Towards Emergency Braking as a Fail-Safe State in Platooning: A Simulative Approach

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***Abstract*— Platooning is anticipated to facilitate automated driving even with semi-automated vehicles, by forming road trains using breadcrumb tracing and Cooperative Adaptive Cruise Control (CACC). With CACC, the vehicles coordinate and adapt their speed based on wireless communications. To keep the platoon fuel-efficient, the inter-vehicle distances need to be quite short, which requires automated emergency braking capabilities. In this paper, we propose synchronized braking, which can be used together with existing CACC controllers. In synchronized braking, the leading vehicle in the platoon does not brake immediately, but instead communicates its intentions and then, slightly later, the whole platoon brakes simultaneously. We show that synchronized braking can avoid rear-end collisions even at a very high deceleration rate and with short inter-vehicle distances. Also, the extra distance travelled during the delay before braking can be compensated by enabling a higher deceleration, through coordinated synchronized braking.**

I. Introduction

Platooning has the potential to enable autonomous driving already with SAE automation level-3 vehicles [1]. A platoon is a group of autonomous or semi-autonomous vehicles driving together with a short inter-vehicle distance to achieve a common goal, e.g., enhancing fuel efficiency, road throughput, safety, operating cost etc.

Although the technical feasibility of platooning has been practically tested e.g., EU Truck Platooning Challenge 2016, its safety is still constrained by two main challenges: maintaining a short inter-vehicle gap and transient errors due to unreliable wireless communication. If the gap is short enough to enable fuel efficiency, a human driver will not have enough time to react in case of emergency [2]. Hence, automated emergency braking is required to enable a fail-safe state. A fail-safe state implies a state that will cause no harm to equipment, environment or people, and is triggered in the event of system failure or emergency. In order to avoid rear-end collisions, the platoon members are required to be informed about the emergency in a timely and reliable manner via wireless communication. It should be noted that the tolerable communication delay decreases when the deceleration rate increases, which may be essential for emergency braking [3]. This paper aims at addressing these challenges by proposing and analyzing an emergency braking strategy termed *synchronized braking* with the aim to provide a fail-safe state which can be used in case of road-hazards or autonomous system failures. In synchronized braking, the leading vehicle communicates its intentions before braking. Moreover, the braking itself is slightly delayed, which enables the information to be broadcasted to the entire platoon, even in case of short transient communicate errors, such that the entire platoon can brake simultaneously, using a higher deceleration rate.

Vehicle to Vehicle (V2V) communication is a key enabling technology in platooning applications for exchanging information, such as braking commands, acceleration, speed, steering angle, position etc. In this paper, we base the communication on the two message types proposed by the European Telecommunications Standards Institute (ETSI) namely: Cooperative Awareness Message (CAM) [4] and Decentralized Environmental Notification Message (DENM) [5]. CAMs include location, speed, and acceleration, whereas DENMs are generated when an event of common interest occurs, and spread within an area of interest for the duration of the event. In the braking strategy proposed in this paper, the platoon leader broadcasts DENMs to its following vehicles to perform synchronized emergency braking. The *synchronized braking* strategy has been implemented in conjunction with the state-of-the-art controllers CACC [6] and PLOEG [7], and extensive simulations shows that it cannot only avoid rear-end collisions, but also brings the platoon into a fail-safe state fast.

The rest of the paper is organized as follows: Section II outlines the background and related works on different platoon controllers and Collision Avoidance Systems (CAS). Section III details our synchronized braking strategy, whereas Simulations and performance evaluation details are given in Section IV. Finally, Section V concludes the paper.

II. Background and Related Work

Radar and sensor based systems such as Adaptive Cruise Control (ACC) without the use of communications, requires maintaining a long inter-vehicle distance [7], [8], making them less suitable for fuel-efficient platooning applications. Using CACC, where the Connected and Automated Vehicles (CAVs) can share vehicle parameters through inter-vehicle communications in order to form vehicle trains enables shorter inter-vehicle distances, such that higher fuel efficiency is obtained. Several Collision Avoidance Systems (CASs) are available in the literature. One solution is to instruct the last vehicle to brake at the highest deceleration rate, and then gradually decreasing the rate upstreams [9]. In [10], the authors studied the possibility of accelerating to avoid rear-end collisions. The authors in [11] propose to adjust to the vehicle with the weakest breaking capability. The idea is that when a vehicle joins the platoon, if its braking capability is lower than that of the

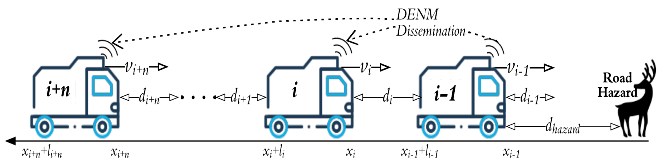


Fig. 1. Platoon model.

other vehicles, then the whole platoon adjusts its maximum deceleration rate to the weakest one. However, these strategies do not exploit the benefits of V2V communication, nor do they utilize the maximum braking capacity which can be indispensable in the event of emergency.

Ploeg *et al.* proposed a CACC controller based on vehicle error dynamics [7]. The design of this controller emphasizes string stability and takes the communication delay in V2V communication into consideration. The theoretical analysis in this work suggests a time headway of 0.67 seconds for a communication delay of 150 ms. Test results show that a platoon of length six can exhibit string stable behavior for the suggested time headway. The authors in [6] propose a CACC controller based on classical control theory that relies on V2V communication of speed and acceleration of both the leader and the preceding vehicle aiming to maintain a desired gap (gap_{des}). This controller can reach a time headway as short as 0.2 s in ideal scenarios and still maintain string stability. In this paper, we incorporate the synchronized braking strategy in these controllers, and demonstrate its benefits over normal braking in dense traffic scenarios.

III. Synchronized Braking Strategy

A. Platoon Model

Let us consider a homogeneous platoon where the i^{th} vehicle is moving at a constant speed of v_i as illustrated in Figure 1. Here, x_i and l_i are the position of the front bumper and the length of the i^{th} vehicle respectively. The desired distance D_i^{des} between the i^{th} vehicle in the platoon and its predecessor $i-1$ can, according to [12], [7] be given by:

$$D_i^{des}(t) = D_i^{st} + h_t v_i(t), \tag{1}$$

where, D_i^{st} is the distance at standstill and h_t is the constant *time headway* defined as the time required by the front of the i^{th} vehicle to reach the point on the road where the front of its predecessor $i-1$ currently is. *Space headway* h_s, on the other hand, is the difference in position between the fronts of the i and $(i-1)^{th}$ vehicles which can be expressed as $x_{i-1}(t)-x_i(t)$. So, the actual distance d_i between the i and $(i-1)^{th}$ vehicle is:

$$d_i(t) = h_s(t) - l_{i-1}. \tag{2}$$

A platoon is said to have a rear-end collision if $d_i(t) < 0$. The space error ε_i of vehicle i can therefore be defined as the difference between the actual and desired distances:

$$\varepsilon_i(t) = d_i(t) - D_i^{des}(t). \tag{3}$$

Finally the velocity error $\dot{\varepsilon}_i$ of the i^{th} vehicle with respect to the leader can be formulated as:

$$\dot{\varepsilon}_i(t) = v_i(t) - v_L(t), \tag{4}$$

where, v_L is the velocity of the leader. While platooning, it is essential to have $\varepsilon_i(t)$ and $\dot{\varepsilon}_i(t)$ as low as possible to minimize the tracking error. While emergency braking, however, the necessary conditions for avoiding rear-end collision and the road hazard ahead are $d_i(t) > 0$ and $d_L \leq d_{hazard}$ respectively where d_L and d_{hazard} are the distance traversed by the leader since the braking maneuver started and the distance to the upcoming hazard respectively.

B. Protocol Description

The proposed braking strategy that we call *synchronized braking* can be used on top of the ETSI ITS-G5 protocol stack and does not require any expensive changes in the vehicle model or dynamics. The rationale behind the name is that when the leader detects a road hazard, it does not perform its braking maneuver immediately. Rather it disseminates DENM and waits for the following vehicles to be informed about the hazard so that the whole platoon can perform a synchronized braking as depicted in Figure 2. DENM is a facilities layer message which is initiated and terminated in the application layer of an ITS station. Upon detection of a hazard by the platoon leader, the transmission of DENMs is triggered in the application layer which is regarded as *AppDENM_trigger* in [5]. The data, such as event detection time, called *referenceTime*, position, DENM validity duration, repetition duration and interval etc., is passed down to the DEN basic service which provides APIs for DENM processing. In our scenario, the *T_O_validity*

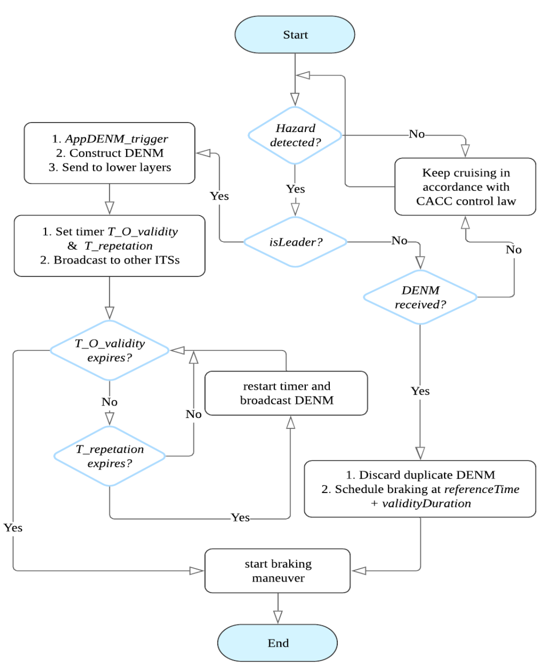


Fig. 2. Synchronized braking strategy.

TABLE I

CONFIGURATION PARAMETERS FOR SIMULATION ANALYSIS.

Category	Parameters	Value	Parameters	Value
Communication	Tx power	100 mW	Sensitivity	-94 dBm
	Thermal noise	-102 dBm	Path loss model	Free space (alpha = 2.0)
	Frequency	5.89 GHz	Bit rate	6 Mbps
	Packet size	200 B	Bit rate (non-platooning vehicle)	3 Mbps
Mobility	Leader speed	100 kmh^{-1} (27.778 ms^{-1})	No. of non-platooning vehicles	100
Synchronized braking	*brakeAtTime*	20 s	*repetitionInterval*	10 ms
	waitingTime	100 ms	*decelerationRate*	-12 ms^{-2}

timer is set to the waiting time that a platoon should pursue before they start their braking maneuver. In addition, DENM dissemination should be repeated during this entire waiting time which is specified by the parameters *repetitionDuration* and *repetitionInterval* in the application layer. After encoding and processing in the DEN basic service, the message is sent to the lower layers for broadcasting to the other platooning vehicles. Until the following vehicles receive a DENM, they keep cruising in accordance with the CACC control law. Upon receiving a message, the vehicles wait until the *referenceTime* + *T_O_validity* is expired. The referenceTime is the hazard detection time, and it is kept the same for all DENM repetitions as if the platooning vehicles can have the same *referenceTime* + *T_O_validity* despite the reception time of a DENM.

IV. SIMULATIONS AND PERFORMANCE EVALUATION

A. Simulation Settings

We have conducted simulation studies to analyze the behaviour of a platoon while performing emergency braking following the proposed synchronized braking strategy. To this end, we use Plexe [13], an OMNeT++ [14] based simulation platform built on top of Veins [15], which is specifically designed for VANET simulations. Several cruise controllers have been implemented in Plexe and we use the ones termed ACC, CACC [6] and PLOEG [7] to test together with our synchronized braking strategy. Recall, however, that in ACC no communication is involved, and thus it is not possible to implement synchronized braking here. A platoon of length eight has been simulated in the presence of 100 non-platooning vehicles which are located within the vicinity of the considered platoon. The non-platooning vehicles transmit IEEE 802.11p frames periodically for generating interference and increase contention. Most of the PHY and MAC layer parameters have been kept the same as in the Plexe simulator which follows the IEEE 802.11p standard, but some settings are altered and some new parameters are introduced as outlined in Table I.

B. Results And Analysis

The analysis begins with finding a suitable waiting time that a platoon should pursue to minimize the stopping time, but still being able to avoid rear-end collisions. To this end, we have carried out simulations for a number of waiting times 20, 40, 60, 80, 100, 150, 200 and 300 ms, 10 runs for each. For each run, the minimum inter-vehicle distance between any two vehicles in the platoon after it has come into complete standstill has been recorded and represented by the box plot

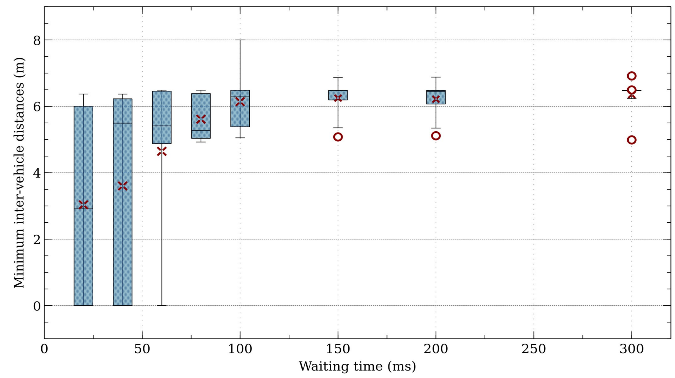
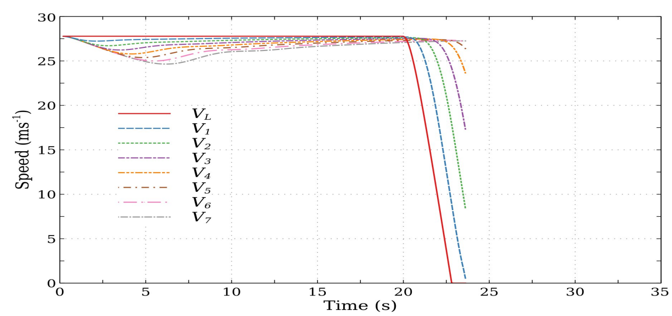
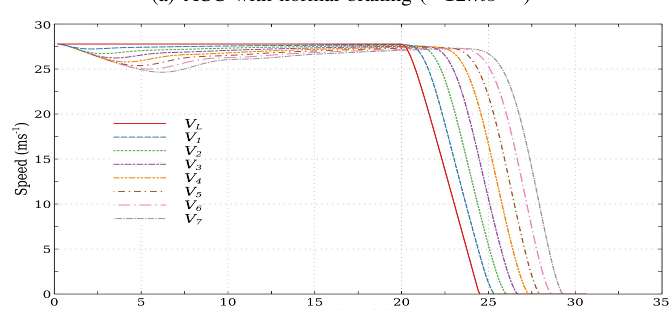


Fig. 3. Minimum inter-vehicle distances for different waiting times for a platoon of length 8 cruising at a speed of 100 kmh^{-1} with an initial inter-vehicle distance of 8 meters.

in Figure 3, in which x marks the mean and o marks outliers. In case there is a rear-end collision, the inter-vehicle distance is considered to be zero. The size of the Inter-Quartile range (IQR) represents how spread the data points are, which also reflects the platoon stability. In this case, the platoon started cruising at 100 kmh^{-1} with an initial inter-vehicle distance of 8 meters. For waiting times 20, 40 and 60 ms, there are collisions in the platoon for some runs. For a waiting time of 80 ms all 10 runs can avoid rear-end collision. For 100 ms or higher, we can observe even better average and shorter IQR. In the following analysis, all vehicles travel at 100 kmh^{-1} and wait 100 ms, and this corresponds to traveling 2.78 meters before starting synchronized breaking.

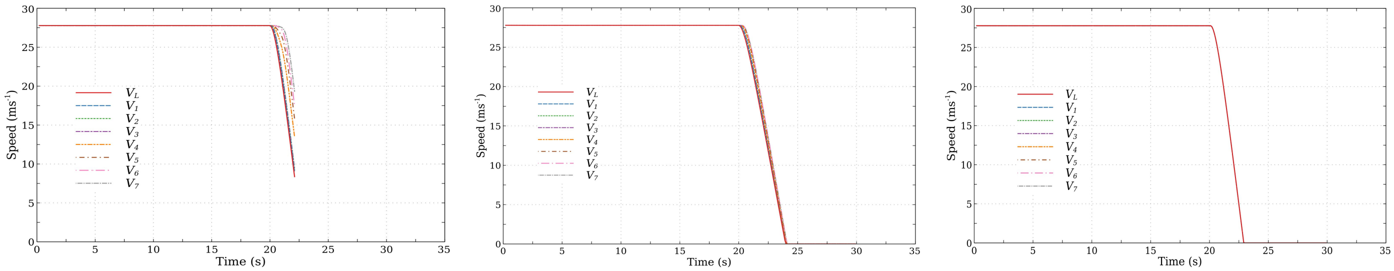


(a) ACC with normal braking ($-12ms^{-2}$)



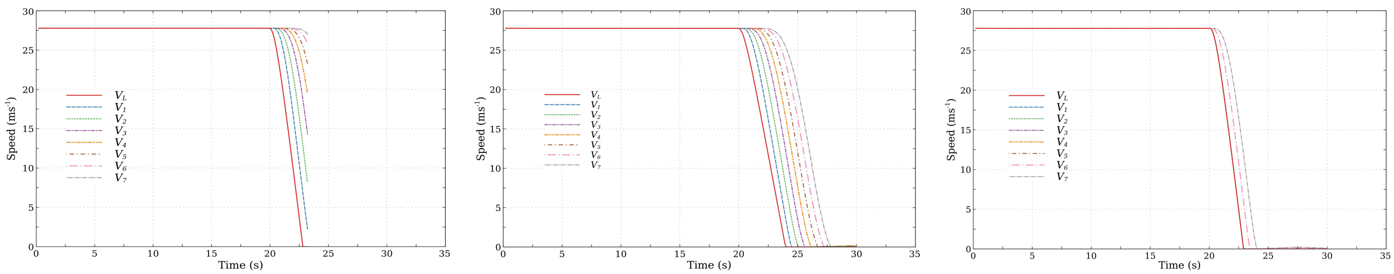
(b) ACC with normal braking ($-7ms^{-2}$)

Fig. 4. Speed profiles of platooning vehicles for ACC controller with an initial inter-vehicle distance of 19.45 meters and speed 100 kmh^{-1}.



(a) CACC with normal braking ($-12ms^{-2}$) (b) CACC with normal braking ($-8ms^{-2}$) (c) CACC with synchronized braking ($-12ms^{-2}$)

Fig. 5. Speed profiles of platooning vehicles for CACC controller [6] with an initial inter-vehicle distance of 5 meters and speed 100 kmh^{-1}.



(a) PLOEG with normal braking ($-12ms^{-2}$) (b) PLOEG with normal braking ($-8ms^{-2}$) (c) PLOEG with synchronized braking ($-12ms^{-2}$)

Fig. 6. Speed profiles of platooning vehicles for PLOEG controller [7] with an initial inter-vehicle distance of 15.889 meters and speed 100 kmh^{-1}.

For the sake of analyzing the performance of our synchronized braking strategy together with ACC, CACC and PLOEG controller, let us first look at their speed profiles as illustrated in Figures 4, 5 and 6. Note that the purpose of Figures 4-7 is not to analyze which controller performs better, as a qualitative analysis of this can be found in [16]. When using the simulation settings from Table I and initial inter-vehicle distances of 19.45, 5 and 15.889 meters for ACC, CACC and PLOEG respectively as suggested by the authors themselves [7], [8], all three controllers undergo rear-end collisions with normal braking at a deceleration rate of –12 ms^{-2} as illustrated in Figures 4(a), 5(a), 6(a) respectively. However, at a lower deceleration rate (–7ms^{-2} for ACC and –8ms^{-2} for CACC and PLOEG at their respective inter-vehicle distances) the controllers can avoid rear-end collisions using normal braking, Figures 4(b), 5(b), 6(b). The main reasons behind the collisions with normal braking using the CACC and PLOEG controllers are communication problems due to high interference from non-platooning vehicles which increases the time required to deliver DENMs to all vehicles. Segata *et al.* also reported that the tolerable communication delay decreases with the increase of deceleration rate in [3]. In case of synchronized braking as shown for CACC and PLOEG in Figures 5(c) and 6(c), all vehicles wait 100 ms but then complete their braking maneuver successfully even with a deceleration rate of –12 ms^{-2}. Recall that during the 100 ms delay, the leading vehicle will have traveled 2.78 meters, which is not visible in the time scale used in the figures. Due to the long inter-vehicle distances with PLOEG, the last two vehicles did not receive any DENM within the 100 ms waiting period and thus, completed the braking maneuver based only on the periodic beacons in accordance with the PLOEG control law.

In Table II, a quantitative analysis of how far the leader travels before stopping using the normal braking and the synchronized braking scenarios for different deceleration rates are presented. Although the platoon can avoid rear-end collisions for a normal braking scenario with lower deceleration rate, in case of using ACC, CACC or PLOEG controllers, it is obvious that the leader will traverse longer and thus, endanger the purpose of emergency braking. With synchronized braking, the gain of avoiding rear-end collision comes at the cost that the leader traverses 2.78 meters longer before braking due to waiting for 100 ms. However, the leader has to traverse 16.5 meters more by applying a lower deceleration rate in order to avoid rear-end collisions for normal braking using the CACC and PLOEG controllers, Table II. To further clarify the trade-offs between synchronized braking and the distance traversed by the leader, we have recorded the distances traversed by the leader in the simulator for different waiting times in the synchronized braking scenario and show them in Table III. For the normal braking scenario with no waiting time, the leader traverses 44.24 meters, and the platoon experiences rear-end collisions. Even for a waiting time of 500 ms in synchronized braking, the leader traverses a shorter distance in total (58.13 m) compared to the normal braking scenario (60.817 m), which needs to decelerate slower to avoid rear-end collisions.

TABLE II

DISTANCES TRAVERSED BY LEADER TO AVOID REAR-END COLLISIONS.

Controller	Normal braking scenario				Synchronized braking scenario	
	Deceleration rate (ms^{-2})	Distance traversed (m)	Deceleration required to avoid collision (ms^{-2})	Distance traversed (m)	Deceleration rate (ms^{-2})	Distance traversed (m)
ACC	-12	44.243	-7	67.827	-	-
CACC	-12	44.243	-8	60.817	-12	47.02m
PLOEG	-12	44.243	-8	60.817	-12	47.02m

TABLE III

DISTANCE TRAVERSED BY LEADER FOR DIFFERENT WAITING TIMES.

Synchronized braking	Waiting time (ms)	20	40	60	80	100	150	200	300	500
	Distance traversed (m)	44.70	45.35	45.90	46.46	47.02	48.40	49.79	52.57	58.13
Braking	Waiting time (ms)	0	0	0	0	0	0	0	0	0
	Distance traversed (m)	44.24	44.24	44.24	44.24	44.24	44.24	44.24	44.24	44.24

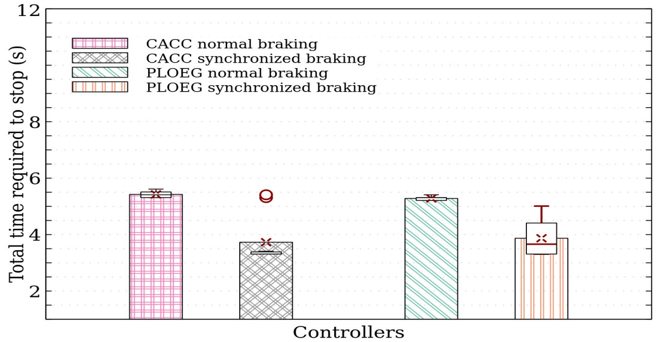


Fig. 7. Total time required for the platoon to come into complete standstill for different controllers.

TABLE IV
TOTAL TIME TO STOP FOR DIFFERENT WAITING TIMES.

Synchronized braking	Waiting time (ms)	20	40	60	80	100	150	200	300	500
	Time to stop (s)	4.53	5.06	4.88	4.54	3.72	3.45	3.53	3.73	3.85
	No. of collisions	3	2	2	0	0	0	0	0	0
Braking	Waiting time (ms)	0	0	0	0	0	0	0	0	0
	Time to stop (s)	5.43	5.43	5.43	5.43	5.43	5.43	5.43	5.43	5.43
	No. of collisions	3	3	3	3	3	3	3	3	3

In this part, we analyze the total time required for the whole platoon to come into complete standstill from the moment of detecting the road hazard, and we show that waiting for a certain period of time when using the synchronized braking strategy does not necessarily prolong the total time to stop. To this end, we have performed 10 simulation runs for the CACC and PLOEG controllers and recorded the average total time required to stop the platoon as illustrated in Figure 7 with the help of bars and boxplots. The number of platoon members is now six, the speed is 100 kmh^{-1} and the inter-vehicle distances are 5 and 15.889 meters for CACC and PLOEG controllers respectively, while the other parameters are set according to Table I. Synchronized braking outperforms normal braking in this respect as well. Moreover, the average of the total time to stop for different waiting times is presented in Table IV. The table also shows the number of runs for which the platoon has experienced rear-end collisions. For waiting times of 20, 40 and 60 ms, there has been collisions for some runs and the total stopping time is quite long. This is due to inadequate waiting time, i.e., one or two vehicles in the tail of the platoon fail to receive DENMs and either end up colliding or stop with the aid of regular periodic beacons and thus, take longer time. The main purpose of Table IV is to disclose that inadequate waiting time does not necessarily avoid rear-end collisions. So, if the danger imposed by a road hazard is so imminent that the leader cannot afford to traverse a few more meters despite the fact that synchronized braking can possibly eradicate rear-end collisions and ensure fail-safety, then it might be appropriate to brake immediately.

V. Conclusion and Future Work

We have presented and analyzed synchronized braking, and showed that it can avoid rear-end collisions even for a platoon with short inter-vehicle distance which brakes with high deceleration. With synchronized braking, which can be used together with existing CACC controllers, the leading vehicle in the platoon does not brake immediately, but first communicates its intentions, after which the whole platoon brakes simultaneously. For a platoon cruising at 100 kmh^{-1}, waiting 100 ms before braking causes the leader to traverse 2.78 meters more while waiting, but the small delay increases the chance of DENMs to be received successfully by all vehicles, and the synchronized braking maneuver enables using a higher deceleration rate such that the over-all stopping time of the platoon is still 16.5 meters lower than braking such that rear-end collisions are avoided without using communications. As future work, some state-of-the-art CAS will be implemented in Plexe in order to carry out a comparison analysis with the proposed synchronized braking.

VI. Acknowledgement

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