Hindawi
Wireless Communications and Mobile Computing
Volume 2018, Article ID 5641258, 12 pages
https://doi.org/10.1155/2018/5641258

Research Article

Modeling and Analysis of Safety Messages Propagation in Platoon-Based Vehicular Cyber-Physical Systems

Liqiang Qiao,[1] Yan Shi ,[1] Shanzhi Chen,[2] and Wei Gao[1]

[1] *State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications, Beijing 100876, China*
[2] *State Key Laboratory of Wireless Mobile Communications, China Academy of Telecommunications Technology, Beijing 100083, China*

Correspondence should be addressed to Yan Shi; shiyan@bupt.edu.cn

Received 3 November 2017; Accepted 10 January 2018; Published 8 February 2018

Academic Editor: Hongwei Wang

Safety messages propagation is the major task for Vehicular Cyber-Physical Systems in order to improve the safety of roads and passengers. However, reducing traffic and car accidents can only be achieved by disseminating safety messages in a timely manner with high reliability. Although mathematical modeling of the delay of safety messages is extremely beneficial, analyzing the safety messages propagation is considerably complex due to the high dynamics of vehicles. Moreover, most previous works assume vehicles drive independently and the interaction between vehicles is not taken into consideration. In this paper, we proposed an analytical model to describe the performance of safety messages propagation in the VCPSs under platoon-based driving pattern. Infrastructure-less and RSU-supported scenarios are evaluated independently. The analytical model also takes into account different transmission situations and various system parameters, such as communication range, traffic flow, and platoon size. The effectiveness of the analytical model is verified through simulation and the impacts of different parameters on the expected transmission delay are investigated. The results will help determine the system design parameters to satisfy the delay requirement for safety applications in VCPSs.

1. Introduction

Vehicular Cyber-Physical Systems (VCPSs), which take advantage of the latest advances in communication, computing, sensing, control, and so on, have attracted the attention of many researchers, for the great potential of providing different applications, such as safety-related services, traffic information services, and entertainment services [1–5]. In a typical VCPS, moving vehicles are all equipped with various sensors to collect the up-to-date information about the road and disseminate the collected information to all neighbor vehicles in order to avoid the traffic jam, reduce car accidents, and save fuel consumption [6]. Generally, a platoon-based VCPS consists of two main processes: the platoon mobility process which describes the platoon mobility pattern under a control strategy and the communication process that generalizes the communication request of VCPSs applications [7]. VCPSs can support both ad hoc and infrastructure-based communications [8]. Particularly, vehicles on the road can communicate with each other through a direct and indirect multihop ad hoc connection. In addition, these vehicles can also communicate with roadside units (RSUs) deployed in the road, which provide Internet access and real-time data services to passing vehicles.

Among the vast array of potential applications, safety messages propagation has been the major task of VCPSs. The majority of the VCPSs safety applications require that each vehicle broadcasts safety messages to all the surrounding vehicles. There are two main types of safety messages broadcast by each vehicle, namely, beacon and event-driven message [9, 10]. The former is automatically sent by each vehicle at regular intervals to inform others about its current position, speed, and direction of movement. The latter is broadcast by certain vehicles only in case of an unexpected event. When on-board sensors detect an accident or a sudden brake, the vehicle immediately generates an emergency message and broadcasts it to the following vehicles to notify other drivers before they reach the potential danger zone. A relatively small reduction in the driver's reaction time may potentially avoid the trigger of an accident. Thus, message transmission delay is a main quality-of-service (QoS) metric for safety application in VCPSs. However, data communication in VCPSs is a challenging task due to the highly dynamic network topology and intermittent connectivity caused by the high mobility and speed of vehicles [11–14].

Recently, several works have been conducted to study the safety messages propagation in VCPSs [15–18]. Zhou et al. [15] proposed an analytical model to investigate the safety message propagation process and derived the probability of delivering safety messages to all neighbor vehicles for different traffic condition. Wang et al. [16] derived a mathematical model to describe the relationship between the average delay and the deployment distance between two neighbor RSUs. In [17], the authors analyzed the safety messages delivery delay with general store-carry-forward mechanism and decelerating store-carry-forward mechanism, respectively. Li et al. [18] analyzed the delay of multihop safety message broadcast by taking propagation distance, distribution of vehicles, vehicle density, and minimum safe distance between vehicles into consideration. However, these theoretical analyses are useful to understand the safety message propagation delay in VCPSs. The main limitation of these works is that they usually assume vehicles drive in free traffic state, that is, each vehicle moves independently at constant velocity, and the interaction between vehicles is seldom taken into consideration.

In practice, vehicles that move in the same direction with close space can naturally be grouped into a platoon. Platoon-based driving pattern in highway is regarded as a promising driving manner. To the best of our knowledge, there is no equivalent investigation on the performance of safety messages propagation in the VCPSs under platoon-based driving pattern. Therefore, the main purpose of this work is to analyze and provide quantitative insights into the expected transmission delay of safety messages based on platoon driving pattern. The major contributions of this paper are summarized as follows:

(i) We develop an analytical model for safety messages propagation in a dynamic network formed over vehicles traveling in opposing direction. The model captures the platoon mobility characteristics of vehicles. Under the model, we derive the expected transmission delay of safety messages under infrastructure-less and RSU-supported scenarios.

(ii) The analytical model takes into account different transmission cases and various system parameters, such as communication range, traffic flow, and platoon size. The effectiveness of the mathematical model is verified, and the impacts of different parameters on the expected transmission delay are investigated through simulation results.

(iii) The derived mathematical model can be used to estimate the safety message transmission delay, which will help determine the system design parameters to satisfy the delay requirement for safety applications in VCPSs.

The rest of the paper is organized as follows: The scenario and necessary assumptions are introduced in Section 3. The analysis of safety messages propagation delay in an infrastructure-less scenario is derived in Section 4. With the help of RSUs, the delay of safety messages propagation will be discussed in Section 5. Numerical and simulation results are shown in Section 6. The last section is for a brief summary.

2. Related Works

In the literature, several works have been conducted on how to improve the communication quality of safety messages propagation in various aspects, including the network connectivity, medium access control (MAC), and routing protocols. Network connectivity is a fundamental requirement of safety messages propagation in VCPSs. The authors in [19] developed an analytical model with a general radio channel to fully characterise the access probability and connectivity probability in a vehicular relay network. The empirical studies [20, 21] have investigated the instantaneous network connectivity and the impacts of vehicles mobility on the connectivity. Efficient and scalable medium access control (MAC) protocol is crucial to guarantee the reliable broadcast of safety messages in VCPSs. A MAC protocol named VeMAC is proposed in [22] which supports a reliable one-hop broadcast service for safety applications in VCPSs. They also analyzed the total delivery delay of VeMAC for periodic and event-driven safety messages. Lyu et al. [23] designed a novel time slot-sharing MAC, named SS-MAC, to support diverse beacon rates for safety applications in VCPSs. Suthaputchakun et al. [24] introduced a mini-distributed interframe (DIFS) in the MAC protocol to give the safety message a higher access priority and selected the farthest possible vehicle to perform forwarding to increase the dissemination speed by reducing the number of forwarding hops.

From the perspective of routing, an efficient broadcast protocol called Density-aware Emergency message Extension Protocol (DEEP) is proposed in [25]. Different vehicles are given different forwarding priorities by segmenting roads into multiple blocks according to vehicle density. Binary partition approach is used in the forward node selection process to improve the efficiency of broadcast by reducing the delay incurred before choosing the relay node in each hop in [26]. Wu et al. [27] used fuzzy logic algorithm to choose the best relay node by taking intervehicle distance, vehicle velocity, and link quality into account. To lower safety message transmission delay and reduce message redundancy, Bi et al. [28] utilized iterative partition, mini-slot, and black-burst to quickly select forwarding node. Although these works are useful to improve the performance of safety messages propagation, they mainly focus on the design of broadcast protocol, so as to make safety messages be received by other relevance vehicles with low dissemination delay and high reliability.

Other works have developed analytical models studying safety messages propagation in VCPS. In [29], Abboud and Zhuang developed a mathematical model to compute the total delay in emergency message broadcasting based on the traffic flow theory for three traffic flow levels (high,

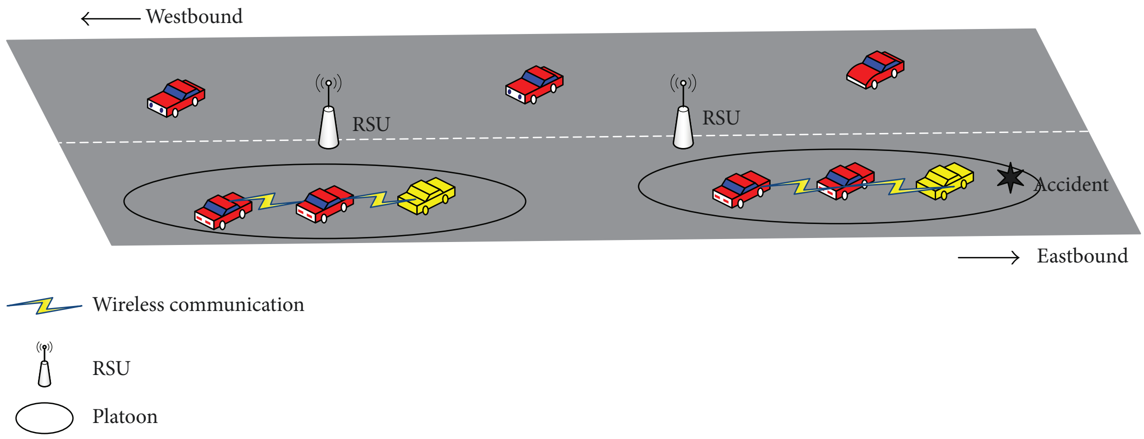

Figure 1: Network scenario.

medium, and low). The impact of two different network parameters on the communication delay in infrastructure-less highway scenarios was studied in [30]. A time/location-critical framework for emergency message dissemination is proposed in [31]. Nevertheless, the literatures [29–31] only took into account the delivery delay in a highway scenario without RSUs. In [32], the maximum message delivery delay from a vehicle to the nearest RSU was estimated. They also derived the minimum number of RSUs required to cover a straight road. The probability of a rear-end collision between two vehicles that travel in the same direction when a sudden event occurs is derived in [33]. However, the literatures [32, 33] consider the unidirectional scenario that the vehicle only moves in one direction, so the message delivery process cannot get the help from the vehicles moving in the reverse direction. The improvement in the rehealing delay when a number of RSUs are deployed was investigated in [34, 35], and the results show the rehealing time is significantly reduced in the presence of RSUs. Jia et al. [7] proposed a novel architecture for platoon VCPSs and derived the intraplatoon and interplatoon spacing in the steady state. Our paper is based on the results of intraplatoon and interplatoon spacing derived in [7]. We investigated the expected transmission delay of safety messages under different scenarios. In addition, we also discussed the benefits of RSU deployed at fixed interval to enable relaying of information when there is severe disconnection between vehicles.

3. System Model

This section describes our system model with necessary assumptions in terms of the network scenario, distribution of traffic flow, and vehicle mobility model, for tractability in establishing the analytical model.

3.1. Network Scenario. In this paper, we consider a straight two-lane highway that goes in opposite directions (i.e., the eastbound and the westbound directions) shown in Figure 1. We assume that all vehicles are equipped with storage, computation, and communication capabilities. Thus, vehicles can quickly and accurately collect the real-time information about the status of the road and notify neighboring vehicles of potential dangerous events. The communication radius of each vehicle is denoted by R within which reliable V2V communication is guaranteed. Vehicles that move in the same direction and within each other's communication range will form a platoon. The foremost vehicle in a platoon is the platoon leader which is responsible for creating and managing the platoon. The platoon tail is located at the end of a platoon and is responsible for communicating with the following platoon leader. All vehicles in the same platoon can directly communicate with each other. As shown in Figure 1, the vehicles in the same circle belong to the same platoon and the foremost vehicle (e.g., the yellow one) is the platoon leader. When an accident occurs, the vehicle first passing the accident location is referred to as the source node Src which immediately generates a safety message containing the traffic condition and broadcasts it to the succeeding vehicles traveling in the same direction. The safety message can be delivered to the tail of the platoon through the direct wireless communication. However, the target vehicle Dst (the leader of the following platoon) is not within the platoon tail's communication range. For such a scenario, the message can be stored and forwarded to a vehicle that travels in the opposite direction. Then, the relay node can forward the message until it enters the communication range of the target node. The average safety message delivery delay is the time from the instant when it is issued to the instant when the target node Dst has received it. Therefore, the problem considered in this paper is to develop a mathematical model to calculate the average information delivery delay.

3.2. Distribution of Traffic Flow. In this paper, we adopt the statistics of time headway as the fundamental parameter to describe the traffic flow distribution. Time headway is defined as the elapsed time of the passage of identical points on two consecutive vehicles [36]. So far numerous probability density distribution models have been proposed to fit the empirical distributions of time headway, including normal distribution, exponential distribution, gamma distribution, and log-normal distribution [37–40]. The exponential distribution is widely accepted as a very good model for relative

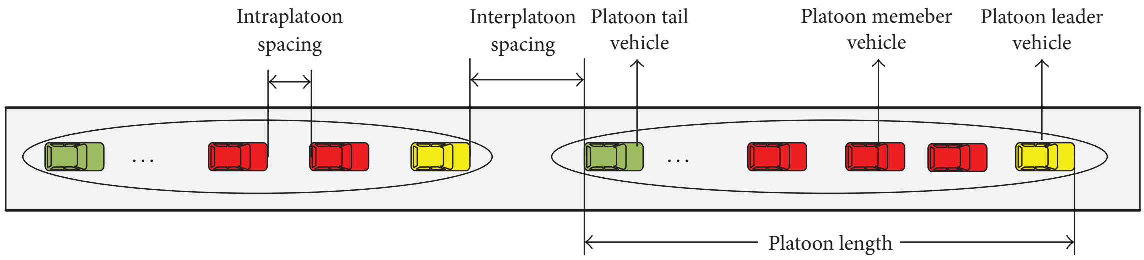

FIGURE 2: An illustrative example of platoon parameters.

long headway. However, it fails to describe the smaller variability in the headways observed in groups of vehicles that follow each other [41]. Through statistical analysis of empirical vehicle trajectory data collected from highways, the authors of [42] found that the log-normal distribution model is a good fit for the interarrival time of traffic during day-time hours. It is also confirmed in [37] that log-normal distribution fits well the intermediate traffic demand level. Therefore, we assume that the time headway has a log-normal distribution, which is expressed as

$$f_{T_h}(t_h,\mu,\sigma,\tau) = \frac{1}{\sqrt{2\pi}\sigma(t_h-\tau)}\exp\left(-\frac{(\log(t_h-\tau)-\mu)^2}{2\sigma^2}\right), \quad t_h>\tau, \tag{1}$$

where t_h represents the possible value of the time headway, τ represents the minimum value of the time headway, μ is the scale parameter, and σ is the shape parameter. Therefore, the mean and variance of time headway can be calculated as

$$\mu(T_h) = \tau + e^{\mu+(1/2)\sigma^2}, \qquad \sigma^2(T_h) = e^{2\mu+\sigma^2}\left(e^{\sigma^2}-1\right). \tag{2}$$

3.3. Vehicle Mobility Model. Car-following model, which falls into the category of microscopic level description, is the most common vehicle mobility model to describe the interaction among adjacent vehicles in the same platoon. In a car-following model, the behavior of each driver is described in relation to the vehicle ahead. A typical car-following model, known as Intelligent Driver Model (IDM) [43], is applied in this paper. According to IDM, acceleration of a following vehicle can be expressed as follows:

$$a_{fv}(t) = a\left[1-\left(\frac{v_{fv}(t)}{v_0}\right)^4-\left(\frac{s^*(v_{fv}(t),\triangle v(t))}{s(t)}\right)^2\right], \tag{3}$$

where v represents the velocity of the following vehicle, the gap to the preceding vehicle is s, and velocity difference between the following and preceding vehicle is $\triangle v$. Subscript fv denotes the following vehicle. In (3), the instantaneous acceleration consists of a free acceleration $a[1-(v_{fv}(t)/v_0)^4]$ to achieve the desired speed v_0 and an interaction deceleration $-a(s^*(v_{fv}(t),\triangle v(t))/s(t))^2$ based on the existing gap and the desired minimum gap between the subject and preceding vehicles. The desired minimum gap is as follows:

$$s^*(v_{fv}(t),\triangle v(t)) = s_0 + T_0 v_{fv}(t) + \frac{v_{fv}(t)\triangle v(t)}{2\sqrt{ab}}, \tag{4}$$

where s_0 and T_0 represent the minimum intraplatoon spacing and the desired time headway, respectively, and a and b represent maximum acceleration and desired deceleration.

4. Delay Analysis of Safety Messages under Infrastructure-Less Scenario

In this section, we first present platoon analysis, and then, based on the communication scenario shown in Figure 1, we study the average delay of safety message propagation under two different situations: the best-case where the source node can immediately relay the information to a westbound car and the worst-case where no westbound vehicles are located in the communication range of the source node, respectively.

4.1. Platoon Analysis

4.1.1. Intraplatoon Spacing. Following the illustrative example presented in Figure 2, the intraplatoon spacing between two adjacent vehicles in the same platoon is denoted by S_{intra}. According to (3) and (4), the intraplatoon spacing is

$$S_{\text{intra}} = \frac{s_0 + T_0 v_{fv}(t) + v_{fv}(t)\triangle v(t)/2\sqrt{ab}}{\sqrt{1-(v_{fv}(t)/v_0)^4 - a_{fv}(t)/a}}. \tag{5}$$

In this paper, we consider that all vehicles in the scenario run at the same velocity in the steady state [44], where $a_{fv}=0$ and $\triangle v(t) = 0$. Let v_{stb} and S_{stb} be the velocity and intraplatoon spacing in the steady state, respectively; then, the intraplatoon spacing can be rewritten as [44]

$$S_{\text{intra}} = S_{\text{stb}} = \frac{s_0 + v_{\text{stb}}T_0}{\sqrt{1-(v_{\text{stb}}/v_0)^4}}. \tag{6}$$

4.1.2. Interplatoon Spacing. Similar to intraplatoon spacing, the gap between the tail of the leading platoon and the

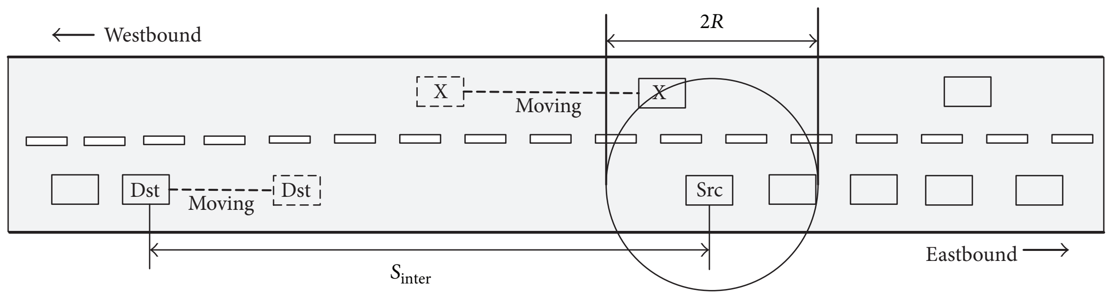

Figure 3: Best-case scenario.

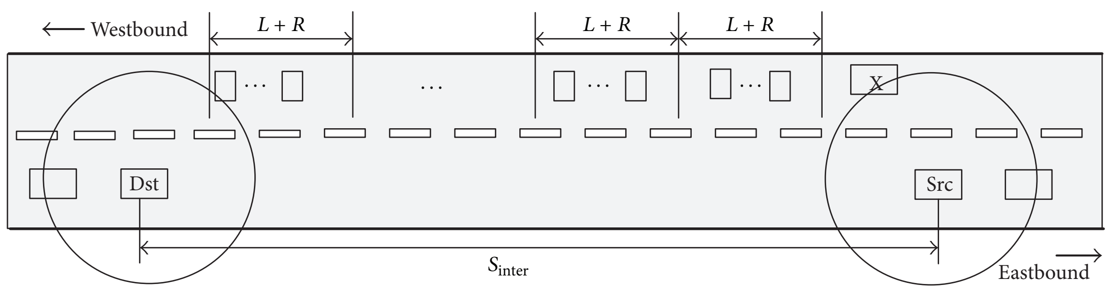

Figure 4: Case 1.

leader of the following platoon is referred to as interplatoon spacing, which is represented by S_{inter}. Under the assumption that all platoons have the same platoon size n and the same IDM parameters, the probability density function of the interplatoon spacing is derived in [7]

$$f_{S_{\text{inter}}}(x) = \frac{1}{\sqrt{2\pi}\sigma_D x}\exp\left(-\frac{(\log(x)-\mu_D)^2}{2\sigma_D^2}\right), \quad x > 0, \tag{7}$$

where the scale parameter μ_D and the shape parameter σ_D are given by

$$\sigma_D^2 = \log\left(\frac{\sigma^2(T_h)}{n(\mu(T_h)-\tau)^2}+1\right), \qquad \mu_D = \log(nv_{\text{stb}}(\mu(T_h)-\tau)) - \frac{\sigma_D^2}{2}. \tag{8}$$

4.2. Delay Analysis of Safety Messages Propagation. Without loss of generality, we assume the source node Src is located in the end of a platoon and has to deliver safety message to the vehicle Dst which is the following platoon leader. Because the distance between the source node Src and the target node Dst is out of the communication range, the vehicle Dst cannot receive the safety message directly. The message waits on the source node Src until the gap is filled by westbound vehicles. The expected transmission delay of safety message from Src to Dst is denoted by $E[T]$. In order to relay the message, the source node Src could run into one of the following cases.

4.2.1. Best-Case Scenario. As shown in Figure 3, the source node Src can immediately relay the safety message to a westbound vehicle X as the relay node which is the closet vehicle to the target node Dst. Let $f(x)$ denote the probability density function of the position of X. According to [7], the probability density function $f(x)$ is

$$f(x) = \frac{1}{e^{\mu_D}+L}, \tag{9}$$

where L represents the platoon length and is calculated by $L \approx n\tau v_{\text{stb}}$. Thus, the probability of this case is given by

$$\begin{aligned} p_1 &= P\{-R < x < R,\ S_{\text{inter}} > R\} \\ &= \int_{-R}^{R}\frac{1}{e^{\mu_D}+L}dx\int_{R}^{+\infty} f_{S_{\text{inter}}}(y)\,dy \\ &= \frac{2R}{e^{\mu_D}+L}\Phi\left(\frac{\mu_D-\log R}{\sigma_D}\right). \end{aligned} \tag{10}$$

Once the safety message arrives at the first relay node X, there can be two possible subcases.

Case 1. In this case, the relay node X is spatially connected to the target node Dst as illustrated in Figure 4. That is to say, the safety message can be continuously forwarded by each platoon leader and eventually received by the Dst. In order to calculate the probability of this event, we discrete the westbound roadway segment $S_{\text{inter}}-R$ into multiple cells, each of size $L+R$. The number of cells is $m = \lceil (S_{\text{inter}}-R)/(L+R)\rceil$. We consider a cell to be occupied if one or more platoon leaders are positioned within that cell. The probability of each

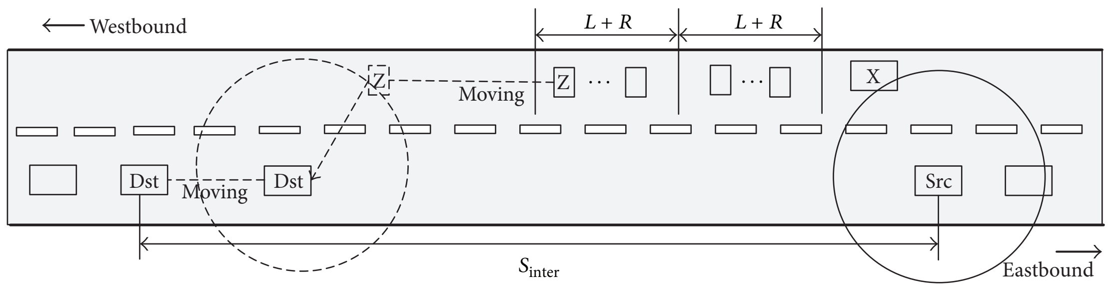

Figure 5: Case 2.

cell being occupied by at least one platoon leader is calculated by

$$p_w = P\left(0 < S_{\text{inter}} < R\right) = \int_0^R f_{S_{\text{inter}}}(x)\,dx = \Phi\left(\frac{\log R - \mu_D}{\sigma_D}\right). \tag{11}$$

Case 1 happens when all of the m adjacent cells are occupied and the probability of this event is $p_{10} = p_w{}^m$. Because the speed of wireless communication is much faster than that of the vehicle, we ignore the delay caused by direct wireless transmission between two vehicles. Thus, the corresponding expected transmission delay $E[T_{10}] \approx 0$.

Case 2. As shown in Figure 5, not all of the m cells are occupied. The safety message can only be forwarded by X between adjacent cells where platoon leaders are located. The last forwarder is vehicle Z which carries the message until it comes into contact with the target node Dst. The probability of Case 2 is simply the complement of p_{10} and is given by $p_{11} = 1 - p_{10}$. Let $E[d]$ denote the expected distance traversed by adjacent cells, which can be calculated by

$$E[d] = (L+R)\frac{1}{m}\sum_{i=1}^{m} i p_w{}^i = (L+R)\left[\frac{p_w\left(1-p_w{}^m\right)}{m\left(1-p_w\right)^2} - \frac{p_w{}^{m+1}}{1-p_w}\right]. \tag{12}$$

The safety message transmission delay is the time that the relay node Z has to carry the message until it comes into Dst's communication range. Let $E[T_{11}]$ denote the expected transmission delay of this case, which can be calculated by

$$E[T_{11}] = \frac{E[S_{\text{inter}}] - R - (1-p_w)E[d]}{2v_{\text{stb}}} = \frac{e^{\mu_D+(1/2)\sigma_D^2} - R - (L+R)\left[p_w\left(1-p_w{}^m\right)/m\left(1-p_w\right) - p_w{}^{m+1}\right]}{2v_{\text{stb}}}. \tag{13}$$

Given all the given cases, we have

$$E[T_1] = p_{10}E[T_{10}] + p_{11}E[T_{11}]. \tag{14}$$

4.2.2. Worst-Case Scenario. In this case, the source node Src cannot immediately relay the message to a westbound vehicle. The probability that this case happens can be calculated:

$$p_2 = 1 - p_1. \tag{15}$$

This case can be further divided into the following two subcases.

Case 3. No westbound vehicles are located within the communication range of the source node Src and other nodes in the same platoon, as shown in Figure 6. Let p_{20} represent the probability that this case happens. We have

$$p_{20} = P\left(S_{\text{inter}} > L\right) = \int_L^{+\infty} f_{S_{\text{inter}}}(x)\,dx = \Phi\left(\frac{\mu_D - \log L}{\sigma_D}\right). \tag{16}$$

In this case, the safety message is carried by the platoon leader in the same platoon until it comes into contact with a westbound vehicle, which will further forward the information to the target node Dst. We assume that the platoon leader is statistically located in the center of interplatoon spacing. Thus, the westbound vehicle closest to the source node Src is at least $E[S_{\text{inter}}] + L + (1/2)E[S_{\text{inter}}]$ away from the target node Dst. The expected transmission delay $E[T_{20}]$ is calculated by

$$E[T_{20}] = \frac{E[S_{\text{inter}}] + L + (1/2)E[S_{\text{inter}}]}{2v_{\text{stb}}} = \frac{L + (3/2)e^{\mu_D+(1/2)\sigma_D^2}}{2v_{\text{stb}}}. \tag{17}$$

Case 4. As shown in Figure 7, there is no relay node traveling in the westbound direction within the communication range of the source node Src, but there is one or more westbound vehicles within the communication range of a node other

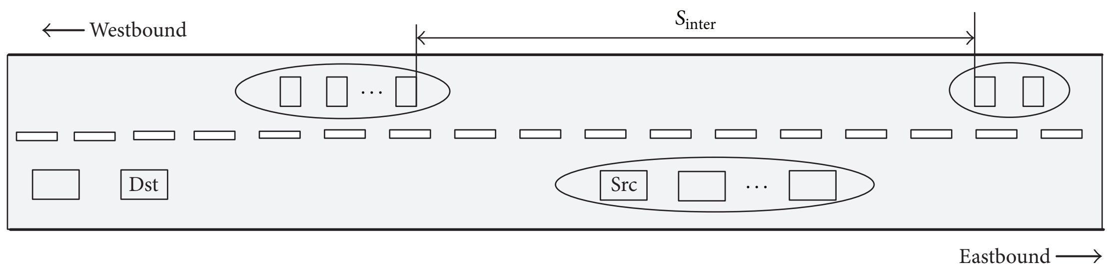

Figure 6: Case 3.

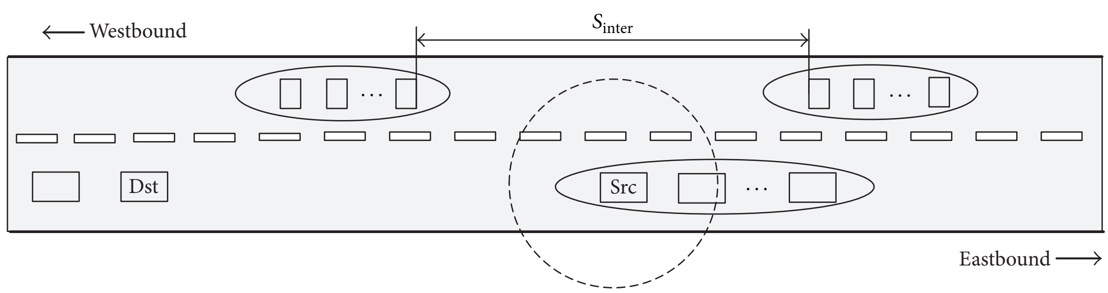

Figure 7: Case 4.

than the source node Src in the same platoon. This case happens with the following probability:

$$p_{21} = 1 - p_{20} = \Phi\left(\frac{\log L - \mu_D}{\sigma_D}\right). \quad (18)$$

Since the closest westbound vehicle to the source is at most $E[S_{\text{inter}}] + L + R$ away from the target node Dst, the delivery delay can be approximately calculated as

$$E[T_{21}] = \frac{E[S_{\text{inter}}] + L + R}{2v_{\text{stb}}} = \frac{e^{\mu_D + (1/2)\sigma_D^2} + L + R}{2v_{\text{stb}}}. \quad (19)$$

Under the worst-case scenario, the expected transmission delay $E[T_2]$ is

$$E[T_2] = p_{20}E[T_{20}] + p_{21}E[T_{21}]. \quad (20)$$

Consequently, the total expected transmission delay $E[T]$ is

$$E[T] = p_1 E[T_1] + p_2 E[T_2]. \quad (21)$$

5. Delay Analysis of Safety Messages with RSU Supported

In this section, we present the analytical model to describe the delay of safety messages transmission with RSU-supported VCPSs. RUSs usually have larger communication range due to the availability of power source and more powerful devices. Thus, they are capable of quickly disseminating a message to most of vehicles in a region of VCPSs. We consider the most critical scenario where RSUs are deployed at fixed interval of D_u to enable relaying of information when there is severe disconnection between vehicles. Thus, the probability of finding an RSU is a uniformly distributed random variable in $[0, D_u]$:

$$f_{\text{RSU}}(r) = \begin{cases} \dfrac{1}{D_u} & 0 < r < D_u \\ 0 & \text{others.} \end{cases} \quad (22)$$

Working with the analytical model in Section 4, we determine which communication scenarios can benefit from the presence of RSUs. Best-case and worst-case are evaluated independently, as each leads to a different set of benefits.

5.1. Best-Case Scenario. In this case, as shown in Figure 3, the source node Src can immediately relay the safety message to a westbound vehicle X. The improvements are obtained when an RSU is deployed in a way where it can forward the safety message from X to the destination node Dst. Let R_u represent the communication range of an RSU. We consider the case where the vehicles Dst and X reach a distance of $2R_u$ from one another where an RSU can act as a relay node between the two vehicles. If no RSUs were present, the two vehicles have to travel a distance of $2R_u - R$ to be able to communicate with each other. We see a range of positions where an RSU can be deployed as shown in Figure 8. The most favorable position for the RSU is in front of vehicle Dst by R_u where the travel distance reduction is highest ($2R_u - R$) and vehicles can communicate immediately. No improvements can be obtained when the RSU is on top of either vehicle Dst or X. Let z denote the distance from the RSU to the vehicle Dst. We observe that the reduction in travel distance increases

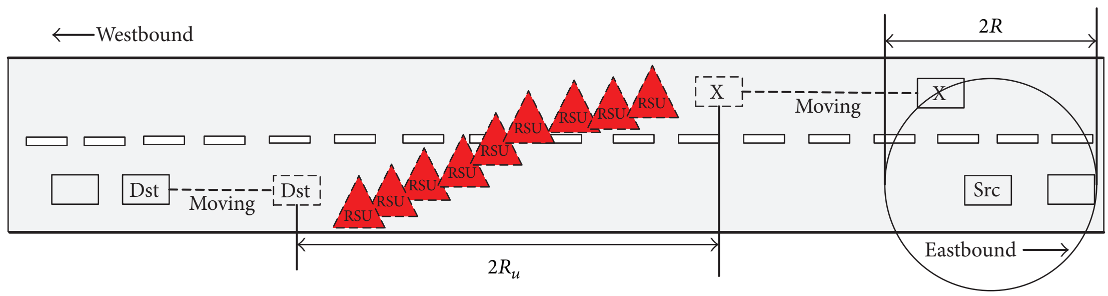

FIGURE 8: Favorable positions for RSUs.

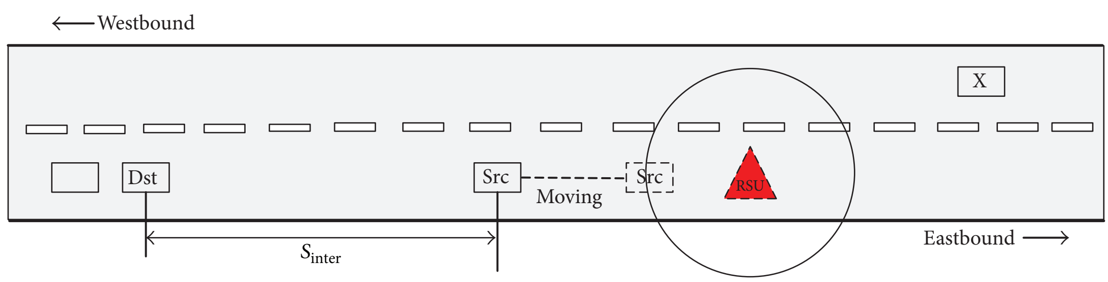

FIGURE 9: RSU acting as a relay node in worst-case.

linearly from $z = 0$ to R_u and decreases linearly from R_u to $2R_u$. The travel distance reduction, $G(z)$, is given by

$$G(z) = \begin{cases} \left(2 - \frac{R}{R_u}\right) z & 0 < z < R_u \\ -\left(2 - \frac{R}{R_u}\right) z + 2(2R_u - R) & R_u < z < 2R_u. \end{cases} \tag{23}$$

Therefore, the mean reduction in travel distance is given by

$$E[L] = \int_0^{2R_u} G(z) f_{\text{RSU}}(z)\, dz = \frac{R_u(2R_u - R)}{D_u}. \tag{24}$$

With the presence of an RSU acting as a relay node, the delay of safety message transmission $E[T_1']$ is

$$E[T_1'] = \frac{E[S_{\text{inter}}] - R - E[L] - (1 - p_w) E[d]}{2v_{\text{stb}}}. \tag{25}$$

5.2. Worst-Case Scenario. In this case, the source node Src does not have any vehicles traveling on the opposite direction within its communication range to relay the safety message. With the presence of RSUs, a new scenario where an RSU act as a relay node becomes possible. This is shown in Figure 9. The source node Src can first deliver the safety message to the RSU. The destination node Dst receives the message from the RSU when it comes into the communication range of the RSU. This case happens when the delay for the destination node Dst to get the message from the RSU is smaller than the delay to forward the message to a vehicle traveling on the opposite direction. The source node Src is at most $(D_u - 2R_u)/2$ away from an RSU. Let p_r represent the probability of an RSU acting as a relay node

$$\begin{aligned} p_r &= P\left[\frac{S_{\text{inter}} + L + (1/2) S_{\text{inter}}}{2v_{\text{stb}}} > \frac{S_{\text{inter}} + (1/2) D_u - R_u}{v_{\text{stb}}}\right] \\ &= \int_{-\infty}^{2(L+2R_u-D_u)} f_{S_{\text{inter}}}(x)\, dx \\ &= \Phi\left(\frac{\log(2(L + 2R_u - D_u)) - \mu_D}{\sigma_D}\right). \end{aligned} \tag{26}$$

The delay of safety message transmission $E[T_{20}']$ in this scenario is

$$\begin{aligned} E[T_{20}'] &= \frac{E[S_{\text{inter}}] + (1/2) D_u - R_u}{v_{\text{stb}}} \\ &= \frac{e^{\mu_D + (1/2)\sigma_D^2} + (1/2) D_u - R_u}{v_{\text{stb}}}. \end{aligned} \tag{27}$$

If the above scenario does not occur, the delay of safety message transmission is sum of two components: the source node Src has to wait for an opposite-lane vehicle Z and Z comes into the communication range of Dst.

Thus, under the worst-case scenario with RSU-support, the expected transmission delay $E[T_2']$ is

$$E[T_2'] = p_r E[T_{20}'] + (1 - p_r) E[T_{21}'], \tag{28}$$

where $E[T_{21}']$ is the previous worst-case expected transmission delay.

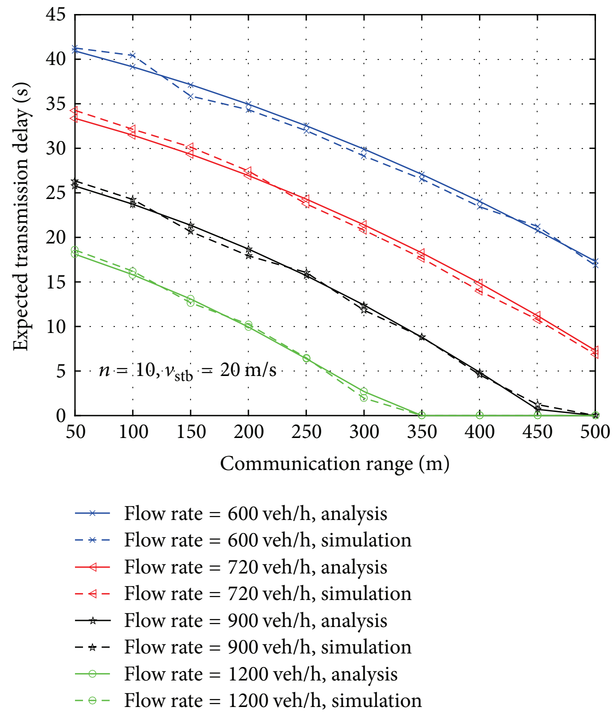

FIGURE 10: Impact of the communication range on the expected transmission delay ($n = 10$, $v_{stb} = 20$ m/s).

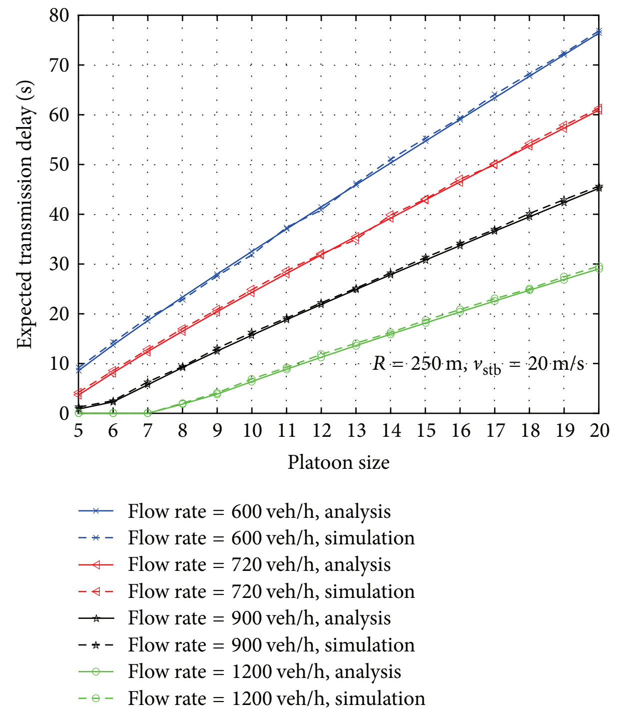

FIGURE 11: Impact of the size of platoon on the expected transmission delay ($R = 250$ m, $v_{stb} = 20$ m/s).

Given all cases, the expected transmission delay $E[T']$ with RSU supported is

$$E\left[T'\right] = p_1 E\left[T_1'\right] + \left(1 - p_1\right) E\left[T_2'\right]. \quad (29)$$

6. Numerical and Simulation Results

In this section, we verify the effectiveness of the analytical model through simulation results and investigate the impacts of different parameters on the expected transmission delay, respectively, including the communication range of a vehicle (i.e., R), the platoon size (i.e., n), and the steady velocity (i.e., v_{stb}). To perform the simulation experiments, we have developed a MATLAB simulator. In the simulation experiments, vehicles are generated at the beginning of each road at time intervals obtained from a log-normal random number generator. Vehicles move at a constant speed in steady state and there is no overtaking. The value of σ is set to 0.4 like in [7], which normally does not vary much over different traffic low levels. The minimum value of headway time is $\tau = 1$ s. By setting different value of μ, we can simulate the traffic scenarios with various traffic flow rates.

6.1. Impact of Communication Range of Vehicle. We now study how different communication ranges impact the expected transmission delay $E[T]$. Given the platoon size $n = 10$ and steady velocity $v_{stb} = 20$ m/s, we show the expected transmission delay of safety message when the communication range R varies from 50 m to 500 m under various traffic flow conditions in Figure 10. We can observe that the simulation results and the analytical results fit very well for all cases of traffic flow rates, which means the analytical model is effective. It is easy to see that the expected transmission delay of safety message decreases as the communication range R increases. Particularly, when the traffic flow rate is 1200 veh/h, the expected transmission delay $E[T]$ decreases from 18 s to 0 s as the communication range increases from 50 m to 350 m. That is to say, the safety message can be directly transmitted from the succeeding tail of platoon to the following platoon header when the communication range is 350 m. Even in sparse scenario (i.e., 600 veh/h), the expected transmission delay still significantly decreases as R increases. This is mainly due to the fact that R can significantly enhance the network connectivity. There are more high probabilities that two vehicles are connected and forward the message to each other when the communication range increases. As expected, for a given value of communication range R (i.e., 250 m), it also takes less time to forward a safety message to the following platoon header in the dense traffic condition. This is because as the traffic flow rate increases, the interplatoon spacing gets smaller.

6.2. Impact of Platoon Size. To study the impact of platoon size on the expected transmission delay, we fix the communication range $R = 250$ m and the steady velocity $v_{stb} = 20$ m/s, respectively. Figure 11 shows the expected transmission delay $E[T]$ under different traffic flow rates. It is seen that simulation results are very close to the analytical results. Moreover, with an increasing platoon size, the expected transmission delay increases in various traffic flow conditions. The graph shows that, for the traffic flow rate of 720 veh/h, the expected transmission delay increases from 4 s to 61 s as the platoon

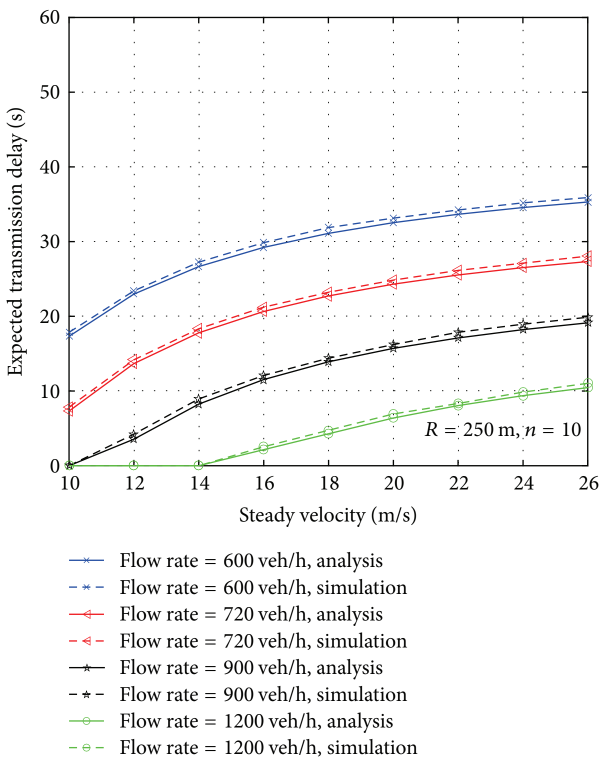

Figure 12: Impact of the steady velocity on the expected transmission delay ($R = 250$ m, $n = 10$).

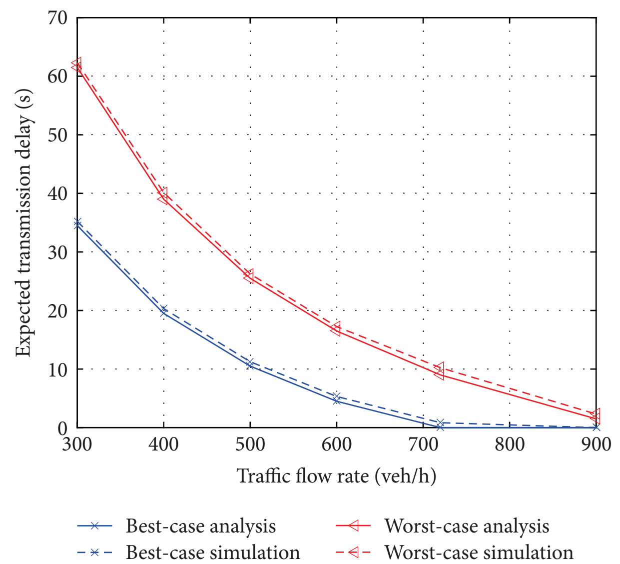

Figure 13: The expected transmission delay of best-case and worst-case with RSU supported ($D_u = 1000$ m, $R_u = 400$ m).

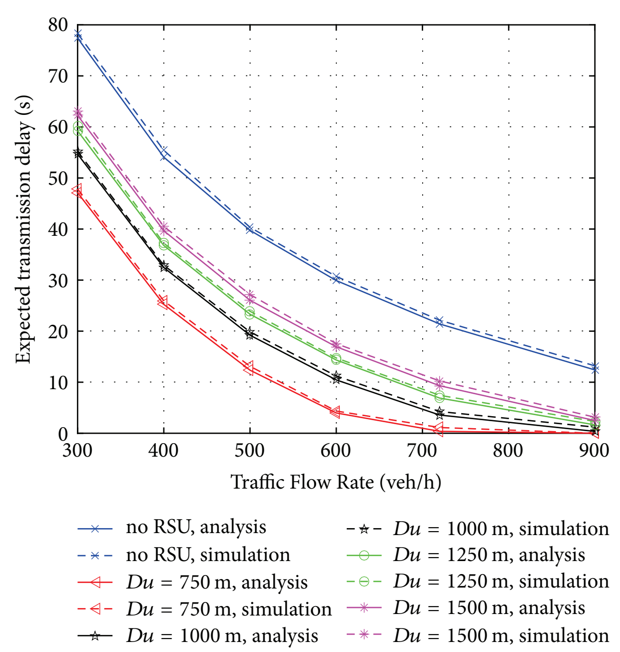

Figure 14: The expected transmission delay with RSU supported under different deployment interval.

size increases from 5 to 26. A similar phenomenon is also observed in other traffic flow rates. This is due to the fact that the interplatoon spacing is enlarged when the platoon size increases. As a result, the possible distance traversed during store-carry-forwarding process will be maximized.

6.3. Impact of Steady Velocity. Figure 12 plots the expected transmission delay $E[T]$ against the steady velocity of vehicles in various traffic flow rates, where $R = 250$ m and $n = 10$. Similar to the effect of platoon size, the expected transmission delay slowly increases with the increase of steady velocity. For the traffic flow rate of 1200 veh/h, we notice that there is no transmission delay when $v_{stb} \leq 14$ m/s, and the transmission delay is less than 10 s when the steady velocity reaches 26 m/s. That is because increasing steady velocity results in large interplatoon spacing for a given traffic flow rate.

6.4. The Benefits on the Expected Transmission Delay with RSU Supported. First, we investigate the two main components of the expected transmission delay $E[T']$ with RSU supported. We conduct the simulation under different flow rate conditions, where the value of RSU deployment interval D_u is set to 1 km and the communication range of RSU is set to 400 m.

Figure 13 shows the analytical and simulation results for the best-case and worst-case scenario with RSU supported, for traffic flow rate ranging from 300 to 900 veh/h. We observe a very good match between the predictions of our analytical model and the output of the simulations. The results clearly show that the expected transmission delay of both best-and worst-case scenarios decreases as the traffic flow rate increases. When the traffic flow rate is below 600 veh/h, the network is essentially disconnected, and the likelihood of being in the presence of a worst-case scenario is high. As the traffic flow rate increases, the networks are largely connected, and the safety messages are more likely propagated under the best-case scenario, which gives a lower penalty in expected transmission delay.

The expected transmission delay $E[T']$ under different deployment intervals is shown in Figure 14. It is easy to see that the delay of safety message propagation can be reduced obviously with the help of RSUs. When the traffic flow rate is 300 veh/h, the expected transmission delay decreases almost 45% by a regular space 750 m deployment of RSUs. There is still 22% reduction when the deployment interval increases to 1500 m. On the other hand, the safety message propagation can be done almost instantly when the traffic flow rate reaches 700 veh/h with RSU supported. That indicates sufficient number of RSUs can significantly reduce the expected transmission delay of safety messages. However, with too many RSUs, it would also incur high installation cost and maintenance cost of these RSUs.

7. Conclusions

The message transmission delay is a main QoS metric for safety application in VCPSs. In this paper, we developed an analytical model to analyze the safety message transmission delay in both infrastructure-less and RSU-supported scenarios. The vehicles are assumed to move based on Intelligent Driver Model. The analytical model takes into account different transmission cases and various system parameters, such as communication range, traffic flow, and platoon size. We conducted extensive simulation to validate the effectiveness of the analytical model. The results will help determine the system design parameters to satisfy the delay requirement for safety applications in VCPSs.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported in part by the National Natural Science Foundation Projects under Grant 61731004, the National Science and Technology Major Projects of China under Grant 2017ZX03001014, and the National Science Fund for Distinguished Young Scholars under Grant 61425012.

References

[1] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, "A survey on platoon-based vehicular cyber-physical systems," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 263–284, 2016.

[2] K. Liu, V. C. S. Lee, J. K.-Y. Ng, J. Chen, and S. H. Son, "Temporal data dissemination in vehicular cyber-physical systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 6, article no. A6, pp. 2419–2431, 2014.

[3] O. Kaiwartya, A. H. Abdullah, Y. Cao et al., "Internet of vehicles: motivation, layered architecture, network model, challenges and future aspects," *IEEE Access*, vol. 4, no. 99, pp. 5356–5373, 2016.

[4] J. Wan, D. Zhang, S. Zhao, L. T. Yang, and J. Lloret, "Context-aware vehicular cyber-physical systems with cloud support: architecture, challenges, and solutions," *IEEE Communications Magazine*, vol. 52, no. 8, pp. 106–113, 2014.

[5] S. Chen, J. Hu, Y. Shi et al., "Vehicle-to-everything (v2x) services supported by LTE-based systems and 5G," *IEEE Communications Standards Magazine*, vol. 1, no. 2, pp. 70–76, 2017.

[6] Y. Wang, J. Zheng, and N. Mitton, "Delivery delay analysis for roadside unit deployment in intermittently connected VANETs," in *Proceedings of the 2014 IEEE Global Communications Conference, GLOBECOM 2014*, pp. 155–161, December 2014.

[7] D. Jia, K. Lu, and J. Wang, "On the network connectivity of platoon-based vehicular cyber-physical systems," *Transportation Research Part C: Emerging Technologies*, vol. 40, pp. 215–230, 2014.

[8] S. Chen, J. Hu, Y. Shi, and L. Zhao, "LTE-V: a TD-LTE-based V2X solution for future vehicular network," *IEEE Internet of Things Journal*, vol. 3, pp. 997–1005, 2016.

[9] H. A. Omar, N. Lu, and W. Zhuang, "Wireless access technologies for vehicular network safety applications," *IEEE Network*, vol. 30, no. 4, pp. 22–26, 2016.

[10] H. P. Luong, M. Panda, H. Le Vu, and Q. B. Vo, "Analysis of multi-hop probabilistic forwarding for vehicular safety applications on highways," *IEEE Transactions on Mobile Computing*, vol. 16, no. 4, pp. 918–933, 2017.

[11] C. Shao, S. Leng, Y. Zhang, A. Vinel, and M. Jonsson, "Performance analysis of connectivity probability and connectivity-aware MAC protocol design for platoon-based VANETs," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 12, pp. 5596–5609, 2015.

[12] J. He, L. Cai, J. Pan, and P. Cheng, "Delay analysis and routing for two-dimensional VANETs using carry-and-forward mechanism," *IEEE Transactions on Mobile Computing*, vol. 16, no. 7, pp. 1830–1841, 2017.

[13] Y. Wang, Y. Liu, J. Zhang, H. Ye, and Z. Tan, "Cooperative store-carry-forward scheme for intermittently connected vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 1, pp. 777–784, 2017.

[14] Y. Huo, W. Dong, J. Qian, and T. Jing, "Coalition game-based secure and effective clustering communication in vehicular cyber-physical system (VCPS)," *Sensors*, vol. 17, no. 3, article no. 475, pp. 1–23, 2017.

[15] H. Zhou, S. Xu, D. Ren, C. Huang, and H. Zhang, "Analysis of event-driven warning message propagation in vehicular Ad Hoc networks," *Ad Hoc Networks*, vol. 55, pp. 87–96, 2017.

[16] Y. Wang, J. Zheng, and N. Mitton, "Delivery Delay analysis for roadside unit deployment in vehicular ad hoc networks with intermittent connectivity," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 10, pp. 8591–8602, 2016.

[17] B. Pan and H. Wu, "Analysis of safety messages delivery in vehicular networks with interconnected roadside units," *IEEE Access*, vol. 5, pp. 24873–24883, 2017.

[18] X. Li, B.-J. Hu, H. Chen, B. Li, H. Teng, and M. Cui, "Multi-hop delay reduction for safety-related message broadcasting in vehicle-to-vehicle communications," *IET Communications*, vol. 9, no. 3, pp. 404–411, 2015.

[19] S. C. Ng, W. Zhang, Y. Zhang, Y. Yang, and G. Mao, "Analysis of access and connectivity probabilities in vehicular relay networks," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 1, pp. 140–150, 2011.

[20] D. Naboulsi and M. Fiore, "Characterizing the instantaneous connectivity of large-scale urban vehicular networks," *IEEE Transactions on Mobile Computing*, vol. 16, no. 5, pp. 1272–1286, 2017.

[21] X. Hou, Y. Li, D. Jin, D. O. Wu, and S. Chen, "Modeling the impact of mobility on the connectivity of vehicular networks in large-scale urban environments," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 4, pp. 2753–2758, 2016.

[22] H. A. Omar, W. Zhuang, A. Abdrabou, and L. Li, "Performance evaluation of VeMAC supporting safety applications in vehicular networks," *IEEE Transactions on Emerging Topics in Computing*, vol. 1, no. 1, pp. 69–83, 2013.

[23] F. Lyu, H. Zhu, H. Zhou et al., "SS-MAC: a novel time slot-sharing MAC for safety messages broadcasting in VANETs," *IEEE Transactions on Vehicular Technology*, pp. 1-1, 2017.

[24] C. Suthaputchakun, M. Dianati, and Z. Sun, "Trinary partitioned black-burst-based broadcast protocol for time-critical emergency message dissemination in VANETs," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 6, pp. 2926–2940, 2014.

[25] M.-C. Chuang and M. C. Chen, "DEEP: density-aware emergency message extension protocol for VANETs," *IEEE Transactions on Wireless Communications*, vol. 12, no. 10, pp. 4983–4993, 2013.

[26] J. Sahoo, E. H.-K. Wu, P. K. Sahu, and M. Gerla, "Binary-partition-assisted MAC-layer broadcast for emergency message dissemination in VANETs," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 3, pp. 757–770, 2011.

[27] C. Wu, S. Ohzahata, Y. Ji, and T. Kato, "Joint fuzzy relays and network-coding-based forwarding for multihop broadcasting in vanets," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 3, pp. 1415–1427, 2015.

[28] Y. Bi, H. Shan, X. S. Shen, N. Wang, and H. Zhao, "A multi-hop broadcast protocol for emergency message dissemination in urban vehicular ad hoc networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 3, pp. 736–750, 2016.

[29] K. Abboud and W. Zhuang, "Modeling and analysis for emergency messaging delay in vehicular ad hoc networks," in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '09)*, pp. 1–6, Honolulu, Hawaii, USA, December 2009.

[30] A. B. Reis, S. Sargento, and O. K. Tonguz, "Parameters that affect safety message delay in sparse infrastructure-less vehicular networks," in *Proceedings of the 2014 1st IEEE International Conference on Communications, ICC 2014*, pp. 2568–2574, June 2014.

[31] Y. Zhuang, J. Pan, Y. Luo, and L. Cai, "Time and location-critical emergency message dissemination for vehicular Ad-hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 1, pp. 187–196, 2011.

[32] A. Abdrabou and W. Zhuang, "Probabilistic delay control and road side unit placement for vehicular ad hoc networks with disrupted connectivity," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 1, pp. 129–139, 2011.

[33] S.-I. Sou, "Modeling emergency messaging for car accident over dichotomized headway model in vehicular ad-hoc networks," *IEEE Transactions on Communications*, vol. 61, no. 2, pp. 802–812, 2013.

[34] S.-I. Sou and O. K. Tonguz, "Enhancing VANET connectivity through roadside units on highways," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 8, pp. 3586–3602, 2011.

[35] A. B. Reis, S. Sargento, F. Neves, and O. K. Tonguz, "Deploying roadside units in sparse vehicular networks: what really works and what does not," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 6, pp. 2794–2806, 2014.

[36] A. D. May, *Traffic Flow Fundamentals*, Prentice-Hall, 1990.

[37] D.-H. Ha, M. Aron, and S. Cohen, "Time headway variable and probabilistic modeling," *Transportation Research Part C: Emerging Technologies*, vol. 25, pp. 181–201, 2012.

[38] G. Yan and S. Olariu, "A probabilistic analysis of link duration in vehicular Ad Hoc networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 4, pp. 1227–1236, 2011.

[39] K. Abboud and W. Zhuang, "Stochastic analysis of a single-hop communication link in vehicular ad hoc networks," *IEEE Intelligent Transportation Systems Magazine*, vol. 15, no. 5, pp. 2297–2307, 2014.

[40] L. Cheng and S. Panichpapiboon, "Effects of intervehicle spacing distributions on connectivity of VANET: a case study from measured highway traffic," *IEEE Communications Magazine*, vol. 50, no. 10, pp. 90–97, 2012.

[41] J. S. Baras, A. J. Dorsey, and W. S. Levine, "Estimation of traffic platoon structure from headway statistics," *IEEE Transactions on Automatic Control*, vol. 24, no. 4, pp. 553–559, 1979.

[42] N. Wisitpongphan, F. Bai, P. Mudalige, V. Sadekar, and O. Tonguz, "Routing in sparse vehicular ad hoc wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 8, pp. 1538–1556, 2007.

[43] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Physical Review E: Statistical, Nonlinear, and Soft Matter Physics*, vol. 62, no. 2, pp. 1805–1824, 2000.

[44] D. Jia, K. Lu, and J. Wang, "A disturbance-adaptive design for VANET-enabled vehicle platoon," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 2, pp. 527–539, 2014.


Journal of Engineering
The Scientific World Journal
International Journal of Rotating Machinery
Journal of Sensors
Advances in Multimedia
Advances in Civil Engineering
Hindawi
Submit your manuscripts at
www.hindawi.com
Journal of Control Science and Engineering
Journal of Robotics
Journal of Electrical and Computer Engineering
Advances in OptoElectronics
VLSI Design
International Journal of Navigation and Observation
Modelling & Simulation in Engineering
International Journal of Aerospace Engineering
International Journal of Chemical Engineering
International Journal of Antennas and Propagation
Active and Passive Electronic Components
Shock and Vibration
Advances in Acoustics and Vibration