Citation for the original published paper:

S. Hasan, S. Girs and E. Uhlemann, "Cooperative Automated Emergency Braking for CAVs under Time-Varying Communication Delays," *2023 IEEE International Automated Vehicle Validation Conference (IAVVC)*, Austin, TX, USA, 2023, pp. 1-7, doi: 10.1109/IAVVC57316.2023.10328108.

Cooperative Automated Emergency Braking for CAVs under Time-Varying Communication Delays

Shahriar Hasan, Svetlana Girs, Elisabeth Uhlemann
School of Innovation, Design and Engineering, Mälardalen University, Västerås, Sweden
E-mail:{shahriar.hasan, svetlana.girs, elisabeth.uhlemann}@mdu.se

Abstract—**Connected and Automated Vehicles (CAVs) have the potential to significantly improve road safety, fuel efficiency, and traffic flow by forming platoons with short inter-vehicle gaps, enabled by vehicle-to-vehicle communications and onboard sensors. However, wireless connectivity for CAVs is subject to time-varying delays, which can significantly impact platoon safety during emergency braking. To this end, this paper evaluates the communication delays incurred by platoon vehicles during emergency braking under various data and traffic densities. Additionally, an emergency braking strategy named adaptive emergency braking is proposed and compared with five other strategies based on their ability to meet the functional requirements of collision avoidance and minimizing the stopping distance of the platoon lead vehicle, which are crucial for transitioning a platoon to a fail-safe state. Moreover, the emergency braking strategies are evaluated through rigorous simulations, considering non-functional criteria such as required inter-vehicle gaps, maximum allowable deceleration rates, and their robustness under time-varying communication delays.**

I. INTRODUCTION

Platooning is a promising application of Connected and Automated Vehicles (CAVs) that has garnered significant attention from the automotive industry and traffic authorities worldwide [1]. In platooning, a Lead Vehicle (LV) leads a group of Following Vehicles (FVs), which rely on Vehicle-to-Vehicle (V2V) communications and sensors to track the LV's movements in both the lateral and longitudinal directions. The LV periodically transmits *time-triggered messages* containing essential data, including its position, speed, acceleration, and steering angle, to enable the FVs to maintain autonomous control. In case of an emergency, the LV can send out *event-driven messages* to trigger, e.g., emergency braking, specifying the hazard's type and severity, when and how to brake, and the necessary deceleration rate to avoid the hazard. These event-driven messages must be delivered with high reliability to all vehicles in the area of interest and, therefore, are repeated periodically at a certain frequency for the duration of the event. *Frequency* (Hz) can be defined as the number of times time-triggered or event-driven messages are transmitted per second.

In order to enable the platooning benefits, such as fuel efficiency, road efficiency, traffic flow, etc., the FVs require maintaining short inter-vehicle distances [2], which puts high demands on wireless connectivity and, consequently, platoon safety. In particular, if a platoon encounters a hazard, emergency braking requires successful avoidance of inter-vehicle collisions and the hazard, which depends on factors such as the initial inter-vehicle gaps, wireless connectivity, speed, as well as the required deceleration rate to avoid the hazard. Examples of hazards in a platoon include stalled vehicles or accidents on the road, sudden appearance of debris or animals, emergency braking by a vehicle in front, inclement weather conditions reducing visibility and increased risk of collisions, and more. Under such circumstances, there is limited room for maneuvering or steering away from the hazard, as the vehicles are closely coupled [3]. To this end, cooperative and automated emergency braking is essential to transition a platoon to a known *safe state* called the *fail-safe* state to prevent the harm posed by platoon-related hazards, e.g., harm to the environment, people, or equipment. To avoid a hazard and enact the conditions of a fail-safe state [4], the functional requirements are that *inter-vehicle collisions* within the platoon must be avoided and that the *stopping distance to the LV* needs to be smaller than the distance to the hazard.

Cooperative and automated braking in platooning heavily relies on wireless communications, which are prone to experiencing time-varying communication delays. Specifically, communication delays refer to the elapsed time between two successful receptions of packets of the same type, i.e., either time-triggered or event-driven. *Packet drops are the primary cause of communication delays* in wireless communications. When one or more packets are dropped, a vehicle requires waiting longer for the next update, which results in a delay. Packet drops can be caused by various factors, including *path loss* due to the increasing distance between the transmitter and receiver, multipath propagation resulting in *signal fading*, *interference* from multiple devices transmitting in the same frequency band, and multiple devices trying to access the same shared medium, among others. These time-varying communication delays significantly impact the inter-vehicle distances that can be maintained during platoon cruising or at the time of emergency braking and the maximum deceleration rate that can be utilized for emergency braking [4]. However, the evaluation of emergency braking strategies under *functional criteria*, such as collision avoidance and minimizing stopping distance of the LV, and *non-functional criteria*, including initial inter-vehicle gaps, attainable deceleration rate, and robustness under time-varying delays, is currently missing in the literature.

To this end, this paper conducts rigorous simulations under various levels of data and road traffic scenarios to determine the communication delays that platooning vehicles incur during emergency braking. The simulation results inspire us to propose an emergency braking strategy called Adaptive

Emergency Braking (AEB), which aims to avoid collisions during emergency braking and adapt the stopping distance of the LV as a function of both the distance to the hazard and the communication delays experienced by platoon vehicles. Furthermore, we evaluate the AEB strategy under the functional criteria to determine its efficacy in transitioning a platoon to a fail-safe state and under non-functional criteria to determine the initial inter-vehicle gaps and deceleration rates that facilitate safe emergency braking. Finally, we quantitatively compare six different braking strategies, including AEB, under fail-safe conditions (functional criteria) and scenarios where the platoon uses different initial inter-vehicle gaps with different controllers and emergency braking is conducted in the presence of time-varying communication delays (non-functional criteria).

The paper is structured as follows: Section II provides background on platoon controllers and describes the state-of-the-art braking strategies. After that, the communication delays incurred by platooning vehicles under different network and data traffic loads are demonstrated in Section III. The proposed AEB strategy is then presented in Section IV, followed by the evaluation of AEB and state-of-the-art braking strategies in Section V. Finally, Section VI concludes the paper.

II. BACKGROUND AND RELATED WORKS

During cruising, a platoon maintains a certain speed and specific inter-vehicle gaps, which are regulated by a controller. In sensor-based controllers like Adaptive Cruise Control (ACC) [5], a vehicle uses radar or lidar sensors to maintain a Constant Time Gap (CTG) with its front vehicle by measuring relative distance and speed. In CTG policy, inter-vehicle gaps in meters change with speed but remain constant in seconds. When V2V communications are added on top of ACC, it becomes Cooperative Adaptive Cruise Control (CACC). CACC laws are broadly categorized into two strategies: Predecessor-Following (PF) and Leader-Predecessor-Following (LPF). PF-CACC, such as [6], computes an ego vehicle's acceleration and maintains a certain CTG based on information obtained from its preceding vehicle through V2V communications and onboard sensors. In contrast, LPF-CACC, such as [7], requires information from both the LV and the preceding vehicle through V2V communications (in addition to sensors) to compute the ego vehicle's desired acceleration. LPF-CACC maintains a Constant Distance Gap (CDG) within a platoon, meaning that inter-vehicle gaps in meters remain unchanged with speed changes.

If the LV detects a hazard in a platoon, and the FVs begin braking as soon as they receive information from the LV, preceding vehicle, and/or onboard sensors, it is referred to as *Normal Braking (NB)* in this paper. With the NB strategy, different vehicles can have different deceleration rates to avoid collisions. For instance, Zheng *et al.* [8] conducted experimental studies with actual vehicles in which the deceleration rates of the lead, middle, and last vehicles were –4.4, –5.0, and –6.5 ms^{-2}, respectively. This way of arranging vehicles according to the decreasing order of deceleration rates in the downstream direction of a platoon is regarded as *Gradual Deceleration (GD)* strategy in this paper.

In contrast to the NB and GD strategies, the *Synchronized Braking (SB)* strategy proposed in [9] involves a waiting period of τ_{wait} before braking upon receiving a hazard notification. Once the τ_{wait} period expires, the entire platoon synchronously applies brakes at the same deceleration rate. In the Enhanced Synchronized Braking (ESB) strategy proposed by the authors [4], platooning vehicles perform soft-braking at a slower rate until the expiration of the τ_{wait} period in the SB strategy. Once the τ_{wait} period is over, all vehicles interrupt their soft deceleration and start braking at the full deceleration rate. The rationale for waiting until the τ_{wait} period with the SB and ESB strategies is to eliminate the effects of communication delays during emergency braking, as suggested in [10].

Bergenhem *et al.* proposed the Cooperative Emergency Braking Protocol (CEBP) in [11], in which the last vehicle in the platoon initiates braking first, and the LV brakes last. In this strategy, the LV broadcasts event-driven messages, and the last vehicle initiates braking when it receives the first message. The last vehicle then broadcasts Acknowledgements (ACKs), and its preceding vehicles, including the LV, perform emergency braking upon receiving an ACK from the immediate FV. Therefore, with the CEBP strategy, every vehicle starts braking upon receiving an ACK from the immediate successor. Magdici *et al.* propose a braking strategy in which the deceleration rate of an ACC-enabled vehicle is exponentially decreased until full deceleration is achieved [12]. Ligthart *et al.* build on this strategy by adding a PF communication strategy in [13]. Murthy and Masrur propose the law of the weakest, i.e., all the platoon vehicles match their deceleration rates to the vehicle with the weakest braking capacity [14]. However, these braking strategies mainly focus on collision avoidance, overlooking the stopping distance of the platoon LV, which is crucial for hazard avoidance.

While various braking strategies exist in the literature with different focuses, such as collision avoidance, minimizing stopping distance, or driver comfort, additional constraints must be considered for platoon emergency braking. In particular, the need to minimize the stopping distance of the LV to avoid the hazard, short inter-vehicle gaps to ensure traffic safety and efficiency, and robustness against time-varying delays. Although individual strategies, such as [8], [11], or [14], may satisfy one or two of these constraints, a comparative evaluation of these strategies under all constraints is lacking in the literature. This paper aims to address this gap and also proposes an improvement to the CEBP strategy that considers both functional and non-functional requirements of platoon emergency braking. A portion of this work was presented in the technical report [15] by the author.

III. COMMUNICATION DELAYS INCURRED BY PLATOONING VEHICLES DURING EMERGENCY BRAKING

This section presents simulation results to demonstrate the communication delays experienced by platooning vehicles

TABLE I: Configurations for varying the channel load.

Configuration no.	Neighbouring traffic				Message frequency (Hz)		
	vehicles	vehicles/km	beacon frequency (Hz)	packets $s^{-1}km^{-1}$	CAM	DENM	ACK
Config 1	500	95	40	3800	20	20	20
Config 2	400	95	50	4750	10	10	10
Config 3	400	95	50	4750	10	50	50
Config 4	300	65	30	1950	15	15	15
Config 5	300	65	20	1300	15	15	15
Config 6	150	65	10	650	15	15	15
Config 7	50	36	10	360	10	10	10
Config 8	0	0	0	0	10	10	10

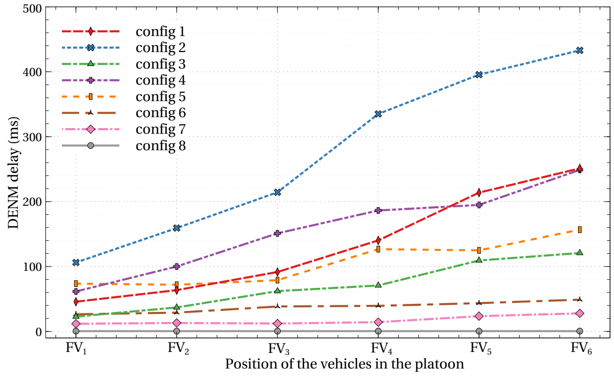

Fig. 1: Average DENM delays for different configurations.

during emergency braking. To this end, the configurations in Table I are introduced to generate various data and road traffic scenarios under which a platoon may have to operate. Moreover, a platoon of seven vehicles cruising with LPF-CACC and a 5 m gap is assumed. The simulations consider the Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs) specified by the European Telecommunications Standards Institute (ETSI) as periodic beacons and event-driven messages, respectively [16]. Moreover, the IEEE 802.11p Medium Access Control (MAC) protocol [17] is considered. We also assume that the platoon brakes with the CEBP strategy 20 s into the simulation time, and the average of 100 simulation runs are calculated to determine the DENM and ACK delays experienced by different vehicles. These delays are defined as:

- The *DENM delay* is the elapsed time between the LV broadcasting the first DENM upon detecting a road hazard and an FV receiving its first DENM. This delay is incurred only by the FVs in the platoon.
- The *ACK delay* refers to the time elapsed between the LV broadcasting the first DENM and the first ACK received from the immediate successor. In the CEBP strategy, the last vehicle in the platoon starts broadcasting ACKs upon receiving the first DENM, and the FVs relay the ACKs up to the LV. Hence, the ACK delay applies to all vehicles in the platoon except the last vehicle.

DENM delay: Fig. 1 presents the average DENM delays experienced by the FVs in the platoon under different scenarios listed in Table I. It can be observed that the rear vehicles in the platoon experience higher DENM delays due to the increasing effects of path loss and fading, leading to more packet losses. Table II shows the average number of repetitions required for the FVs to receive the first DENM, indicating that *packet drops are the primary reason for high DENM delays*. Config 1 exhibits significantly lower DENM delays than Config 2 due to a higher DENM frequency and lower data traffic density. A similar trend can be observed with Config 3, which has the same neighboring traffic density as Config 2 but a higher DENM frequency. The results demonstrate that a higher DENM frequency reduces DENM delay since repetitions come faster in case of lost packets. While Configs 1 and 3 have a higher number of packet losses than Config 2, the higher DENM frequency compensates for the packet losses. DENM delays for Configs 4 and 5 reflect the impact of data and vehicle densities of the neighboring traffic. Config 4 has a significantly higher DENM delay than Config 5 due to the waiting time for channel access. Configs 6 and 7 exhibit an acceptable level of DENM delay due to fewer packet drops caused by lower vehicle and data densities. Finally, Config 8 represents an ideal case with no packet losses.

TABLE II: The average no. of repetitions before reception.

Config / FV_i	Config 1	Config 2	Config 3	Config 4	Config 5	Config 6	Config 7	Config 8
FV_1	0.84	1.02	0.9	0.87	1.01	0.42	0.08	0
FV_2	1.19	1.55	1.62	1.37	0.99	0.47	0.18	0
FV_3	1.75	2.1	2.88	2.09	1.05	0.58	0.18	0
FV_4	2.73	3.31	3.35	2.57	1.73	0.6	0.19	0
FV_5	4.2	3.91	5.26	2.74	1.76	0.65	0.25	0
FV_6	4.94	4.29	5.83	3.49	2.2	0.68	0.25	0

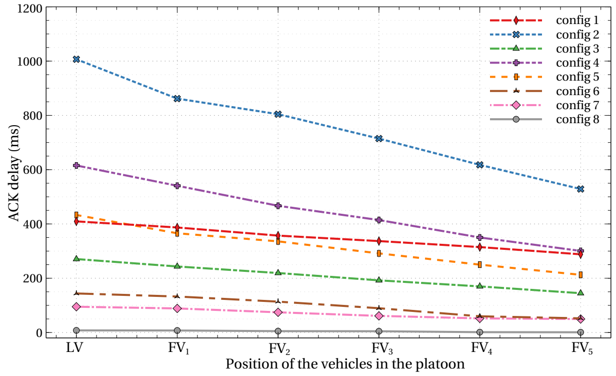

Fig. 2: Average ACK delays for different configurations.

ACK delay: The results of ACK delays for the platooning vehicles are presented in Fig. 2. The LV experiences the highest ACK delay as the ACK packets are sequentially relayed by every vehicle up to the LV. The ACK delay is measured as the time between broadcasting the first DENM and receiving the first ACK from the immediate successor. The ACK delays for the LV in configurations 1–8 are 409.45, 1006.8, 270.6, 615.47, 432.98, 143.89, 94.97, and 7.79 ms, respectively. The results suggest that the ACK delay is largely influenced by the number of vehicles in the platoon and the neighboring traffic's vehicle and data densities.

IV. ADAPTIVE EMERGENCY BRAKING (AEB)

The results above clearly highlight the impact of data density induced by neighboring traffic on communication delays. Therefore, designing emergency braking strategies for

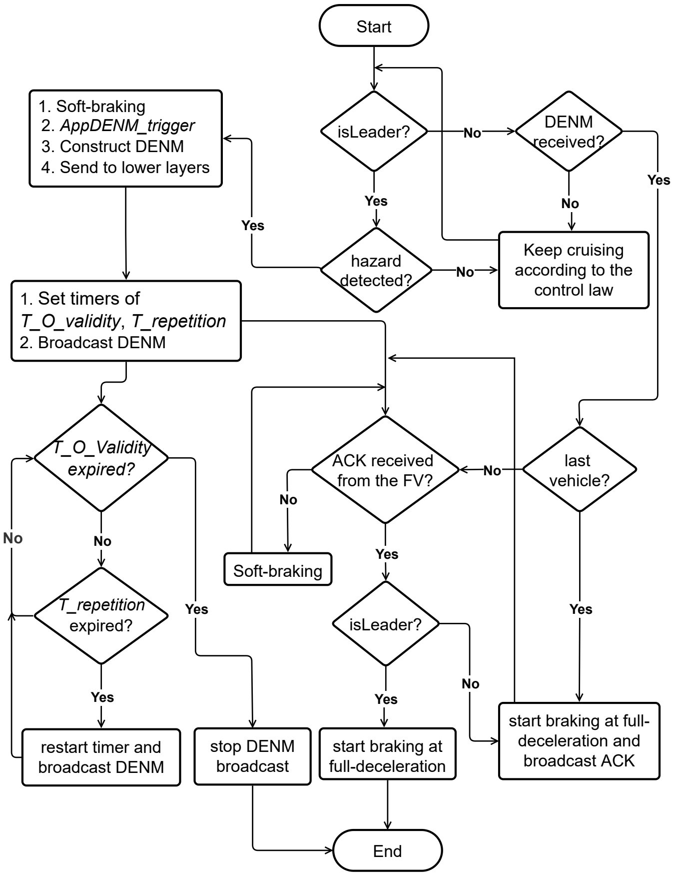

Fig. 3: Adaptive Emergency Braking strategy.

safety-critical systems such as platooning while only considering communication scenarios like Config 8 in Table I is inadequate. Additionally, DENM and ACK delays can be significantly high in dense data and road traffic scenarios, as can be seen in Figs. 1 and 2, and such delays cannot be known in advance due to the non-deterministic channel access delays with IEEE 802.11p protocol [17]. Therefore, remaining idle instead of braking until the duration of ACK delays, as done in the CEBP strategy, can lead to a significant increase in the stopping distance of both the LV and the platoon as a whole. Thus, we propose the AEB strategy that leverages the DENM and ACK delays to fulfill the following *fail-safe conditions* [4]:

1) The inter-vehicle distances (m) between any two platooning vehicles must be greater than zero at a complete standstill.
2) The stopping distance of the LV (m), i.e., the distance traversed from when the LV detects a hazard until it completely stops, must be less than the distance to the hazard.
3) The total time to stop the whole platoon (s) since hazard detection should be sufficiently low to ensure a fast transition to the fail-safe state.

The AEB algorithm presented in Fig. 3 adheres to the specifications of the ETSI Decentralized Environmental Notification (DEN) basic service [18], which defines applications for Road Hazard Warning (RHW). In AEB, when the LV detects a hazard, it constructs DENMs and sends them to the lower layers for broadcasting; in the meantime, it starts soft braking. In addition, the *T_O_validity* and *T_repetition* timers are activated that define the DENM broadcast duration and the DENM repetition interval, respectively. When an FV in the platoon, except the last vehicle, receives a DENM, it also starts soft braking. The last vehicle does not perform soft braking when it receives a DENM; instead, it starts braking at a full deceleration rate and broadcasts ACK packets at the same interval as the DENMs. When the second to last vehicle receives an ACK from the last vehicle, it interrupts its soft braking and starts full deceleration. This way, the ACK packets are relayed by every hop in the upstream direction of the platoon up to the LV, and every vehicle on the way starts full deceleration upon receiving an ACK from its immediate successor.

TABLE III: Simulation settings and parameters.

Parameter	Value	Parameter	Value
Path loss model	Free space ($\alpha = 2$)	Fading model	Nakagami-m (m = 1.86)
PHY/MAC model	802.11p/1609.4	Frequency	5.89 GHz
Sensitivity	-94 dBm	Thermal noise	-95 dBm
Packet size	200 B	Tx power	100 mW
Platoon size	7	BrakeAtTime	70 s
softDecelerationRate	$-3\ ms^{-2}$	fullDecelerationRate	$-8\ ms^{-2}$
τ_{wait}	1.12, 0.433 s	simulation time limit	80 s

TABLE IV: Time gaps (s) expressed in meters at 100 kmh^{-1} speed.

time gap (s)	0.2	0.3	0.4	0.5	0.6	0.8	1.0
gap (m)	7.5	10.3	13.1	15.8	18.6	24.2	29.7

Notice that the LV starts soft braking first, but it performs full deceleration last. Moreover, full deceleration is only initiated upon receiving an ACK packet except for the last vehicle, whereas DENM triggers soft deceleration, also except for the last vehicle. The last vehicle directly performs full deceleration on DENM. We must also ensure that a full deceleration maneuver is not interrupted by soft deceleration if a vehicle already receives an ACK while preparing the brake. To this end, the algorithm first checks if a vehicle has already received an ACK.

V. EVALUATION OF EMERGENCY BRAKING STRATEGIES

In this section, we first describe the simulation scenario and settings during platoon cruising and emergency braking. We then evaluate the AEB strategy under Config 1 in Table I, followed by the evaluation and comparison of the state-of-the-art braking strategies under Config 2.

A. Simulation Scenarios and Settings

We evaluate the braking strategies using PlatoonSAFE [19], an open-source simulation tool for evaluating platoon safety under realistic wireless communication, vehicle dynamics, and road traffic scenarios. The emergency braking strategies evaluated in this paper are made available in PlatoonSAFE to induce reproducibility and verifiability of the presented results. The simulation parameters used for evaluation are listed in Table III.

We consider the same platoon as in Section III consisting of seven vehicles and cruising at a speed of 100 kmh^{-1}.

TABLE V: *Minimum inter-vehicle gaps* d_{min} (m) upon emergency braking using AEB from different controllers and with different initial gaps; soft-deceleration rate = –3 ms^{-2}, full-deceleration rate = –8 ms^{-2}, speed = 100 kmh^{-1}, Config 1.

Initial States	LPF-CACC					PF-CACC					ACC				
Initial gaps	3 m	4 m	5 m	6 m	8 m	0.2 s	0.3 s	0.4 s	0.5 s	0.6 s	0.4 s	0.5 s	0.6 s	0.8 s	1.0 s
d_{min} (run 0)	3.15	3.57	3.07	4.77	6.08	5.17	6.6	9.84	12.26	13.05	8.09	15.88	13.31	14.44	25.14
d_{min} (run 1)	2.99	3.18	4.9	4.75	7.09	3.99	8.25	9.02	13.35	14.53	10.85	15.4	10.43	12.77	22.4
d_{min} (run 2)	2.37	3.57	3.07	5.27	7.8	5.29	8.6	10.39	13.51	13.47	10.68	10.5	10.58	14.06	14.18
d_{min} (run 3)	0.9	3.56	4.36	5.7	6.37	2.63	7.66	8.72	12.64	18.67	9.49	10.51	9.1	20.75	18.89
d_{min} (run 4)	2.65	2.25	3.71	5.7	5.1	4.29	6.82	11.58	11.25	14.67	10.07	10.54	12.36	12.01	19.4

TABLE VI: Average *stopping distance of the LV* S_l (m) for the same configurations as in Table V.

Initial States	LPF-CACC					PF-CACC					ACC				
Initial gaps	3 m	4 m	5 m	6 m	8 m	0.2 s	0.3 s	0.4 s	0.5 s	0.6 s	0.4 s	0.5 s	0.6 s	0.8 s	1.0 s
S_l (m)	70.74	71.77	67.02	72.82	69.6	65.75	64.15	73.35	72.24	72.12	70.73	71.49	75.03	82.5	83.73

TABLE VII: Average of the *total time to stop the whole platoon* t_{total} (s) for the same configurations as in Table V.

Initial States	LPF-CACC					PF-CACC					ACC				
Initial gaps	3 m	4 m	5 m	6 m	8 m	0.2 s	0.3 s	0.4 s	0.5 s	0.6 s	0.4 s	0.5 s	0.6 s	0.8 s	1.0 s
t_{total} (s)	4.41	4.43	4.25	4.43	4.35	4.41	4.71	4.99	4.67	4.49	4.41	4.51	4.71	5.23	5.11

During cruising, the platoon uses either ACC [5], PF-CACC [6], or LPF-CACC [7] controller. The simulations are carried out using different initial inter-vehicle distances with different controllers to evaluate how the proposed AEB strategy handles different gaps and changes in wireless connectivity due to changes in inter-vehicle gaps. The LV in the platoon encounters a simulated road hazard 70 seconds into the simulation time and starts disseminating DENMs. Emergency braking is carried out using either NB, ESB, SB, AEB, CEBP, or GD strategy. In the evaluation of the braking strategies, a homogeneous braking capacity is considered under the assumption that the platooning vehicles match their maximum deceleration rates during braking [14].

B. Evaluation of AEB under Config 1

This subsection evaluates the AEB strategy under fail-safe conditions using Config 1 in Table I. With Config 1, the vehicle density and data density are 95 vehicles/km and 3800 $s^{-1}km^{-1}$, respectively. The platooning vehicles initiate braking from either ACC, PF-CACC, or LPF-CACC, and the results with different initial gaps are presented. The initial gaps with ACC and PF-CACC are expressed in seconds due to following the CTG policy. For reader's convenience, the inter-vehicle gaps in meters at 100 kmh^{-1} for different CTGs are depicted in Table IV.

1) Minimum inter-vehicle gap at a full stop (m): Table V presents the minimum inter-vehicle gaps for five simulation runs using the AEB strategy, and a minimum gap greater than zero indicates that no collision has occurred. The results in Table V demonstrate no collisions with the AEB strategy for all initial inter-vehicle gaps. Note that the CEBP strategy also avoids collisions under these simulation configurations, but the results are not presented here for the sake of brevity. Instead, a comparative analysis is conducted in the next subsection. The results in Table V demonstrate that the AEB strategy inherits the collision avoidance property of the CEBP strategy. Unlike full deceleration, e.g., in NB, soft braking does not lead to collisions because an ego vehicle has more time to react to the deceleration of its preceding vehicle. Moreover, with the AEB strategy, if the information is missing from both the LV and the preceding vehicle, a vehicle can use onboard sensors to detect the deceleration of its predecessor, which is braking at a slow rate. The results in Table V demonstrate that the AEB strategy can brake without collisions even with short inter-vehicle gaps at the time of braking, which enables high fuel efficiency and road efficiency.

2) Stopping distance of the LV (m): Table VI presents the stopping distance of the LV (average of five simulation runs) for various gaps and controllers using the AEB strategy. In general, the LV has higher stopping distances with longer inter-vehicle gaps. The reason is that the rear vehicles experience longer delays due to increasing effects of path loss and fading with longer separation between the transmitter and the receiver; see Fig. 1. Additionally, full deceleration with the AEB strategy cannot commence until the last vehicle receives a DENM. Thus, shorter inter-vehicle gaps improve communication quality and allow the LV to receive an ACK from its immediate FV comparatively sooner, leading to shorter stopping distances. However, the results with the LPF-CACC in Table VI show that a 5 m gap results in a shorter stopping distance than a 3 m gap. This is likely an artifact of the small number of simulation runs, as the average of 100 simulation runs in Fig. 1 shows that communication delays increase with the separation between transmitter and receiver.

3) Total time to stop the whole platoon (s): Table VII presents the total time required to transition the entire platoon from cruising states, i.e., LPF-CACC, PF-CACC, or ACC, to a state in which vehicle speeds are zero. The results show that the total time to stop is lower when braking from LPF-CACC as compared to PF-CACC and ACC. This can be attributed

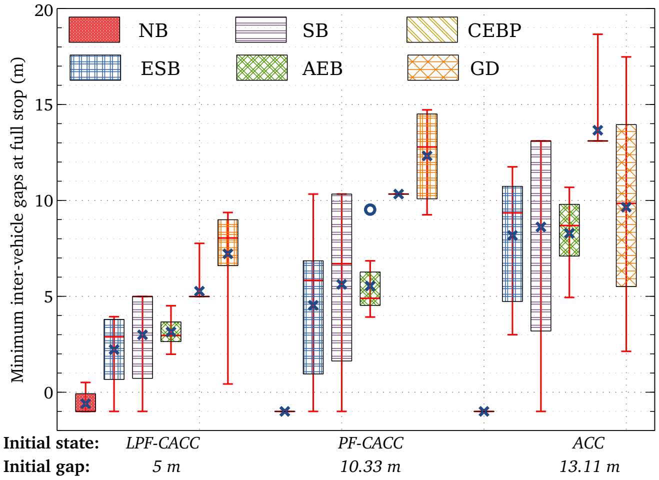

Fig. 4: Minimum gaps at a complete standstill (m).

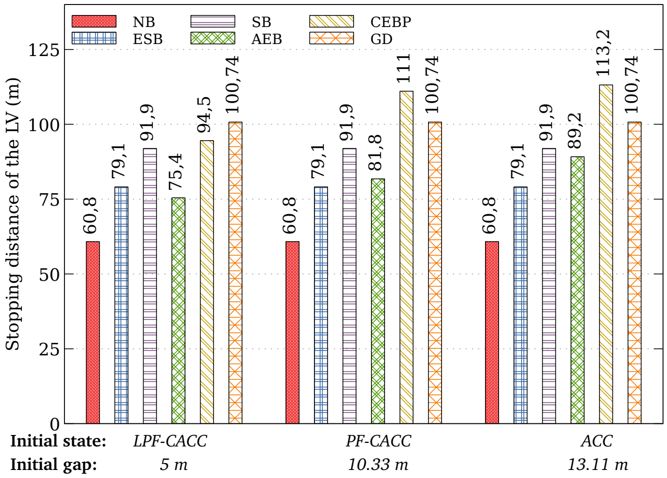

Fig. 5: Average stopping distance of the LV (m).

to the fact that when the platoon is braking from LPF-CACC, the last vehicle experiences lower communication delays due to shorter inter-vehicle gaps.

C. Comparative Evaluation between the Braking Strategies under Fail-Safe Conditions using Config 2

In this subsection, we conduct a quantitative evaluation of six different braking strategies under fail-safe conditions using Config 2 in Table I, which has a vehicle density and data density of 95 vehicles/km and 4700 $s^{-1}km^{-1}$, respectively. Config 2 is chosen because it represents the most challenging scenario in terms of experienced communication delays; see Fig. 1. The comparison is based on the assumption that the platoon starts braking at 70 seconds from either LPF-CACC, PF-CACC, or ACC controller, using one of the following six strategies, i.e., NB, ESB, SB, AEB, CEBP, or GD. We present the results of 10 simulation runs for each strategy. The full deceleration rate considered in the simulations is –8 ms^{-2}, and the soft deceleration rate is –3 ms^{-2} (applicable for ESB and AEB strategies only).

1) Minimum inter-vehicle gaps at a full stop (m): Fig. 4 illustrates the minimum inter-vehicle gaps at a complete standstill when the platoon employs different braking strategies while braking from various controllers. The results indicate that the NB strategy leads to collisions in all ten simulation runs when braking from PF-CACC and ACC with inter-vehicle gaps of 10.33 m and 13.11 m, respectively. In addition, when braking from LPF-CACC with a 5 m gap, the platoon undergoes collisions in seven out of ten simulation runs. The collisions occur mainly because the rear vehicles in the platoon, particularly the last three vehicles, experience considerably longer communication delays than the front vehicles, as shown in Fig. 1. As a result, when a front vehicle starts braking at –8 ms^{-2}, but the ego vehicle has not yet received a DENM, it cannot start braking fast enough to avoid collisions using only the onboard sensors because sensors have detection, processing, and actuation delays. The SB and ESB strategies improve the performance in terms of collisions by instructing the FVs to wait until the τ_{wait} period. However, there are still collisions with the SB and ESB strategies when the last vehicle experiences significantly longer communication delays than the τ_{wait} period. In contrast, Fig. 4 shows that the AEB, CEBP, and GD strategies result in no collisions in any of the simulation runs. Although the CEBP and GD strategies demonstrate the highest average minimum gaps at a complete standstill, this is not necessarily advantageous if it leads to a longer stopping distance for the LV. The AEB strategy leverages this long inter-vehicle gap left at a complete standstill to minimize the stopping distance of the LV. In Figure 4, see that the gaps at a complete standstill with the AEB strategy are shorter than with the CEBP and GD strategies, but there are no collisions.

TABLE VIII: Average total time to stop (s) the whole platoon.

total time to stop (s)	NB	ESB	SB	AEB	CEBP	GD
LPF-CACC	4.86	4.36	4.59	4.69	5.29	7.01
PF-CACC	6.62	4.92	5.49	5.47	5.98	7.01
ACC	7.41	4.92	5.34	5.01	6.24	7.01

2) Stopping distance of the LV (m): Fig. 5 illustrates the average stopping distances of the LV (m) using different braking strategies for the same simulations as in Fig. 4. The results reveal that the NB strategy has the shortest stopping distance as the vehicles start braking as soon as a DENM is received. However, this also leads to collisions, violating the first condition of a fail-safe state. The ESB strategy demonstrates a significantly shorter stopping distance than the SB strategy due to its soft deceleration before full deceleration. The proposed AEB strategy effectively reduces stopping distance while avoiding collisions, especially when braking from LPF-CACC with a short inter-vehicle gap. AEB demonstrates the second-lowest stopping distance when braking from LPF-CACC, and the LV has a 19.1 m shorter stopping distance than the CEBP strategy. When braking from PF-CACC and ACC with longer inter-vehicle gaps, the AEB and CEBP strategies exhibit longer stopping distances with the LV. The rationale is that with the AEB and CEBP strategies, a vehicle relies on ACK from the immediate FV in order to start full deceleration.

However, the AEB strategy still exhibits significantly lower stopping distances than the CEBP and GD strategies when braking from PF-CACC and ACC. Furthermore, since the AEB strategy can facilitate shorter inter-vehicle gaps with all controllers without compromising safety, it can be used to minimize the stopping distance of the LV even further by employing short gaps.

3) Total time to stop the whole platoon (s): Table VIII presents the average time required for the whole platoon to come to a complete stop. It can be observed that the time to stop the platoon is longer when braking from PF-CACC or ACC, where longer gaps lead to longer communication delays. The AEB strategy performs better than the CEBP strategy in terms of total time to stop the platoon. The rationale is that, unlike CEBP, the AEB strategy instructs the vehicles to perform soft braking instead of remaining idle, which improves communication quality and allows the whole platoon to transition to the fail-safe state more quickly. The GD strategy shows the same time to stop from all controllers because the LV with the GD strategy brakes at the same deceleration rate of –4.4 ms^{-2} in all cases.

VI. CONCLUSIONS

This paper proposes an emergency braking strategy called Adaptive Emergency Braking (AEB). Rigorous simulations are carried out to evaluate the communication delays incurred by platoon vehicles and the efficacy of the AEB strategy and five other braking strategies in avoiding collisions and minimizing the stopping distance of the Lead Vehicle (LV) under various initial gaps.

Our simulation results show that the rear vehicles in a platoon, which are the farthest away from the LV, experience longer communication delays due to path loss and fading effects. As a result, maintaining longer gaps in a platoon incurs longer delays in the rear vehicles, and only sensor data are available in such situations. If collisions are to be avoided by relying solely based on sensors, which have detection, processing, and actuation delays, the inter-vehicle gaps must be considerably high. On the other hand, shorter gaps can result in shorter response times and require procedures to mitigate the effects of experienced communication delays. Our analysis of braking strategies from the literature, such as CEBP and GD, shows that they are effective at collision avoidance but can result in longer stopping distances for the LV, which can be problematic if the hazard is imminent. The AEB strategy proposed in this study tackles this problem by directing the platoon vehicles to conduct soft braking during the experienced communication delays before performing full deceleration. Consequently, the reduction in stopping distance with AEB compared to CEBP becomes more substantial as the experienced communication delays increase. Moreover, the simulation results demonstrate that AEB is robust in terms of collision avoidance, even when braking from short inter-vehicle gaps. Therefore, when AEB is used during emergency braking, it can facilitate high fuel efficiency during platoon cruising. Furthermore, the SB and ESB strategies exhibit collisions when the experienced communication delays are significantly longer than the average waiting time. Therefore, an efficient way of forecasting the waiting times with the SB and ESB strategies is necessary. Finally, the NB strategy, i.e., braking as soon as a message is received, is unsuitable for emergency braking in a platoon when braking at a high deceleration rate from a high speed and when the experienced communication delays are high at the time of braking.

REFERENCES

[1] E. Uhlemann, "Platooning: Connected Vehicles for Safety and Efficiency [Connected Vehicles]," *IEEE VT Magazine*, vol. 11, no. 3, pp. 13–18, 2016.

[2] J. Axelsson, "Safety in vehicle platooning: A systematic literature review," *IEEE Trans. on ITS*, vol. 18, no. 5, pp. 1033–1045, 2016.

[3] C. Nowakowski, S. E. Shladover, X.-Y. Lu, D. Thompson, and A. Kailas, "Cooperative Adaptive Cruise Control (CACC) for Truck Platooning: Operational Concept Alternatives," *PATH research report*, 2015.

[4] S. Hasan, S. Girs, and E. Uhlemann, "Characterization of transient communication outages into states to enable autonomous fault tolerance in vehicle platooning," *IEEE OJ-ITS*, vol. 4, pp. 101–129, 2023.

[5] P. Ioannou and C. Chien, "Autonomous intelligent cruise control," *IEEE Trans on VT*, vol. 42, no. 4, pp. 657–672, 1993.

[6] J. Ploeg, B. T. M. Scheepers, E. van Nunen, N. van de Wouw, and H. Nijmeijer, "Design and experimental evaluation of cooperative adaptive cruise control," in *Proc. IEEE ITSC 2011*, Washington, DC, USA, October 5-7, 2011, pp 260–265.

[7] R. Rajamani, H.-S. Tan, B. K. Law, and W.-B. Zhang, "Demonstration of integrated longitudinal and lateral control for the operation of automated vehicles in platoons," *IEEE Trans. on CST*, vol. 8, no. 4, pp. 695–708, 2000.

[8] R. Zheng, K. Nakano, S. Yamabe, M. Aki, H. Nakamura, and Y. Suda, "Study on emergency-avoidance braking for the automatic platooning of trucks," *IEEE Trans on ITS*, vol. 15, no. 4, pp. 1748–1757, 2014.

[9] S. Hasan, A. Balador, S. Girs, and E. Uhlemann, "Towards emergency braking as a fail-safe state in platooning: A simulative approach," in *Proc. IEEE VTC2019-Fall*, Honolulu, HI, USA, 2019, pp. 1-5.

[10] Xiangheng Liu, A. Goldsmith, S. S. Mahal, and J. K. Hedrick, "Effects of communication delay on string stability in vehicle platoons," in *Proc. IEEE ITSC 2001*, Oakland, CA, USA, 2001, pp. 625-630.

[11] C. Bergenhem, K. Meinke, and F. Ström, "Quantitative safety analysis of a coordinated emergency brake protocol for vehicle platoons," in *Proc. ISoLA'2018*, pp. 386–404, Springer, 2018.

[12] S. Magdici and M. Althoff, "Adaptive cruise control with safety guarantees for autonomous vehicles," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 5774–5781, 2017.

[13] J. Ligthart, E. Semsar-Kazerooni, J. Ploeg, M. Alirezaei, and H. Nijmeijer, "Controller design for cooperative driving with guaranteed safe behavior," in *Proc. IEEE CCTA 2018*, Copenhagen, Denmark, 2018, pp. 1460-1465.

[14] D. K. Murthy and A. Masrur, "Braking in close following platoons: The law of the weakest," in *Proc. DSD'2016*, pp. 613–620, Limassol, Cyprus, 2016.

[15] S. Hasan, "Fail-Operational and Fail-Safe Vehicle Platooning in the Presence of Transient Communication Errors," tech. rep., Mälardalen University, Västerås, Sweden, March 2022.

[16] A. Böhm, M. Jonsson, and E. Uhlemann, "Co-existing periodic beaconing and hazard warnings in ieee 802.11p-based platooning applications," in *Proc. ACM VANET '13*, p. 99–102, Taipei, Taiwan, 2013.

[17] K. Bilstrup, E. Uhlemann, E. Ström, and U. Bilstrup, "On the ability of the 802.11 p mac method and stdma to support real-time vehicle-to-vehicle communication," *Eurasip J. Wirel. Commun. Netw.*, vol. 2009, no. 1, p. 902414, 2009.

[18] ETSI, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; part 3: Specification of decentralized environmental notification basic service," ETSI EN 302 637-3 V1.2.1, Nov 2014.

[19] S. Hasan, J. Gorospe, S. Girs, A. Alonso Gómez, and E. Uhlemann, "PlatoonSAFE: An Integrated Simulation Tool for Evaluating Platoon Safety," *IEEE OJ-ITS*, early access, 2023.