Modeling of V2V Communications for C-ITS Safety Applications: A CPS Perspective

Alexey Vinel, Nikita Lyamin, and Pavel Isachenkov

***Abstract*— Tight coupling between the performance of vehicle-to-vehicle (V2V) communications and the performance of cooperative intelligent transportation system (C-ITS) safety applications is addressed. A cyber-physical system analytical framework is developed which links the characteristics of V2V communications (such as packet loss probability and packet transmission delay) with the physical mobility characteristics of the vehicular system (such as safe intervehicular distance). The study is applied to the Day 1 C-ITS application, emergency electronic brake lights, enabled by the European Telecommunication Standard Institute ITS-G5 and IEEE 802.11p standards.**

***Index Terms*— Cyber-physical system (CPS), cooperative intelligent transportation system (C-ITS), emergency electronic brake lights (EEBL), vehicle-to-vehicle (V2V) communications, emergency breaking, road safety, ITS-G5, IEEE 802.11p.**

I. Introduction

ONE can define a *Cyber-Physical System* (CPS) as a combination and coordination between physical systems and communication systems [1]. The Cooperative Intelligent Transportation System (C-ITS) is an example of a CPS which integrates telecommunications, electronics and information technologies with transport engineering aiming at increased road safety, efficiency and driving comfort [2]. Vehicle-to-Vehicle (V2V) communications is a key enabling technology for C-ITS. The European Telecommunication Standard Institute (ETSI) has delivered the first ITS-G5 release of a set of vehicular communication standards in 5.9 GHz band under European Commission Mandate M/453 [3]. ITS-G5 defines the overall vehicular communication protocol stack [4] including IEEE 802.11p standard at the lower layers. A similar protocol stack in North America is specified by IEEE 1609.x WAVE (Wireless Access in Vehicular Environment).

Advanced driver assistance applications for highly automated driving are the enabling force for the massive deployment of C-ITS. These applications improve driving safety through the real-time exchange of status update information among road users. A good example of such an application is "Emergency Electronic Brake Lights" [5] (hereafter *emergency braking*). According to a European Commission strategy document [6] emergency braking is planned to become one of *Day 1 C-ITS services*. Its functioning is fairly straightforward: an Intelligent Transportation System Station (ITS-S) will transmit Decentralized Environmental Notification Messages (DENM) [7] when its deceleration value reaches a predefined emergency braking threshold value. However, 5.9 GHz V2V communications are vulnerable to scattering and reflection of the propagated signal from nearby objects, e.g. large traffic signs, neighbouring vehicles, trucks and bridges [8]. As a result, the probability of DENM packet loss is not insignificant even over short inter-vehicular distances.

Therefore, there is tight coupling between the performance of V2V communications and the resulting vehicular safety of collision avoidance C-ITS services, which is a focus of our study. In this letter we present an analytical framework which links the wireless channel characteristics with the *maximum tolerable delay* between the beginning of the emergency braking by the vehicle, and the moment the following vehicle starts braking, so that rear-end collisions are avoided. We apply the developed CPS analysis approach to demonstrate how V2V communication packet losses and communication delays impact safe inter-vehicular distance for specified kinematic parameters of vehicles movements.

The remainder of this letter is organized as follows. After discussion of related work in Section II, we present our system model as well as the analytical framework for the C-ITS emergency braking application in Section III. Numerical results which characterize the safety of V2V-enabled emergency braking are presented and analyzed in Section IV. Section V discusses the directions for our future work.

II. Related Work

Emergency braking in C-ITS is studied in [9], where the authors evaluate the relevance of the content of emergency braking messages for the recipient vehicle, using a machine learning approach. In [10] a vehicle path prediction algorithm is designed, and it is proposed for use in an emergency braking scenario. The objective is to calculate the safe trajectory of the rear vehicle based on the information received via a communication system using the proposed path prediction method. Communication packet losses are, however, outside the scope of this study.

At the same time, several studies focus on a realistic modeling of V2V communications for safety C-ITS applications. For example, Vinel [11] presents an analytical framework that models the communication message reception probability before the deadline for vehicular communications. In [12] and [13] Markovian approaches are adopted to analyze the performance and reliability (mean transmission delay, collision probability, etc.) of the safety-critical data broadcasting in IEEE 802.11p vehicular networks. The performance of one-hop DENM message dissemination is studied in [14].

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However, all these studies model only the performance of V2V communication and do not link it to the resulting physical movement of vehicles.

A work closely resembling ours is [15], where the authors study both V2V communication and C-ITS safety jointly. They focus on the platooning application where a caravan of highly automated vehicles is moving in unison. A dynamic model of the vehicles' movements is presented and the influence of the communication delays on the system safety is also studied. Safe inter-vehicular distances in a scenario where the first vehicle brakes and this information is disseminated among the platoon members is derived for different information dissemination patterns. However, the authors assume constant V2V communication delays, which does not reflect the probabilistic behaviour of the wireless channel. Our letter attempts to overcome this by linking the analysis of V2V communication protocols and the physical safety of C-ITS scenarios.

III. System Model

A. Model Assumption

Let us consider two vehicles moving at constant speed V_0 with the inter-vehicle distance d_0 (Figure 1). Both vehicles have maximum braking forces F and masses m, which results in emergency braking deceleration $a = \frac{F}{m}$.

We consider an emergency braking scenario in C-ITS, where as soon as the first vehicle begins emergency braking, it applies constant maximum deceleration and starts broadcasting DENM packets over the dedicated communication channel. When the second vehicle receives a packet, it starts emergency braking by applying constant maximum deceleration. Within this scenario, two factors play an important role in avoiding a rear-end collision: *a*) physical parameters (velocities, braking capabilities of the vehicles, etc.) and *b*) communication parameters (transmission delays, packet losses, etc.).

To model V2V communication, we use a probabilistic model of the wireless channel with the transmission duration σ and the Bit Error Rate (BER).

Let $\sigma = \frac{L}{R} + \theta$ be the transmission duration of DENM, where L is the size of the DENM message (for simplicity headers are ignored), R is the channel data rate, and θ is the IEEE 802.11p protocol overhead.

We assume that the second vehicle either receives DENM, with probability $1-p$ or does not receive it, with probability p. Each DENM re-transmission is independent. Assuming independent packet bit corruption, the probability p of a packet being lost can be defined via BER as:

$$p = 1 - (1 - BER)^L. \quad (1)$$

B. Braking Safety

Proposition 1: The maximum DENM communications delay $\tau_{\max}$, which the second vehicle can tolerate to avoid rear-end collision, is:

$$\tau_{\max} = \frac{d_0}{V_0} \quad (2)$$

Proof: The starting point in time for the given model is the time that the first vehicle starts braking. Using the speed formula for constantly decelerating motion $V(t) = V_0 - at$, we can get the moment $t_A = \frac{V_0}{a}$, when the first vehicle stops. Let τ be a delay before the second vehicle successfully receives the DENM. Because the initial speed and applied deceleration are equal for both vehicles, the moment in time, when the following vehicle stops is equal to $t_B = t_A + \tau$.

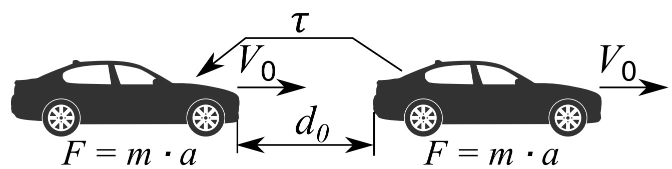
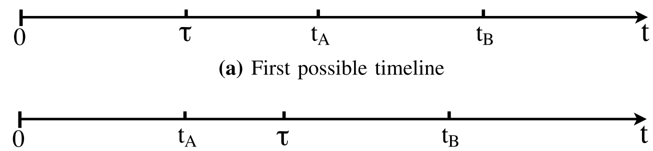


Fig. 1. A sketch of the system model.



(a) First possible timeline

(b) Second possible timeline

Fig. 2. Possible timelines of emergency braking situations, where in 2(a) the second vehicle receives the DENM before the first vehicle stops and in 2(b), the first vehicle stops before the second one receives the DENM.

For our analysis we use the coordinate equation. Considering that the origin is at the front end of the second vehicle, and that the coordinate of the rear end of the first vehicle is d_0, we can express the change of coordinate for each vehicle using piece-wise functions:

$$x_A(t) = \begin{cases} d_0 + V_0 t - \dfrac{at^2}{2}, & 0 < t \leq t_A \\ d_0 + \dfrac{V_0^2}{2a}, & t > t_A. \end{cases} \quad (3)$$

Equation (3) represents the change of coordinate for the first vehicle: at the first time interval it decelerates and after it stops, its coordinate remains constant.

The following equation shows the change of coordinate for the second vehicle – at first it is moving at constant speed; it then decelerates at a constant rate and after it stops, its coordinate remains constant:

$$x_B(t) = \begin{cases} V_0 t, & 0 < t \leq \tau \\ V_0\tau + V_0(t-\tau) - \dfrac{a(t-\tau)^2}{2}, & \tau < t \leq t_B \\ V_0\tau + \dfrac{V_0^2}{2a}, & t > t_B \end{cases} \quad (4)$$

Given that initially the distance between vehicles is d_0, we observe that the necessary condition for safe braking is that the stopping coordinate of the first vehicle is greater than the stopping coordinate of the second one, or $d_0 + \frac{V_0^2}{2a} > V_0\tau + \frac{V_0^2}{2a}$ which leads us to $\tau_{\max} = \frac{d_0}{V_0}$.

There are two possible timelines for emergency braking situations as shown in Figure 2.

In a situation where the second vehicle begins braking while the first one is still moving, see Figure 2(a), $\tau < \frac{V_0}{a}$, the initial distance between vehicles should justify $d_0 < \frac{V_0^2}{a}$.

In a situation, where the second vehicle begins braking when the first one has already stopped, see Figure 2(b), $\tau \geq \frac{V_0}{a}$.

For this situation to take place, the initial distance between vehicles should justify $d_0 \geq \frac{V_0^2}{a}$.

To confirm there was no collision prior to the ending point t_B, we check every interval of the timeline for collision points by equalizing the coordinate equations of both vehicles and checking it against our τ_{max}.

We analyze the first timeline (analysis of the second one is analogous). First we check the interval $t_A < t \leq t_B$. When we equalize the coordinate equations for this time period we get:

$$d_0 + \frac{V_0^2}{2a} = V_0\tau + V_0(t-\tau) - \frac{a(t-\tau)^2}{2}. \quad (5)$$

Which leaves us with a quadratic equation:

$$a^2t^2 - (2aV_0 + 2a^2\tau)t + (2ad_0 + V_0^2 + a^2\tau^2) = 0. \quad (6)$$

The discriminant of this equation is $8a^3\tau V_0 - 8a^3 d_0$. The root of this discriminant is $\tau = \frac{d_0}{V_0}$. If the discriminant is negative ($\tau < \frac{d_0}{V_0}$), there will be no collision. This complies with our previously found $\tau_{\max} = \frac{d_0}{V_0}$.

The next interval we check is $\tau < t \leq t_A$. When we equalize the coordinate equations for this time period we get the collision point for this time period, which happens at:

$$t = \frac{a\tau^2 + 2d_0}{2a\tau} \quad (7)$$

At the considered intervals of τ and d_0, this is a decreasing function of τ, and with given $\tau_{\max}$, the collision time t is outside a valid range. Thus, we see that with $\tau_{\max} = \frac{d_0}{V_0}$ there will be no collision at this interval.

The last interval of this timeline is $0 < t \leq \tau$. When we equalize the coordinate equations for this interval, we get the time of possible collision $t = \sqrt{\frac{2d_0}{a}}$. This means that the collision only can happen if $\sqrt{\frac{2d_0}{a}} \leq \frac{d_0}{V_0}$, which is impossible with $d_0 < \frac{V_0^2}{a}$.

Thus, we have ensured that no collisions are possible at any of the time intervals, given that $\tau_{max} = \frac{d_0}{V_0}$. ■

Remark 1: The derived maximum tolerable communication delay bound is stronger than the one given in [15, pp. 4211, Corollary 1]. Moreover, substitution of inter-vehicle distance $d_{\text{ref}} \geq \frac{V(0)^2}{2\cdot\frac{F_{\max}}{m}}$ (notations are kept as in [15]) into Corollary 1 results in an undefined value of $\tau_{\max}$.

Remark 2: A weaker maximum tolerable communication delay bound $2d_0/v_0$ is suggested in [16].

Proposition 2: The probability of safe braking, i.e. the probability vehicles do not collide during emergency braking, is given by:

$$Q = 1 - p^{\lfloor \frac{d_0}{\sigma V_0} \rfloor}. \quad (8)$$

Proof: Let τ denote the random delay before the second vehicle successfully receives the DENM, then by definition:

$$Q = Pr\{\tau \leq \tau_{\max}\}. \quad (9)$$

From Proposition 1 it follows that a rear-end collision occurs, when $\tau > \tau_{\max}$, what leads to:

$$Q = Pr\{\tau \leq \frac{d_0}{V_0}\}. \quad (10)$$

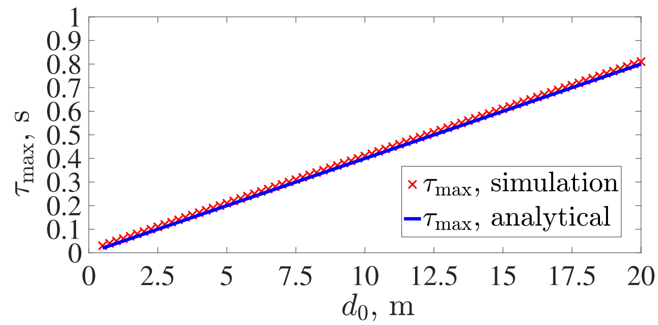


Fig. 3. Values for $\tau_{\max}$ from Proposition 1 for $V_0 = 25$ m/s, $a = 5$ m/s^2.

Since one DENM transmission attempt takes time of σ, then the maximum number of transmission trials, which first vehicle can perform to avoid the collision, is:

$$n_{\max} = \lfloor \frac{\tau_{\max}}{\sigma} \rfloor. \quad (11)$$

The number of transmission attempts n before the DENM is successfully received is a random variable that follows a geometrical distribution:

$$Pr\{X = n\} = p^{n-1}(1-p), \quad (12)$$

where n is a positive integer. Therefore:

$$Q = \sum_{n=1}^{n_{\max}} p^{n-1}(1-p) = 1 - p^{n_{\max}}, \quad (13)$$

what leads to (8). ■

IV. Numerical Results

Proposition 1 provides the relation between the maximum tolerable communications delay $\tau_{\max}$ and the initial inter-vehicle distance d_0. Figure 3 depicts $\tau_{\max}$ values obtained from (2) for a given set of initial parameters, compared to the values, derived from simulation modelling of the vehicles' movement, where for the fixed initial distance d_0 we gradually increase τ up to point when the collision between vehicles occurs.

As a benchmark for BER value, we rely on studies of IEEE 802.11p vehicular communications which demonstrate that the magnitude of BER should be assumed at least in the order of 10^{-3} [17, Figs. 6–11]. We use the channel data rate $R = 6$ Mbit/s as referenced in the IEEE 802.11p standard for DENM. We assume that the protocol overhead θ is the time required to receive a message of length L that roughly corresponds to the ACK timeout in IEEE 802.11. In Figure 4 the probability of safe braking Q with respect to BER is depicted for various initial distances d_0. Naturally, an increase in inter-vehicle distance d_0 also increases the probability of safe braking Q.

The presented framework allows us to analytically estimate both mobility and communication parameters for configuring C-ITS safety applications. For instance, from (8) the following inequality: $p \leq \sqrt[\sigma]{(1 - Q_{\min})^{\tau_{\max}}}$ provides the upper bound on packet loss probability p for given safe braking requirements $Q_{\min}$ and message transmission time σ. We depict maximum tolerable BER ($BER_{\max}$) to meet the given safety requirement $Q_{\min} = 0.999$ in Figure 5. Similarly, one can check other CPS requirements.

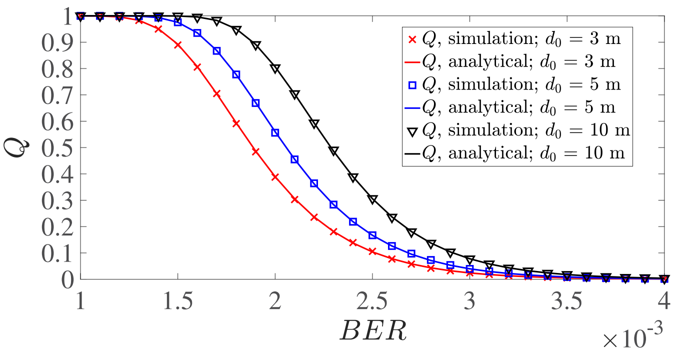


Fig. 4. Probability of safe braking Q with respect to BER for different initial distances. Other parameters are: $V_0 = 30$ m/s, $a = 3$ m/s^2, $L = 375$ B.

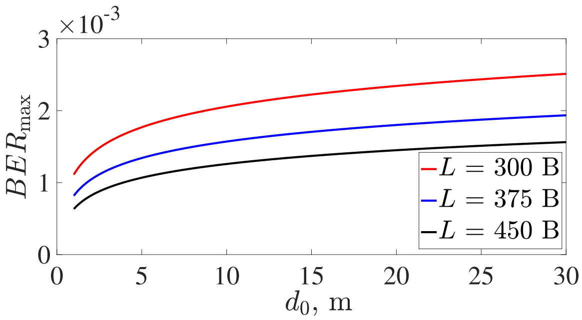


Fig. 5. Tolerable BER bounds for a given reliability parameter $Q_{\min} = 0.999$. Other parameters are: $V_0 = 26$ m/s, $a = 3$ m/s^2.

V. Future Work

It should be noted that the probability of safe braking Q characterizes the safety on the EEBL, based solely on V2V communications. In other words, in our model vehicles do not rely on any other local sensors (such as the front automotive radar or image-based systems) to detect the decreasing inter-vehicle distance. A multi-modal emergency breaking system will be a topic for our future work.

As with other future extensions, the presented reference C-ITS emergency braking model can be enhanced with more realistic vehicular mobility characteristic. For instance: *a*) there are vehicles with different braking capabilities; *b*) the emergency braking force varies with time [15], [18] and is therefore more complex than a constant maximum acceleration model.

Another interesting direction is to increase the number vehicles in the caravan and address the modeling of consequent communication patterns. Within this line of research our approach could be extended, for instance, as follows: *a*) the packet reception process is modelled independently for each vehicle and the packet loss probability between each sender and receiver dependent on their respective positions; *b*) there are heterogeneous vehicles in the caravan that affect the characteristics of different V2V communication links [8]; *c*) more details of IEEE 802.11p, WAVE, ETSI ITS-G5 protocols suite are taken into consideration [19], [20].

These enhancements will allow us to model other C-ITS scenarios, like cooperative adaptive cruise control and platooning [21] from the CPS perspective.

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