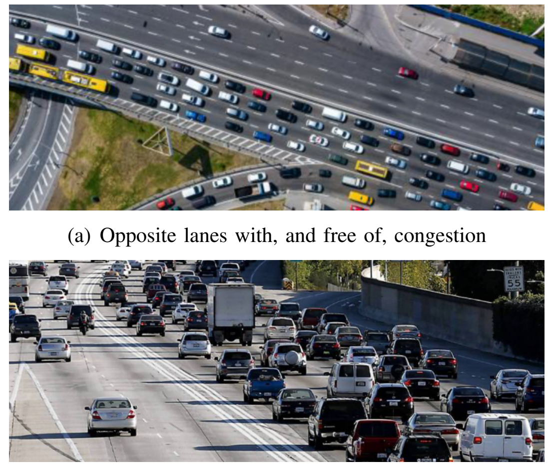
Speed-Aware V2X Congestion Control

Kyeongnam Park, Hojeong Lee and Hyogon Kim

***Abstract*—None of the current V2X congestion control standards on the wireless medium access layers have provisions for the speed difference of vehicles. The situations where vehicles have wildly different speeds are more common than not. Even if a more recent ETSI standard specifies facilities layer congestion control that considers the vehicle speed, the access layer congestion control that performs gate-keeping is still speed-agnostic and can cause safety problems. Therefore, the access layer congestion control standards should also be generalized to cater to the safety communication requirement associated with vehicle speed. In this paper, we propose a new access layer congestion control for V2X communication that accounts for the speed difference between vehicles. We demonstrate such a scheme can effectively differentiate the congestion control based on speed differences, facilitating driving safety especially for high-speed vehicles passing by low-speed vehicles.**

***Index Terms*—V2X, congestion control, speed-aware, safety requirement, packet inter-reception time (PIR)**



(a) Opposite lanes with, and free of, congestion

(b) Paid lanes with much less and speedier traffic

Fig. 1. Road condition examples with large speed differences

I. Introduction

In the initial implementation of vehicle-to-everything (V2X) communication, known as "Day 1," each vehicle periodically broadcasts Basic Safety Message (BSM) or Cooperative Awareness Message (CAM) that contains the vehicle's position, speed, acceleration, heading, and other relevant data [1]. This enables vehicles to track each other and predict the short-term trajectories of surrounding vehicles to prevent traffic accidents. Upcoming "Day 2" and "Day 3" V2X traffic will also use periodic broadcast traffic [2], [3]. As dedicated Intelligent Transportation System (ITS) band is narrow, however, the increased density of the V2X-capable vehicles will easily cause channel congestion to negatively impact the effectiveness of V2X communication in preventing accidents.

To address the channel congestion issue, standardization bodies such as Society of Automotive Engineers (SAE), European Telecommunications Standards Institute (ETSI), and 3rd Generation Partnership Project (3GPP) all specify their respective congestion control standards and algorithms that should be performed upon wireless medium access [4]–[7]. Unfortunately, however, one aspect that none of them take into account is the speed difference of vehicles. Specifically, the vehicle traffic density or any other means of estimating the channel congestion level that regulate packet transmission are computed as an average measure across all vehicles in a given area, irrespective of their individual speeds. Even if a more recent ETSI standard specifies facilities layer congestion control that considers the vehicle speed [8], the access layer congestion control that performs gate-keeping is still speed-agnostic and can cause safety problems.

In this paper, we propose a new access layer congestion control for V2X communication that accounts for the speed difference between vehicles. The situations where vehicles have wildly different speeds are more common than one may think. Fig. 1 presents some real-life examples. One direction of the road can be severely congested, whereas the other direction has low traffic density. Even in the same direction, only one lane can be extremely slow (e.g. exit lane) or extremely fast (e.g. high-occupancy vehicle lane or paid lane(s)). Because vehicles with different speeds have disparate safety requirements [9], V2X communication and its congestion control should be designed to accommodate them. By doing so, congestion control mechanisms residing on different layers in communication stack can be better aligned. Otherwise, the access control layer can nullify the speed-aware control from the higher layers.

In the rest of the paper, we demonstrate that the current speed-agnostic control on the access layer can cause unnecessary and safety-threatening communication bottleneck between high-speed vehicles when there is a dense, slow-moving vehicle crowd in the proximity. We propose a speed-aware congestion control mechanism to show the feasibility and benefit. It works to secure the desired messaging rate for high-speed vehicles, without sacrificing the safety of low-speed vehicles.

II. Speed-aware congestion control

A. Background

A substantial body of literature exists on V2X congestion control; however, there is a noticeable dearth of research concerning congestion control that takes vehicle speed into account. The proposed and standard schemes use either message rate control, transmit (Tx) power control, or a combination of both. It is difficult to list all of them here, and we focus on how the standards define their control. ETSI Decentralized Congestion Control (DCC) [6] specifies the access layer congestion control. It utilizes rate control based on channel busy ratio (CBR), which can be implemented either in reactive or adaptive mode. For cellular V2X (C-V2X) environment, standardization is underway. ETSI TS 103 574 [10] specifies that the rate control should be implemented based on the CBR and packet priority. SAE J2945/1 for Dedicated Short Range Communication (DSRC) environment [4] and J3161/1 for C-V2X environment [5] perform rate control based on the vehicle density (VD) as the number of vehicles in the 100-meter radius. The control regulates the interval between consecutive transmissions called the Inter-Transmission Time (ITT) as follows:

$$ITT\ (\mathrm{s}) = \begin{cases} 0.1, & \overline{VD} \le 25 \\ \overline{VD}/250, & 25 < \overline{VD} < 150 \\ 0.6, & 150 \le \overline{VD} \end{cases} \quad (1)$$

where $\overline{VD(t)} \leftarrow 0.05 \times VD + 0.95 \times \overline{VD(t-1)}$.

In contrast to many congestion control algorithms for the access layer, there is only one that is designed for the facilities layer. It is the CAM generation rule [11]. Essentially, the rule allows the vehicle to transmit a CAM only when it is necessary for neighboring vehicles to track its movement by suppressing a periodic CAM that would report only minor vehicle movements (moving less than 4 m or turning less than 4° or accelerating less than 0.5 m/s since the last CAM transmission).

B. Problem definition

The problem with current congestion control standards on the access layer is that the input measures such as traffic density [4], [5] and channel utilization [4], [6], [7] are averaged over all vehicles in either communication range or an artificially established awareness range. The same average measures with the same actions used in the current proposals completely disregard the speed differences and the correspondingly different safety communication requirements.

Conceptually, there could be two almost equivalent approaches to resolving the speed difference issue in V2X congestion control. First, we could collect the input measures to the control algorithm separately for different speed groups. Then, by applying either common or separate control based on the measures, speed can be reflected in the control. Second, we could keep using the conventional average input measures but apply different control modulated by the individual speed at each vehicle. In this paper, we take the second approach for it is more intuitive. In particular, we take the case of SAE J3161/1 control algorithm [5] and modify it to demonstrate the feasibility and the benefit of speed-aware V2X congestion control. Similar approach can be applied to other standards.

C. Speed-aware generalization

In order to reflect vehicle speed to congestion control, we grade ITT control function in J3161/1 in the speed domain. To achieve this, we introduce vehicle speed v and a constant reference speed v_k to J3161/1 control. Let the scaling factor be defined as $\sigma = v_k/v$. Then, the modified control operates as follows:

$$ITT\ (\mathrm{s}) = \begin{cases} 0.1, & \sigma \cdot \overline{VD} \le 25 \\ \sigma \cdot \overline{VD}/250, & 25 < \sigma \cdot \overline{VD} < 150 \\ 0.6, & 150 \le \sigma \cdot \overline{VD} \end{cases} \quad (2)$$

Notice that the scaling factor makes the ITT increase more slowly in $\overline{VD}$ if $v > v_k$ (i.e., high-speed vehicles) and faster if $v < v_k$ (i.e., low-speed vehicles). Namely, the messaging rate for fast vehicles is relatively slowly lowered compared to slow vehicles so that their update rate is higher. Note that it is not a two-group dichotomy. A single scaling factor enables continuously graded control across all vehicle speeds, modulated by the reference speed v_k. In this paper, we set $v_k = 33$ km/h. Fig. 2 pictorially illustrates the relation between the J3161/1 control and the speed-aware modification. In the figure, we exemplify how the vehicle speeds $v = 15$ km/h and $v = 70$ km/h would render the speed-aware control. Notice that the vehicle speed dictates both the starting point and the slope of the control.

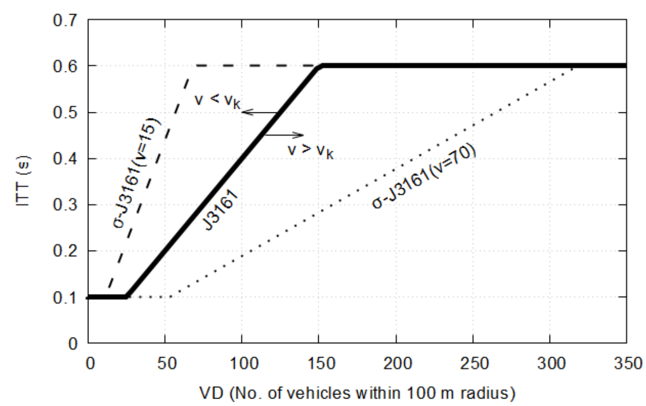


Fig. 2. Illustrative comparison of J3161 and σ-J3161 for different speeds

Finally, note that the proposed speed-aware control requires cross-layer coordination because the speed is user-level information that is not originally available on the access layer. Although not yet specified, we could use the defined interface ("interface 4") between the application and the congestion control components in the Decentralized Congestion Control architecture [12]. In fact, such cross-layer information is already being used in J2945/1 and J3161/1, because VD is counted in the application layer through the unique vehicle identifiers in BSM contents [4], [5]. We argue that the increased safety benefit for higher-speed vehicles more than justifies this complexity cost, which will be shown in the next section.

III. Performance evaluation

In this section, we evaluate the impact of the proposed change in terms of packet delivery performance through extensive simulation. For convenience, we refer to the original SAE J3161/1 congestion control "J3161", and the speed-aware modification, "σ-J3161" where σ is the speed scaling factor as discussed above.

A. Metrics

To evaluate the effectiveness of each scheme, we employed Packet Inter-Reception time (PIR), communication volume between high-speed vehicles, and Channel Busy Ratio (CBR). According to [13], PIR is defined as the time elapsed between two successive receptions of two different packets transmitted from the same vehicle within the range of 400 meters, where CBR is a fraction of used transmit resources in the most recent past of length 100 ms. Although the Packet Reception Ratio (PRR) is considered the most important metric in V2X communication in many previous works, it is a myth when rate control is employed and the traffic is periodic. It should be understood that it can be arbitrarily lowered by drastically lowering the messaging rate thereby minimizing collision losses. However, in periodic safety communication, the whole purpose is updating neighboring vehicles' information as to the ego vehicle as frequently as possible. Therefore, excessively lowering the messaging rate (i.e., increasing ITT) will boost PRR, but it will not serve the purpose of V2X safety communication built on periodic beaconing. Instead, the packet inter-reception ratio (PIR) that is determined both by ITT and by PRR is the most important metric in periodic safety beaconing. This has been noticed early on [14], [15] in the literature.

The reason that we also use the number of successfully received packets between fast vehicles is that higher vehicle speed increases the likelihood of an accident. Drivers driving much faster than the average driver have a higher accident risk. A broad average level by Finch [9] shows that 1 km/h increase in speed translates to 3% increase in accidents. Therefore, the assistance provided by V2X is more crucial to the drivers in fast lanes.

B. Simulation setting

For simulating inter-vehicle communication in cellular V2X (C-V2X) environment, we employed LTEV2Vsim [16], an open-source simulator designed for C-V2X environment. The specific V2X simulation model is as follows. The Intelligent Transport System (ITS) channel has a bandwidth of 20 MHz [5], which is divided into ten subchannels. Each transport block (TB) is composed of two subchannels, to carry a single BSM of up to 277 bytes at modulation and coding scheme (MCS) level 7. Consequently, two Tx resources are provided per time slot. Antenna gain is set to 3 dB, and the noise figure of receiver to 9 dB. The path loss model is Winner+B1, and the log-normal distribution is used as the shadowing distribution. The maximum Tx power is set to 20 dBm according to J3161/1. The antenna height is set to 1.5 m, where the effective antenna height is also set to 1.5 m (highway environment). We configured Sensing-Based Semi-Persistent Scheduling (SPS) [7] parameters for the reselection counter (RC) and selection window size to [5..15] and 100 ms, respectively. After the RC limit is reached, each Tx resource can be retained with a probability of $P_{keep} = 0.8$. Table I summarizes the simulation configuration related to V2X communication.

As to the road environment modeling, we assume two distinct speed groups with different moving directions as shown in Fig. 3. According to traffic engineering, the vehicle speed is inversely proportional to the vehicle density [18]. Therefore, vehicle speeds v_1 and v_2 determine the vehicle traffic density in each direction. For the relation between the two, we use an empirical observation that the average headway distance (m) on expressway is

TABLE I
SIMULATION CONFIGURATION FOR V2X COMMUNICATION

	Parameter	Value
PHY	Bandwidth (MHz)	20 [5]
	No. subchannels	10
	Subchannels/transport block	2
	Antenna gain (dB)	3
	Tx power (dBm)	20 [5]
	Noise figure of receiver (dB)	9
	Pathloss model	WINNER+B1 [17]
	Shadowing distribution	Log-normal
	Shadowing std. dev. (dB)	0 (LOS), 4 (NLOS)
	Antenna height (m)	1.5
	MCS index	7
MAC	Reselection counter value	[5..15]
	Selection window width (ms)	100
	HARQ	Off
	Reference speed, v_k	33 km/h
	Resource keep probability	0.8 [7]
Application	Message size (bytes)	250
	Awareness range (m)	400
Vehicles	Road length (km)	2
	Number of lanes	3
	Ratio of slow vehicles to fast vehicles	[6:4, 7:3, 8:2, 9:1]

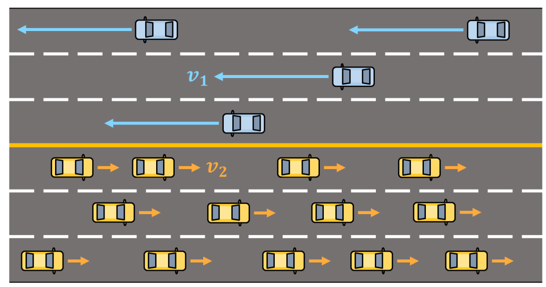


Fig. 3. Simulation scenario with two distinct speed groups: e.g. $v_1 = 144$ km/h, $v_2 < 30$ km/h

$$H = 3.06 \cdot V - 13.88 \tag{3}$$

where V is the vehicle speed (m/s) [19]. The road is set to 2 km in length and wraps around so that vehicles exiting one end re-enter the road on the other end. It has six lanes, three in each direction. For the congested direction, v_1 is set to slightly lower speed than 30 km/h, to have 540 vehicles on the 2-km stretch according to Eq. (3). For the faster direction, we vary v_1 from 36 km/h to 144 km/h and set the vehicle population according to Eq. (3). We will observe its impact on the traditional speed-agnostic and the proposed speed-aware congestion control. Table II summarizes the number of vehicles in each direction over the 2 km road section as we vary the vehicle population ratios between the two speed groups.

C. Results

1) Packet Inter-Reception time (PIR): For space reason, we present two highest-speed cases among the four population ratios: $v_1 = 144$ km/h and $v_1 = 70$ km/h. These speeds are more safety-critical than 47 km/h or 36 km/h. As for the two

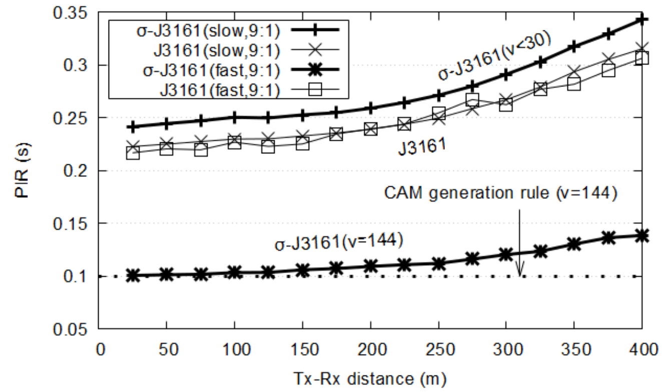
TABLE II
ROAD TRAFFIC ENVIRONMENT

Population ratio	Fast vehicles		Slow vehicles	
slow : fast	Speed	Population	Speed	Population
9:1	144 km/h	60	< 30 km/h	540
8:2	70 km/h	132		
7:3	47 km/h	230		
6:4	36 km/h	360		

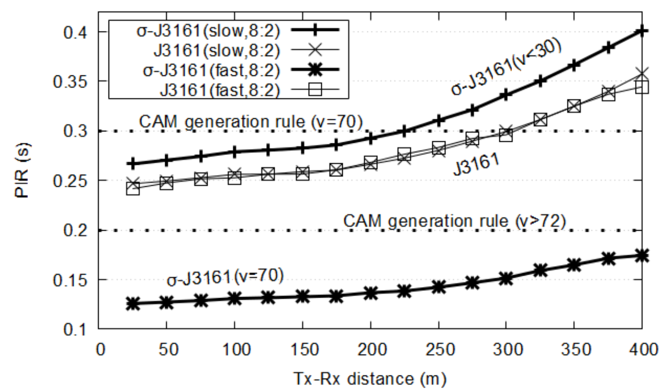
latter cases, they have the same qualitative results although the PIR differentiation is not as stark as in the highest-speed cases. To put the numbers in perspective, we match the PIR for J3161 and σ-J3161 up against the facilities layer congestion control that is more speed-aware [8]. In the highway scenario that we consider, vehicles cruise without change of velocity or heading. According to the CAM generation rule [8], a CAM is produced as the vehicle progresses every 4 meters. At $v_1 = 144$ km/h, the time gap between consecutive CAM packets pushed down by the facilities layer onto the access layer is approximately 100 ms. On the other hand, at $v_2 = 30$ km/h, the time gap is 500 ms. The access layer gate-keeping through J3161 or σ-J3161 may or may not allow the time gaps. If not, CAMs will get purged by the access layer congestion control, potentially threatening driving safety, especially for high-speed vehicles.

Fig. 4 shows the PIR as a function of Tx-Rx distance for J3161 and σ-J3161. Unsurprisingly, the PIR values in J3161 are essentially identical for the two speed groups. For $v_1 = 144$ km/h in Fig. 4(a), J3161 has PIR values starting from approximately 220 ms and converging towards 300 ms, irrespective of vehicle speed differences. In contrast, in σ-J3161, PIR values are completely separated between speed groups. Slow vehicles in close proximity to the transmitting node start with PIR of 240 ms, increasing towards 340 ms as the receiver is located farther. On the other hand, fast vehicles enjoy PIR values starting close to 100 ms in the most safety-critical distances, which is the message gap dictated by the CAM generation rule for $v_1 = 144$ km/h [8]. Considering that the PIR value at the closest distance (i.e, Tx-Rx distance of 25 m) reflects the ITT being used, the PIR with the speed-agnostic J3161 is egregiously large. Less than half of the CAM from the facilities layer produced by the CAM generation rule will be dropped before transmission, potentially threatening the safety of high-speed vehicles. Furthermore, the risk is caused by no good reason for low-speed vehicles, either. According to the CAM generation rule, slow vehicles with $v < 30$ km/h only need 500 ms for ITT anyway [8], and it will not need excessively frequent transmit opportunities provided by the access layer. In Fig. 4(b), σ-J3161/1 similarly exhibits its effectiveness. For $v_1 = 70$ km/h, the desired message gap by the CAM generation rule is 300 ms, which is readily satisfied. J3161/1, on the other hand, exceeds it for the Tx-Rx distance larger than 300 m. What is more problematic is that for $v_1 > 72$ km/h, the desired message gap is reduced to 200 ms [8]. Then σ-J3161 still satisfies it for all distances, whereas J3161 cannot for any Tx-Rx distance.

2) Volume of communication between fast vehicles: Fig. 5 compares the volume of communication between fast vehicles in the two schemes over the entire simulation duration. Naturally, the number of packets received by a high-speed vehicle from other high-speed vehicles absolutely increases when there are more vehicles with higher speed (i.e., at 8:2). More importantly, we observe that regardless of the speed composition in the vehicle population, σ-J3161 multiplies the communication volume between fast vehicles compared to J3161. Therefore, speed-aware V2X congestion control helps reduce the risk of accidents for them by facilitating communication between fast vehicles.



(a) Slow:fast = 9:1



(b) Slow:fast = 8:2

Fig. 4. Packet inter-reception (PIR) according to distance and vehicle population composition

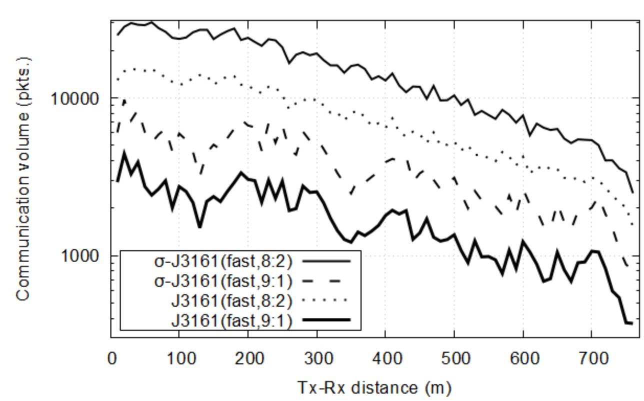


Fig. 5. Volume of communication between faster vehicles

3) Channel busy ratio (CBR): Fig. 6 compares the CBR of the two schemes. For all tested vehicle population composition, it shows that σ-J3161 incurs comparable channel load J3161. Moreover, it readily fits within the target channel load between 50% and 80% as stipulated by J2945/1 [4] and its successor J3161/1. Therefore, speed-aware congestion control can protect the messaging rate of the high-speed vehicles required for driving safety while effectively controlling the channel load upon channel congestion.

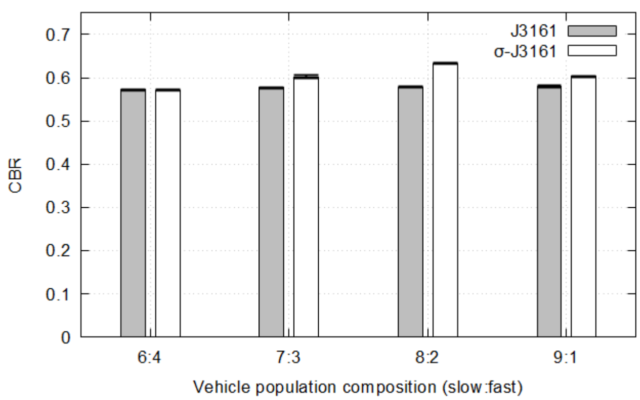


Fig. 6. Channel busy ratio (CBR) of J3161 and σ-J3161

Note that the CBR values in Fig. 6 are maintained rather consistently across different vehicle speed composition that inevitably implies different vehicle population density (see Table II). The reason for the consistency is the congestion control (i.e., J3161 or σ-J3161) working across the different traffic densities. Fig. 7 shows how the ITT changes under the control. Recollect from Table II that due to the vehicle traffic characteristics, a smaller fraction of the high-speed group implies higher speed. Then, notice that σ-J3161 can quickly reduce the ITT with the increase in the vehicle speed, at the cost of increased ITT for slower vehicles (still, the slow vehicles meet the message gap by the CAM generation rule). In particular, it decreases ITT much faster for high-speed vehicles than the standard J3161. Still, the channel load is not excessively impacted because the high-speed lanes have lower vehicle traffic densities.

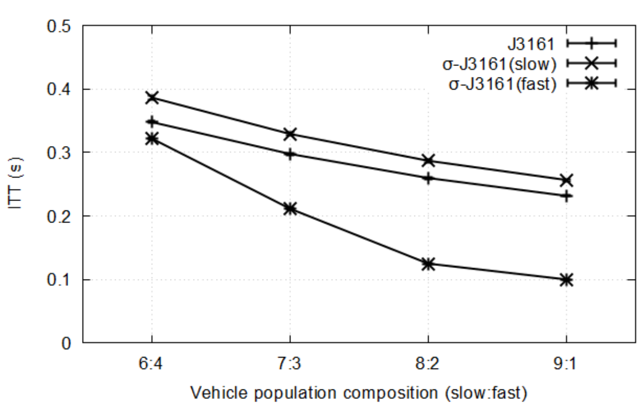


Fig. 7. Inter-transmission time (ITT) of J3161 and σ-J3161

IV. Conclusion

This paper argues for V2X congestion control that accommodates individual vehicle speed into the control logic. No access layer V2X congestion control standard or proposal has attempted to include vehicle speed in the control framework. Although a recent facilities layer congestion control standard utilizes the information, the access layer cannot forfeit its final gate-keeping role. Therefore, the access layer congestion control standards should also be generalized to cater to the safety communication requirement associated with vehicle speed. This paper demonstrates the safety benefit of the proposed speed-aware V2X congestion control for more vulnerable high-speed vehicles when they pass by an area congested with slowly moving vehicles.

Acknowledgments

This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the ICT Creative Consilience program (IITP-2023-2020-0-01819) supervised by the IITP (Institute for Information & communications Technology Planning & Evaluation.

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