibility for vehicle 3 to use the CDG due to vehicle 2 share its local range sensor measurements about vehicle 1. It makes the vehicle 3 and the rest vehicle to have knowledge about vehicle 1 even if the vehicle 1 is unconnected vehicle. Then, shared information from vehicle 2 will be processed by controller of vehicle 3 and the rest vehicle in order to generate proper control signal to fulfil the control objective as defined in (4) and (6), and string stability requirement in (9).

Remark 2. In this paper, we only analyze the negative effect of unconnected vehicle if it is as a leader of group CAVs. Surely, inserting unconnected vehicle randomly into a group of CAVs can figure out more realistic mixed traffic condition. However, that issue will address as future work.

As mentioned before, to guarantee string stability or to avoid traffic oscillation, the CAVs controller implementing CDG need the information about the leader group and predecessor or otherwise the CAVs need to implement CTG as shown in Fig. 1. The information about predecessor vehicle can be obtained by vehicle's local sensor and defined in (2). Need to remember, the vehicle 1 is unconnected vehicle. To obtain information about leader vehicle or vehicle 1, the vehicle 2 will share its local range sensor measurement to other vehicles. It is obviously advantage of cooperative perception. As a result, the other vehicles have the knowledge about the distance to vehicle 1 and can be computed in (3).

$$\Delta r_{N,N-1} = p_{N-1} - p_N \tag{2}$$

$$\Delta r_{N,1} = p_1 - p_N = \sum_{i=2}^{N} \Delta r_{i,i-1} + \sum_{i=2}^{N-1} L_i \tag{3}$$

where p_N is the position of vehicle N and L_i is the vehicle's length. $\Delta r_{N,N-1}$ is the relative distance between vehicle N-th and vehicle (N-1)-th. It is clearly that $\Delta r_{N,N-1}$ can be directly obtained by vehicle's local range sensor. $\Delta r_{N,1}$ is the distance between vehicle N-th and vehicle 1. $\Delta r_{N,1}$ cannot be directly measured by vehicle's local range sensor. For instance, local range sensor of vehicle 3 cannot directly measure the relative distance between vehicle 3 and vehicle 1 because blocked by vehicle 2. Moreover, vehicle 1 is unconnected vehicle so that the position of vehicle 1 cannot be known by vehicle 3. With cooperative perception, $\Delta r_{N,1}$ can be computed. For instance, based on equation (3), we can compute the relative distance between vehicle 3 and vehicle 1 such as $\Delta r_{3,1} = p_1 - p_3 = \Delta r_{2,1} + \Delta r_{3,2} + L_2$. $\Delta r_{3,2}$ will be directly measured by local range sensor of vehicle 3. L_2 is obtained from CAM messages that sent by vehicle 2 via C-V2X. $\Delta r_{2,1}$ is the local range sensor measurement of the vehicle 2 that also sent through C-V2X (cooperative perception).

The control objectives can be defined as follows,

$$\lim_{t\to\infty} \left| \varepsilon_{N,1}(t) = \Delta d_{N,1}(t) - \Delta r_{N,1}(t) \right| \to 0 \tag{4}$$

$$\Delta d_{N,1} = \sum_{i=2}^{N} \Delta d_{i,i-1} + \sum_{i=2}^{N-1} \delta_0 \tag{5}$$

$$\lim_{t\to\infty} \left| \varepsilon_{N,N-1}(t) = \Delta d_{N,N-1}(t) - \Delta r_{N,N-1}(t) \right| \to 0 \tag{6}$$

where $\Delta d_{N,1}$ is the safe distance between vehicle N-th and vehicle 1. Based on (4) and (6), the control law can be written as follows,

$$u_N(s) = C_N(s)\left(\varepsilon_{N,1}(s) + \varepsilon_{N,N-1}(s)\right) + a_{x,N-1}(s) \tag{7}$$

$$C_N(s) = k_p + k_d s\left(\omega s + 1\right)^{-1} \tag{8}$$

$\varepsilon_{N,1}$ is the error distance between vehicle N-th and vehicle 1. $\varepsilon_{N,N-1}$ is the error distance between vehicle N-th and vehicle (N-1)-th. $C(s)$ is the controller transfer function. $u(s)$ is the control law. k_p, k_d, ω are the proportional gain, derivative gain, and the filter constant. $a_{x,N-1}$ is the predecessor vehicle's longitudinal acceleration that sent via C-V2X.

IV. Simulation and Discussion

A. Setup Simulation

The simulation is done by integrating Matlab/Simulink and PreScan. The decision making, control algorithm, and C-V2X model are built in Matlab/Simulink while the vehicle dynamics, scenario, and sensor model are provided in PreScan. The C-V2X model is built utilizing Communications Toolbox, LTE Toolbox, and 5G Toolbox from Matlab/Simulink. The simulation consists of four vehicles. The vehicle 1 is unconnected vehicle while the other vehicles are CAVs. Based on Fig. 1b and Fig. 1c, the vehicle 2 will use ACC mode and the rest vehicles will use CACC mode. The parameters for this simulation are shown in Table II.

TABLE II. Simulation settings

Parameters	Value	Parameters	Value
k_p, k_d, ω	0.2, 0.8, 5	Traffic density	0.3 vehicle/meter
δ_0	5 meters	Packet transmission	10 Hz
t_g for ACC, t_g for CACC	1.6 seconds, 0.65 seconds	Transmission power	20 dBm
Simulation rate	100 Hz	sub-channels per sub-frame	2
Sensor TIS rate	25 Hz	Packet size in bytes	300
L	5.210 meters	Sensing threshold	-90.5 dBm
Latency	rand(0,0.05) seconds	RBs per sub-channel	17
Rx-Tx height	1.4 meters	Modulation and coding scheme	MCS 7 (QPSK 0.5, for 2 sub-channels)

B. Performance Metric

We used three performance metrics such as lane occupy, string stability, and jerk acceleration. The lane occupy is defined how long a group of vehicles occupy the road lane as shown in Fig. 5. It used for road capacity metric. Another one is string stability. It is important metric to judge whether a group of vehicles stable or unstable as defined in (9). The string stability strongly related with traffic oscillation [20].

$$\left\| v_{x,N} \right\| \leq \left\| v_{x,N-1} \right\| \quad (9)$$

The jerk acceleration of CAVs determined the comfortable aspect. As a result, the control signal in (7) should respect the following constraint as follow,

$$-3ms^{-2} \leq u_N \leq 2ms^{-2} \quad (10)$$

$$-1ms^{-3} \leq \dot{u}_N \leq 1ms^{-3} \quad (11)$$

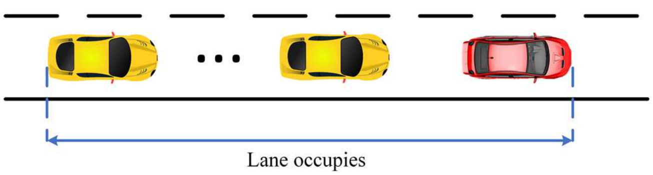

Fig. 5. Lane occupies.

C. Result and Discussion

Fig. 2 show the lane occupies comparison between CTG, CDG, and cooperative perception strategy. The CTG means that all vehicle used CTG spacing policy. The CDG referred to Fig. 1b while the cooperative perception strategy referred to Fig. 1c. We can observe that CTG have the largest lane occupies. It is reasonable due to the vehicle's velocity proportional with the spacing between vehicles. As a result, at high velocity, the lane occupies are getting large. As mentioned in Section III, the CTG cannot significantly improve the traffic capacity. However, the CTG only required predecessor information to guarantee stable string stability. The CDG have less lane occupies than CTG as shown in Fig. 2. However, it can increase the traffic capacity due to use fixed distance between vehicles. Fig. 2 show even if CDG used fixed distance between vehicles, however, it varied depend on vehicle's velocity. It is caused by the vehicle 2 and vehicle 3 in Fig. 1b using CTG spacing policy. It is necessary in order to guarantee stable string stability. As mentioned in Section III, the CDG required two information from its predecessor and leader. The cooperative perception strategy as the proposed method in this paper has the smallest lane occupies. The reason is that the vehicle will share its local range measurements to the others. It made the others vehicle have the knowledge about vehicle 1 which is unconnected vehicle. As a result, the CDG spacing policy is able to implement in vehicle 3 as shown in Fig. 1c. Without cooperative perception, the vehicle 3 does not have knowledge about vehicle 1 which then the vehicle 3 need to implement CTG spacing policy as shown in Fig. 1b to guarantee stable string stability. With vehicle 3 used CDG spacing policy in cooperative perception strategy, it made less lane occupies than other strategies.

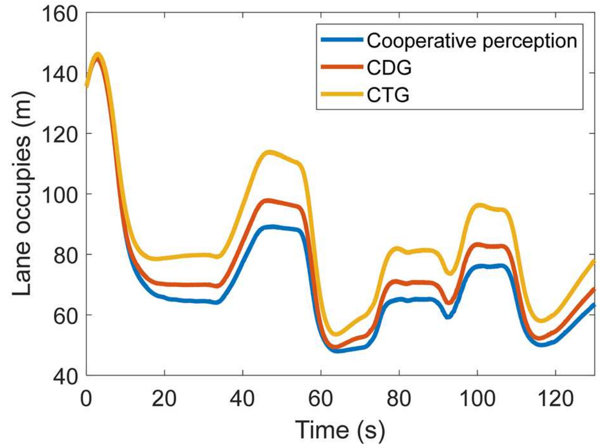

Fig. 2. Lane occupies comparison between CTG, CDG, and cooperative perception strategy.

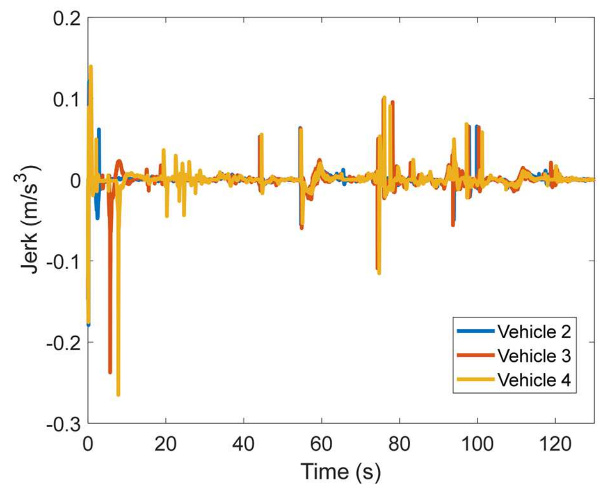

Fig. 3. Jerk of vehicle 2, vehicle 3, and vehicle 4.

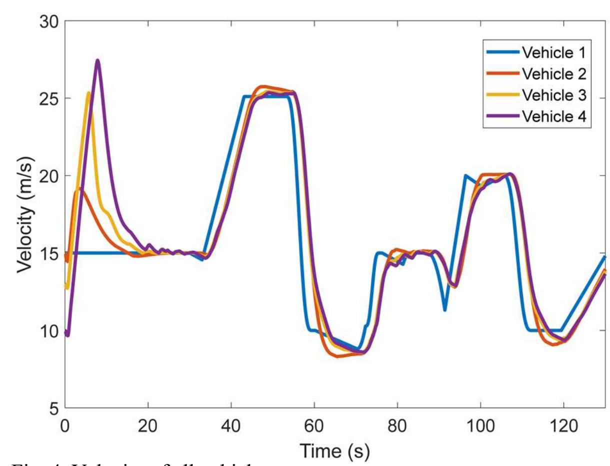

Fig. 4. Velocity of all vehicles.

Fig. 3 show the jerk of vehicle 2, vehicle 3, vehicle 4 using cooperative perception strategy. The jerk is small that indicated comfortable driving. Fig. 4 show all vehicle's velocities. The velocity of vehicle 4 is smaller than the velocity of vehicle 3 and also for the velocity of vehicle 3 is smaller than the velocity of vehicle 2. It fulfils the stable string stability condition as defined in (9). Vehicle's 2 velocity is bigger than vehicle 1 due to vehicle 2 is in ACC mode. It is different with vehicle 3 that used CACC mode. Moreover, string stability can be achieved by vehicle 2 using ACC mode with an extra time gap.

V. Conclusion and Future Work

In this paper, we propose the cooperative perception strategy to improve road capacity under mixed traffic. The CV2X is utilized to support cooperative perception between CAVs. We also consider the error transmission of C-V2X during simulation. The simulation is built by integrating Matlab/Simulink and PreScan. The proposed method enhances the transportation efficiency by increasing the lane occupancy. Even if the unconnected vehicle is subject to jerky behavior, the jerk of CAVs is maintained to be small. Moreover, the stable string stability is fulfilled. In the future, we will analyze and investigate the cooperative perception with inserting several unconnected vehicles in a group of CAVs.

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