Research Paper Presentation

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Title

Safety analysis in Vehicle-to-Vehicle Communications for Platooning

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Abstract

This letter proposes an analytical framework that combines the characteristics of V2V communication with the physical mobility characteristics of vehicles .

1. First, we Present the feasible region of communications delays which guarantees safe emergency braking in platooning scenarios
2. Second, we Derive a bound on the probability of safe braking.

Terms and definitions

Platoon

A PLATOON consists of a number of highly automated vehicles following each other with a preset time headway, where vehicle-to-vehicle communication (V2V communication is the wireless transmission of data between motor vehicles) provides the means to pull vehicles together

Packet Error Rate (PER)

Packet Error Rate is used to test the performance of an access terminal's receiver.
PER is the ratio, in percent, of the number of Test Packets not successfully received by the access terminal (AT) to the number of Test Packets sent to the AT by the test set

System model

Let us consider a platoon of N vehicles

1. Moving at a constant speed v_0.
2. Inter-vehicle distance between the i-th and the (i + 1)-th vehicles is d_i.
3. Each vehicle i has a maximum braking capacity with an absolute value a_i .

When the first vehicle applies constant maximum deceleration and with time period T starts transmitting packets.The i-th vehicle either receives the packet with probability $(1 - p_i)$ or does not receive it with probability p_i. All packet receptions are independent.

SAFETY ANALYSIS

Let us introduce the sets

1. $I_N = \{1, 2, ..., N\}$
2. $I_N^+ = \{i \in I_N : a_i > a_{i+1}\}$
3. $I_N^- = \{i \in I_N : a_i < a_{i+1}\}$
4. $I_N^0 = \{i \in I_N : a_i = a_{i+1}\}$

And $\tau = [\tau_1, \tau_2, ...\tau_{N-1}]^T$ be the delays between vehicle 1 to vehicle 2 up to N, respectively.

$\tau_{max} = [\tau_{max}^1, \tau_{max}^2, ..., \tau_{max}^{N-1}]^T$ is used to define the largest feasible region of τ's guaranteeing safe braking and which depends on τ.This region is given as a polytope.

Proposition-1

Proposition : for each i,

1. $\tau^i_{max} \geq min\Big\{\frac{d_i}{v_0}, \frac{d_i}{v_0} + \frac{v_0}{2}(\frac{1}{a_i} - \frac{1}{a_{i+1}})\Big\}$,
2. $\tau^i_{max} = min\Big\{\tau^{i,0}_{max}, \tau^{i,+}_{max}, \tau^{i,-}_{max}\Big\}$ where

$$\tau^{i,0}_{max} = \frac{d_i}{v_0} \qquad \text{if i} \in I^0_N, \text{else} + \infty$$

$$\tau^{i,+}_{max} = \frac{d_i}{v_0} + \frac{v_0}{2}(\frac{1}{a_i} - \frac{1}{a_{i-1}}) \qquad \text{if i} \in I^+_N, \text{else} + \infty$$

$$\tau^{i,-}_{max} = \begin{cases} \sqrt{\frac{2d_i(a_{i+1}-a_i)}{a_{i+1}a_i}} & \text{if } \sqrt{\frac{2d_0 a_{i+1}}{a_i(a_{i+1}-a_i)}} \leq \frac{v_0}{a_i}, \\ \frac{d_i}{v_0} + \frac{v_0}{2}\left(\frac{1}{a_i} - \frac{1}{a_{i+1}}\right) & \text{else,} \end{cases} \qquad \text{if i} \in I^-_N, \text{else} + \infty$$

1. provides a lower bound that can be shown to be tight for most practical scenarios
2. has a somewhat more complicated structure, but can be shown to be a tight bound for all scenarios

Proof

Let x_i and y_i be the front position and rear position of vehicle i.
Safe braking is to guarantee that it does not exist t such that $y_i(t) - x_{i+1}(t) < 0$.
If the delay for vehicle i is $\tau_i > 0$, then the maximal allowable delay for vehicle i + 1 is larger than if $_i$ would be 0.
$\implies$ Thus,the assumption $\tau_i = 0$ is made.

Suppose $i \in I_N^0$

In this case, As the value of a_i is equal to a_{i+1}.The value ofτ is maximum when the delay is upto just before collision.
So $\tau^i_{max} = \frac{d_i}{v_0}$

Suppose $i \in I_N^-$

Let us consider the $x^0_{i+1}(t)$. As the value of a_{i+1} is greater compared to a_i .
It holds that $x^0_{i+1}(t) \geq x_{i+1}(t)$ i.e., x^0_{i+1} dominates x_j
Thus $\tau^{i,-}_{max} \geq \frac{d_i}{v_0}$

Suppose $i \in I_N^+$

Without loss of generality assume that $x_{i+1}(0) = 0$ and $y_i(0) = d_i$

The segments of vehicle i

$$y_i(t) = d_i + v_0 t - \frac{a_i t^2}{2}, \qquad 0 \le t \le \frac{v_0}{a_i} \tag{1}$$

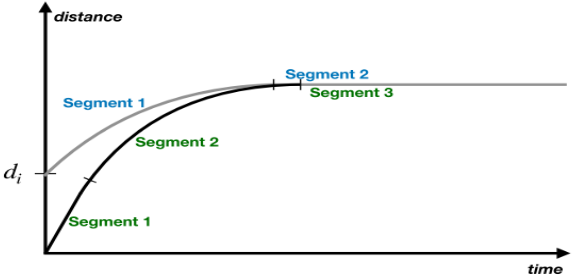
$$y_i(t) = d_i + \frac{v_0^2}{2a_i}, \qquad \frac{v_0}{a_i} \le t \tag{2}$$

The segments of vehicle i+1

$$x_i(t) = v_0 t, \qquad 0 \le t \le \tau \tag{3}$$

$$x_i(t) = v_0 t - \frac{a_{i+1}(t-\tau)^2}{2}, \qquad \tau \le t \le \tau + \frac{v_0}{a_{i+1}} \tag{4}$$

$$x_i(t) = v_0 \tau + \frac{v_0^2}{2a_{i+1}}, \qquad \tau + \frac{v_0}{a_{i+1}} \le t \tag{5}$$



Figure

There are potentially six ways of collision.All the five can be neglected when the distance in (2) is greater than distance in (5)

$$d_i + \frac{v_0^2}{2a_i} \leq v_0\tau + \frac{v_0^2}{2a_{i+1}}, \tag{6}$$

$$\tau \geq \frac{d_i}{v_0} + \frac{v_0}{2}\left(\frac{1}{a_i} - \frac{1}{a_{i+1}}\right). \tag{7}$$

In case of $i \in I_N^-$

To provide a tight bound, the intersection of segment 1 of vehicle i and segment 2 of vehicle i+1 needs to be considered.

$$d_i + v_0 t - \frac{a_i t^2}{2} = v_0 t - \frac{a_{i+1}(t-\tau)^2}{2} \tag{8}$$

To guarantee that this touch actually happens between segments 1 and 2 of the trajectories, we need to make sure that the derivatives with respect to t at time t_c of the expression at both sides are positive.
This happens when $t_c \leq \frac{v_0}{a_i}$
Using (8) we get

$$\tau_{max}^{i,-} \leq \sqrt{\frac{2d_i(a_{i+1} - a_i)}{a_{i+1} a_i}} \tag{9}$$

Proposition-2

Safe breaking Probability Q justifies

$$Q^* = \prod_{i=1}^{N-1} [1 - (1 - p_i)^{\lceil \frac{\tau^i_{max}}{T} \rceil}] \leq Q \tag{10}$$

given that $\tau^i_{max} \geq T$ holds for each i

Condition $\tau^i_{max} \geq T$ reflects the fact that at least one packet transmission attempt should be possible to get accomplished within a feasible delay region.

Numerical Results

A V2V platooning protocol is currently being developed within the European research project ENSEMBLE

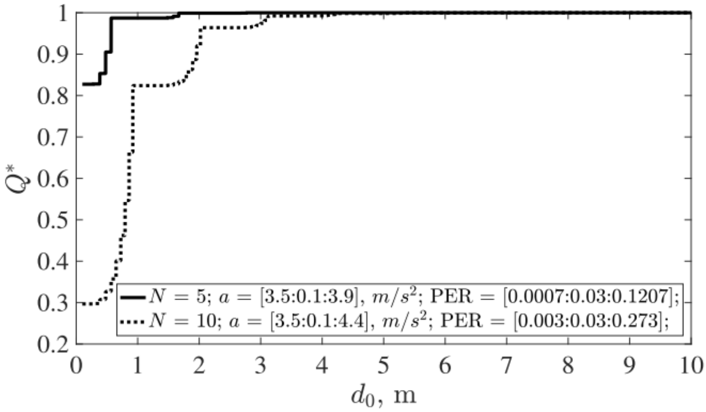


Figure: Platoon ordering($a_1 < ... < a_i < ... < a_N$) $V_0 = 22m/s, f = 20Hz$

In above figure

1. vehicles are ordered according to their increasing braking capability a_i.
2. results that even in shorter distance between the vehicles to reach Q close to 1.

The communication scenario in a platoon exhibits in general low PER due to that at least two antennas will be used on each truck, mounted on each side of the cabin or in the wing mirrors.
$\implies$ more or less always line-of-sight between transmitter and receiver antennas and given the default output power results in a favorable communication environment

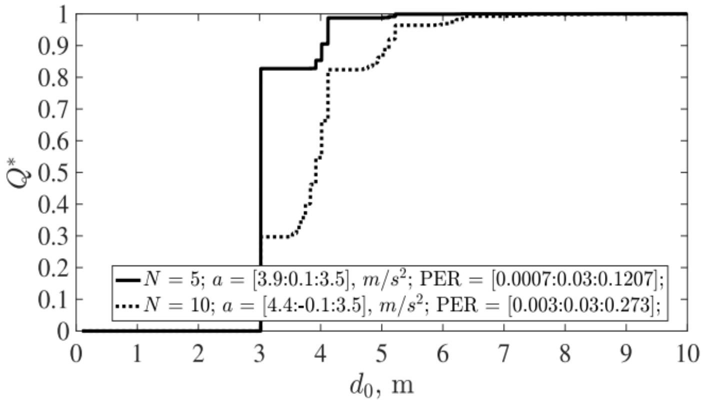


Figure: Platoon ordering($a_1 > ... > a_i > ... > a_N$) $V_0 = 22m/s, f = 20Hz$

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Both Figures demonstrates the lower bound on the safe braking probability, Q, for different inter-vehicular distances $d_1 = \cdots = d_N = d_0$

In above figure

1. the vehicles are ordered reversely in terms of braking capability a_i
2. results in that longer distances are a necessity between the trucks to reach a safe braking capability close to 1

Conclusion

1. Platooning holds great promise of increasing both road traffic safety as well as efficiency but the functional safety analysis of it is still benighted
2. The framework is used to evaluate the platooning protocol approach developed in the research project ENSEMBLE.Our numerical and analytical results reveal that the ENSEMBLE approach can reach a safe emergency braking probability close to 1.