A Cyber-Physical Approach for Emergency Braking in Close-Distance Driving Arrangements

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In addition to fuel/energy savings, close-distance driving or platooning allows compacting vehicle flows and, hence, increasing throughput on congested roads. The shorter the inter-vehicle separation is in such settings, the more the benefits. However, it becomes considerably harder to guarantee safety, in particular, when braking in an emergency. In this paper, we are concerned with this problem and propose a cyber-physical approach that considerably reduces the stopping distance of a platoon with inter-vehicle separations shorter than one vehicle length (i.e., $5m$) without sacrificing safety and independent of the road profile, i.e., whether on a flat road or in a downhill. The basic idea is to implement a cooperative behavior where a vehicle sends a distress message, if it fails to achieve an assigned deceleration when braking in a platoon. This way, other vehicles in the arrangement can adapt their decelerations to avoid collisions. We illustrate and evaluate our approach based on detailed simulations involving high-fidelity vehicle models.

Additional Key Words and Phrases: Emergency braking, cooperative driving/braking, platoons, brake-by-wire controllers, intelligent transport systems (ITS)

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1 INTRODUCTION

The existing road infrastructure cannot keep up with the ever increasing number of vehicles. This results in more frequent traffic jams, leading to a considerable economic loss and simply to a waste of time. As a result, concepts like cooperative driving or platoons are gaining in importance as a way of counteracting this predicament and, at the same time, saving up fuel/energy [7] [20] [21]. That is, vehicles travel at short distances of $5m$ to $10m$ between them, coordinating actions like braking or acceleration via wireless communication typically based on IEEE 802.11p [12] [11] [6]. To this end, control systems perform the necessary longitudinal and lateral maneuvers [7].

Classical and modern control techniques have already been used for developing cruise controllers to operate in an automated platoon [27], [2], and [17]. Basically, existing such controllers aim to achieve *string stability*, where small variations in the lead vehicle's velocity and, hence, the corresponding variations in the inter-vehicle separations are guaranteed not to amplify towards the trail vehicle [23].

Unfortunately, ensuring string stability does not guarantee a collision-free braking [1] [2]. Particularly, during an emergency, the maximum possible brake forces have to be applied by all the participating vehicles to reach a complete standstill in the shortest possible time. This implies

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that control systems work close to or even at saturation, i.e., the condition where computed output forces exceed those that can be applied by actuators.

In addition, heterogeneous deceleration capabilities of vehicles (due to their type and/or loading conditions) operating at short separations make emergency brake maneuvers extremely dangerous. As a result, if one vehicle brakes at a deceleration rate, the same might not be possible for its immediately leading and/or following vehicles, thereby, entailing the risk of inter-vehicle collisions. Hence, such maneuvers need to be analyzed and verified independent of the cruise scenario.

In this case, one intuitive approach we call *Least Platoon Length* is to consider the vehicle with the worst or weakest deceleration capability and brake the whole platoon at its rate. Even though this results in a safe brake maneuver, it leads to the worst or longest possible stopping distance being unsuitable for emergency scenarios.

Another intuitive approach is to have the vehicle with the best or strongest deceleration capability as the lead. This is followed by the vehicle with the second best deceleration capability and so on. This way, we can achieve the optimum (i.e., shortest possible) stopping distance. However, the inter-vehicle separations must be increased to guarantee safety, i.e., avoid collisions between vehicles, thereby, reducing the aforementioned benefits of platooning. We call this latter approach *Least Stopping Distance.*

To overcome the limitations of the above intuitive approaches, in [9], we proposed a cyber-physical approach consisting of *space buffers* that aims to reduce both stopping distance and inter-vehicle separations. However, this approach was designed for flat roads and cannot effectively adapt to varying road profiles, in particular, those involving downhill situations (which constitute the hardest conditions for emergency braking).

Contributions. We consider vehicles with heterogeneous deceleration capabilities (due to different vehicle types and/or loading conditions) in a platoon scenario at inter-vehicle separations below $5m$. Our proposed approach computes individual decelerations that need to be tracked by vehicles during an emergency in order to reduce the overall stopping distance while guaranteeing safety on a flat road. To this end, we present a full-fledged design scheme for the corresponding brake-by-wire controllers.

Now, if the road profile changes to a downhill, some vehicles in the platoon might not be able to track their assigned decelerations, potentially leading to collisions. This is because some vehicles are already working at their limit on a flat road (to reduce the overall stopping distance). Clearly, one can design the system for the worst case instead, i.e., considering the steepest possible downhill, but at the cost of a longer stopping distance on a flat road, in the end, jeopardizing the safety of other traffic participants.

In this paper, we rather propose a cooperative behavior between vehicles to compensate for deviations from the flat road profile. The idea is that a vehicle sends a distress message, if it is unable to track its assigned deceleration. Other vehicles in the platoon then adapt their (previously assigned) decelerations to avoid collisions. This way, a considerable reduction of the overall stopping distance can be achieved independent of the road profile as illustrated by detailed simulations.

Structure of the paper. Related work is discussed in the next section, whereas Section 3 deals with the principles and fundamentals of the proposed approach. Section 4 presents our full-fledged design scheme for brake-by-wire controllers. The cyber-physical scheme enabling coordination among vehicles after a distress message broadcast is detailed in Section 5, and Section 6 is concerned with evaluation results. Finally, Section 7 discusses potential hazards associated with the proposed approach, while Section 8 concludes the paper.

2 RELATED WORK

Close-distance driving has attracted lot of attention both from industry and academia. Most works have concentrated on ensuring string stability in the cruise scenario [14] [27] [17]. However, this property is irrelevant during emergency braking as controllers saturate by applying the maximum possible brake forces to arrive at standstill in the shortest possible distance [1] [2].

Compared to the cruise scenario, the works related to braking are less in number. The work on platoon braking began as early as 2001, where the benefits of vehicle coordination were studied in [28]. The aim was to reduce the probability of inter-vehicular collisions, their expected number, and the relative velocities at impact. The inter-vehicle separations were in the range of $1m$ to $4m$. The study concluded that, through coordination among vehicles, the above mentioned parameters' values can be significantly reduced in comparison to the uncoordinated case [28].

The work done in [25] also demonstrated that vehicle coordination achieved through synchronized braking can avoid rear-end collisions even when short inter-vehicle separations of $8m$ are used. As per [25], once a hazard is detected, the lead vehicle does not brake immediately, but it rather repeatedly broadcasts wireless packets warning the following vehicles of the imminent brake maneuver. After a preset waiting time, the lead vehicle starts braking together with all the following vehicles at a high deceleration rate of $12m/s^2$.[1] Considering potential interference (e.g., transmissions by other road participants, etc.), this work recommends a minimum waiting time of $100ms$ to start decelerating after a hazard is detected. This way, wireless packets have sufficient time to reach all following vehicles [25].

In [25], since the lead vehicle is not decelerating during $100ms$, the resulting stopping distance will be longer. To mitigate this situation, the lead vehicle starts braking immediately, but at a low deceleration rate of $2m/s^2$, while sending warning messages [24]. All the following vehicles apart from the trail decelerate at the same low rate upon reception of a warning from the lead. The trail vehicle begins decelerating at a higher rate of $8m/s^2$ and immediately broadcasts an acknowledgment of the brake maneuver to its immediately leading vehicle, which then switches from the low to the higher deceleration rate of $8m/s^2$ and, in turn, broadcasts an acknowledgment to its immediately leading vehicle. This process continues until the lead is reached and the whole platoon brakes at the higher deceleration rate of $8m/s^2$ [24].

Apart from vehicle coordination, the inter-vehicle distances during platooning also impact the safety of brake maneuvers. Hence, optimal control and game theory were used in [1] to determine the minimum possible safe separation in a heavy-duty vehicle platoon. This separation is a function of several factors like the vehicles' relative velocities, their braking capabilities, and their positions in a platoon. A two-truck platoon was simulated to be operating both in cruise and brake scenario. Additionally, both homogeneous and heterogeneous vehicle masses were considered. The study showed that when operating at cruise speeds of around $25m/s$ ($90km/h$), an inter-vehicle separation greater than or equal to $2m$ is safe. Further, if such short separations are used, it is preferred to have the better braking vehicle as the trail [1].

Similar to cruise scenario, vehicle-to-vehicle (V2V) communication is also critical during brake maneuvers. The brake actions of a platoon lead are broadcast and, hence, the associated communication delay may affect safety. Thus, the same was studied in [18]. Additionally, this work also considers the dependence of platoon safety on the contents of wireless message, their structure, and reliability. For safe platoon braking, the study outlines the necessity of including brake command

[1] It should be noted that deceleration values greater than 0.85g ($8.33m/s^2$), where g is the acceleration due to gravity, are difficult to achieve in practice. This is because the maximum achievable deceleration is limited by the coefficient of road adhesion μ, which has a value of around 0.85 for dry asphalt surfaces [16].

from the lead in the wireless message, rather than just relying on speed and distance information from radar and information from neighboring vehicles [18].

An important factor that affects communication delay is wireless network performance. The platoon control from the perspective of control and network performance together was considered in [13]. The worst-case upper bounds on inter-vehicle distances subject to network performance metrics like packet losses were derived. The results recommend short inter-vehicle spacings of less than $3m$ for a 8-vehicle platoon, if the network is reliable. However, in case of a non-reliable network, either a limit has to be imposed on the number of vehicles or the maximum jerk (rate of change of deceleration) of vehicles has to be restricted to $4m/s^3$ [13].

To obtain maximum aerodynamic benefits and, thereby, fuel/energy savings, in our previous work [9], we considered inter-vehicle separations between $2m$ and $4m$. Thereby, we proposed our Space-Buffer approach to reduce both the platoon length and its stopping distance during an emergency situation on a flat road.

Even though most of the aforementioned works engineer safe brake maneuvers considering vehicle coordination, inter-vehicle separation, and communication delays, very few of them specifically address emergency situations, i.e., where the stopping distance needs to be considerably reduced, under heterogeneous deceleration capabilities (due to different characteristics and loading conditions at vehicles). Moreover, all these works focus on flat roads and do not provide any adaptation mechanism for changing road profiles. However, this is of paramount necessity in the direction of deploying platoons in real-world scenarios where not only the safety of platoon users, but also that of other road participants needs to be preserved.

With the above aim, in this paper, we extend our Space-Buffer approach from [9] to more realistic road profiles including downhill. Further, for vehicles failing to track their required decelerations (e.g., due to steep downhill), we propose a coordination/cooperation scheme among vehicles based on distress messages. To the best of our knowledge, this is the first such attempt in this area.

3 PRINCIPLES AND FUNDAMENTALS

In this section, we discuss our assumptions and introduce concepts and principles, on which our approach is based.

3.1 Assumptions

Our work is based on the below assumptions:

- For simplification, we assume two-axle vehicles, i.e., mostly passenger cars and utility vehicles. The presented work can also be extended to multi-axle vehicles like trucks and truck-trailer combinations, having implications in the design of brake-by-wire controllers, but otherwise none.

- Every vehicle joining a platoon knows its loading conditions and the resulting maximum achievable deceleration on a completely flat road. This implies that it should be able to estimate/measure its load conditions requiring the corresponding sensors to this end.

- Every vehicle is equipped with brake-by-wire systems as these are suitable for automation and control, rather than conventional brake systems. In brake-by-wire systems, the brake force generated can be electrically controlled thus eliminating all hydraulic lines [29].

- Further, for simplification, we assume that there are no quantization errors up to two decimal places in the reference deceleration tracking. We can later remove this restriction, clearly, resulting in longer stopping distances, however, the proposed approach remains valid.

- Every vehicle is equipped with a radar-based system — in particular, a short-range radar operating in the $0.15m$ to $20m$ range is assumed as typically used in driver-assistance applications like blind spot detection, lateral collision avoidance, etc., [15] — that measures the distance to its immediately leading vehicle in real time.[2]
- There is at most one road-profile transition during an emergency braking, i.e., from flat road to downhill or from one grade to another. This is no serious limitation for highways, where road profile changes are smooth, but it implies a maximum platoon length (of around $200m$).
- The maximum road inclination or grade is assumed never to exceed 8° (corresponding to highway regulations in Europe [26] and around the globe).
- We select a cruise speed V_{init} of $30m/s$ (i.e., around $100km/h$). This speed can be increased at the expense of harder reliability requirements on communication, which is, however, beyond the scope of this paper.
- Every vehicle is equipped with an IEEE 802.11p transceiver that is capable of broadcasting and receiving messages over the allocated frequency band by the ongoing standardization of V2V communication.
- We assume that the underlying V2V communication is *stable*, even though we discuss how to implement a fail-safe behavior. On the other hand, a fail-operational behavior requires redundant systems and is beyond the scope of this paper.
- Finally, based on the results from [5], we consider a negligible propagation delay of communication packets within the platoon. This is in line with the selected V_{init} together with the maximum platoon length resulting from the above assumptions.

3.2 Stopping Distance

Fig. 1 shows the forces acting on a two-axle vehicle during braking, resulting in a linear deceleration d (in m/s^2) [16]:

$$\frac{F_b + f_r W\cos(\theta) + R_a \pm W\sin(\theta)}{W} = \frac{d}{g}, \tag{1}$$

where the brake forces at the front and rear axles, F_{bf} and F_{br} respectively, are combined into one resultant total force F_b. The rolling resistances at the front and rear wheels, R_{rf} and R_{rr} respectively, are also combined into $f_r W\cos(\theta)$, where f_r is the coefficient of rolling resistance, and θ is the road grade or inclination in degrees. The weights acting on the front and rear axles, W_f and W_r respectively, constitute the total vehicle weight W acting at the vehicle's center of gravity situated at a height h from the road surface.

As shown in Fig. 1, the aerodynamic force R_a is acting at a height h_a from the road surface and aids braking. On the other hand, the grade force $W\sin(\theta)$ aids braking in an uphill and opposes it in a downhill, hence, the $\pm$ signs respectively. Finally, g is the acceleration due to gravity in m/s^2.

[2]Note that a short-range radar can already provide an update rate of $20ms$ at an accuracy of below $10cm$ [19]. Even if the update rate is greater than $20ms$, a combination with accelerometers (with update rates in the order of a few milliseconds) still allows for a real-time distance measurement by the radar-based system. In this case, the radar provides accurate distance measurements based on its update rate and accelerometers compute by how much the distance changes from the last available radar measurement.

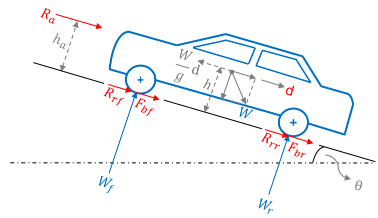

Fig. 1. Forces on a two-axle vehicle during braking [16]

Based on these forces, and assuming that the deceleration d is achieved instantaneously, the stopping distance S from an initial velocity V_{init} can be computed as described in [16]:

$$S = \frac{\gamma_m W}{2gC_A} \ln\left(1 + \frac{C_A V_{init}^2}{\eta_b \mu W + f_r W \cos(\theta) \pm W \sin(\theta)}\right), \tag{2}$$

where γ_m is referred to as *equivalent mass factor* and has a value of 1.03 to 1.05 for passenger cars. It indicates that the brake system has to decelerate a mass slightly greater than the vehicle's mass due to moment of inertia of the rotating components. The coefficient of road adhesion is denoted as μ, whereas C_A and η_b are given by:

$$C_A = \frac{\rho}{2} C_D A_f, \tag{3}$$

and

$$\eta_b = \frac{\left(\frac{d}{g}\right)}{\mu}. \tag{4}$$

In these expressions, ρ is the air-mass density in kg/m^3, A_f is the vehicle's frontal area (in m^2) along the direction of travel, and C_D is its aerodynamic drag coefficient. During platoon operation, C_D's magnitude would be reduced depending on the inter-vehicle separation, leading to lesser aerodynamic resistance and, hence, fuel/energy savings. Particularly, for separations in the range of $1m$ to $4m$, optimum fuel/energy savings result as even the lead vehicle experiences benefits [20] [21].

Note that the magnitude of the maximum achievable deceleration is limited by the coefficient of road adhesion (μ). On dry asphalt surfaces, this is around 0.85g, but it reduces to around 0.2g on snowy surfaces. Hence, η_b denotes a vehicle's braking efficiency [16].

Clearly, a vehicle's loading conditions and its (typically fixed) brake-force distribution to the axles, i.e., what percentage of the brake force acts on the front and rear axles, determine the magnitude of its maximum achievable deceleration and, hence, its braking efficiency. As a result, when vehicles operate in a platoon, their heterogeneous deceleration capabilities have to be considered when designing emergency brake maneuvers. The technique presented next accounts for the same.

3.3 Space Buffers

In this section, we recap our approach from [9]. We use the concept of *space buffer* to compute the deceleration magnitudes of vehicles that help reduce the stopping distance of the whole platoon on a flat road (clearly, avoiding intra-platoon collisions). In principle, every vehicle must know its stopping distance (given by (2) with $\theta = 0$). Moreover, this is assumed to join in at a position with respect to the lead that maintains the order of non-decreasing stopping distances, i.e., if S_i and S_j

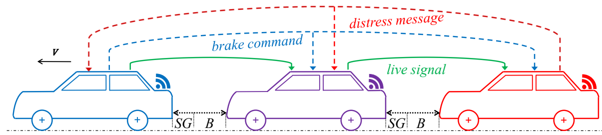

Fig. 2. Communication strategy suggested in this paper for close-distance driving arrangements

are the stopping distances of two consecutive vehicles i and j respectively, $S_i \leq S_j$ provided $i < j$ holds.[3]

The inter-vehicle separations are comprised of two parts namely a *safeguard* (SG) and a *space buffer* (B) as shown in Fig. 2. The *SG* accounts for eventual communication loss between vehicles as discussed in Section 7 and is kept constant at $1m$, whereas B is a design parameter varied from $1m$ to $3m$ in this paper.

Now, the idea is that any vehicle can utilize the space buffers contained in all the inter-vehicle separations towards the lead. The vehicle that has the longest stopping distance in spite of using all space buffers dominates the braking behavior:

$$S_{SB} = \max_{1 \leq j \leq n} \left(S_j - (j-1)B \right), \tag{5}$$

where n denotes the total number of vehicles and j is an index representing the vehicle's position from the lead.

As a consequence, the lead vehicle can be configured to achieve a stopping distance of S_{SB} meters. In other words, the lead brakes within a distance that is a multiple of B meters shorter than that of the worst braking vehicle. Every other vehicle i between the lead and the worst braking vehicle have to brake within $S_{SB} + (i-1)B$ meters, where i is also a vehicle index starting from the lead.

The next step is to compute the required brake force for each vehicle i such that no collisions occur. For simplicity, we replace $K_1 = \frac{\gamma_m W}{2gC_A}$, $K_2 = C_A V_{init}^2$, and $K_3 = f_r W$ $(\theta = 0)$ in (2):

$$S_{SB} + (i-1)B = K_1 \ln \left(1 + \frac{K_2}{\eta_b \mu W + K_3} \right). \tag{6}$$

Next, we need to solve for η_b, i.e., vehicle i's braking efficiency, so we proceed as follows:

$$e^{\frac{S_{SB}+(i-1)B}{K_1}} = 1 + \frac{K_2}{\eta_b \mu W + K_3}, \tag{7}$$

and then:

$$\eta_b = \frac{\frac{K_2}{\left(e^{\frac{S_{SB}+(i-1)B}{K_1}} - 1 \right)} - K_3}{\mu W}. \tag{8}$$

Finally, we can use (4) to compute the necessary deceleration d and (1) to compute the brake force F_b to be exerted by vehicle i. In reality, no vehicle can achieve its assigned deceleration d instantaneously. Hence, we need to address this limitation when designing brake-by-wire controllers.

An example. Consider a four-vehicle platoon with inter-vehicle separations of $4m$, where vehicles are arranged as per their non-decreasing stopping distances. Assume these are $65m$, $70m$, $75m$, and $80m$ respectively (by decelerating at their maximum capability on a flat road from a common initial

[3] This is not an absolutely necessary condition, however, if vehicles are not in this order, the resulting decelerations might not reduce the stopping distance as much as they could if vehicles are sorted this way. Hence, it is recommended that every new vehicle that joins the platoon merges in at the correct position. If vehicles join at arbitrary positions, the impact on stopping distance is discussed in Section 7.

velocity V_{init}). Now, calculating $S_j - (j-1)B$ for each vehicle where $B = 3m$ results in $65m$, $67m$, $69m$, and $71m$ respectively. Hence, $S_{SB} = 71m$ and the platoon lead has to decelerate at a corresponding rate to achieve this stopping distance during an emergency. Similarly, the following vehicles have to achieve stopping distances of $74m$, $77m$, and $80m$ respectively. This way, the achieved overall stopping distance is $9m$ shorter than that of the worst-case scenario, i.e., $80m$ in this case.

Note that every vehicle in the platoon knows the deceleration it has to achieve during an emergency braking beforehand. As a result, the platoon lead only needs to initiate the brake maneuver as explained in the next section.

3.4 Communication Strategy

Our communication strategy is based on three kinds of messages: *live signal*, *brake command*, and *distress message* as shown in Fig. 2. The focus of this section is not on the structure or format of these messages, but rather on the contents that are disseminated for achieving vehicle coordination as explained below.

The live signal has a *time-triggered* nature and can be mapped to a cooperative awareness message (CAM) as per the IEEE 802.11p standard [12]. However, we deviate from the standard's recommendation of a $100ms$ transmission period and choose a period of $20ms$ (to account for speeds of around $100km/h$). Our choice is based on truck manufacturers' observations as mentioned in [4].

Live signals are broadcast both during brake and cruise scenario from every vehicle i, where i is an index representing a vehicle's position in the platoon, i.e., $1 \leq i < n$ and n is the last vehicle (which does not need to send a live signal). Note that, even though live signals from a vehicle are received by all vehicles in its surroundings, they are only processed by the immediately following vehicle. To this end, a live signal must include the index of the vehicle from which it proceeds and every vehicle must know its immediately leading vehicle in the platoon.

For the sake of braking, in addition, a vehicle i's live signal must include its deceleration d_i, its velocity V_i, and the time t_i at which d_i and V_i were measured. A vehicle i also appends to its live signal the maximum deceleration difference Δd_i, the maximum speed difference ΔV_i, and the minimum remaining space buffer B_i in between any two vehicles from the lead up to its position:

$$\Delta d_i = \max\{|d_{i-1}| - |d_i|, \Delta d_{i-1}\}, \tag{9}$$

$$\Delta V_i = \max\{|V_{i-1}| - |V_i|, \Delta V_{i-1}\}, \tag{10}$$

$$B_i = \min\left\{IV_i - SG, B_{i-1} - \left(\Delta V_{i-1} \cdot (t_i - t_{i-1}) - \frac{1}{2}\Delta d_{i-1} \cdot (t_i - t_{i-1})^2\right)\right\}, \tag{11}$$

where IV_i is vehicle i's separation to its immediately leading vehicle[4] and the min function's second argument is the minimum remaining space buffer sent by vehicle $i-1$ in its live signal, which continues to decrease due to vehicles being already braking. Clearly, (11) is valid as long as Δd_{i-1} remains constant in (t_{i-1}, t_i). For this reason, during braking, vehicle $i-1$ has to send an *asynchronous* live signal (i.e., independent of its $20ms$ period) to vehicle i just after its brake controller settles at the desired or saturates at a lower deceleration value and, hence, not only Δd_i but also ΔV_i can be computed accordingly as per (9) and (10).

Apart from disseminating the crucial information mentioned above, live signals help implementing fail-safe mechanisms. As explained later in Section 7, if a given number of live signal updates are lost in a row, the affected vehicle dissolves the platoon by assuming the worst case, i.e., that its leading vehicles are already braking, and performs a (decentralized) emergency brake maneuver by broadcasting a brake command.

[4]Recall that each vehicle is assumed to be equipped with a radar-based system for this purpose — see again Section 3.1.

A brake command has an *event-triggered* nature and can be sent over a decentralized environmental notification message (DENM) [11] and is typically broadcast by the platoon lead (with the exception described above) to initiate an emergency brake maneuver (at any point in time) independent of its live signal. As mentioned before, vehicles are assigned decelerations beforehand (at the moment of joining the platoon) that need to be tracked during an emergency. Hence, this is not included in the brake command. For safety reasons, a brake command has to be confirmed/replicated over the live signal until complete standstill.

Once a brake command is broadcast by the platoon lead, all the following vehicles including the lead will begin braking simultaneously $20ms$ later. Note that this $20ms$ delay has a negligible impact (of at most $0.6m$, assuming platoon cruise velocity of $30m/s$) on the overall stopping distance [9].

During emergency braking, a distress message (also a DENM) is broadcast (also in an event-triggered manner) by any vehicle that is unable to track its assigned deceleration, for example, when it enters a downhill. The purpose is to inform all other vehicles that they need to adapt their originally assigned decelerations. Hence, after a distress message broadcast, all other vehicles perform computations based on the distress message's contents and begin simultaneously tracking their respective new decelerations $20ms$ later. The distressed vehicle continues sending distress messages (every $20ms$) until this is acknowledged by its immediately leading vehicle over the live signal. In turn, this latter requires an acknowledgment from its immediately leading vehicle and so on up to reaching the platoon lead.

Note that there can be cascaded distress messages from the same or different vehicles, e.g., when changing from one downhill to a steeper one. Simultaneous distress messages are less probable, but also possible, if two or more identical vehicles incur a distress situation. In this case, the vehicle being more *distressed*, i.e., the vehicle that has the maximum deviation from its assigned deceleration, must be considered for further computations simply disregarding all others.

Finally, it is important to note that we do not consider propagation delays for any of these messages. Further, we assume that all vehicles are within the reach of the platoon lead (in case of brake command broadcast) as well as the trail vehicle (in case of distress message broadcast). These assumptions are based on the field trials done in [5], where vehicles within $300m$ range of the transmitter receive a broadcast message with 100% probability and almost instantly (as mentioned before, we restrict our platoon length to $200m$).

4 DESIGNING BRAKE-BY-WIRE CONTROLLERS

The stopping distance as per (2) is obtained considering that a constant brake force F_b is applied and, hence, the required deceleration d is tracked instantaneously. However, in reality, no brake-by-wire controller can track an assigned deceleration instantaneously, rather it applies a time-varying force. Variations in the brake force will be negligible when the controller is in steady state, but considerably large during the transient phase. As a result, controller-related effects like rise and settling time affect deceleration tracking. This results in a stopping distance that is longer than the one computed using (2). Therefore, we need to obtain an expression of the stopping distance by a vehicle that takes these effects into account and can be used in our space buffer computations (instead of relying on the stopping distance computed using (2)). To that end, we first introduce our vehicle model and controller performance specifications (that are to be met by the brake-by-wire controllers present at each vehicle) to then derive this expression on their basis.

4.1 Vehicle Model and Controller Specifications

Since rolling and aerodynamic forces aid braking, but are nonlinear in nature, we can neglect them in the model of Fig. 1 yielding a linear and time-invariant (LTI) system, for which we obtain the

Table 1. Controller design specifications

Property	Value	Description	Reason
Overshoot	0%	The deceleration magnitude (expressed as a percentage) during the transient that exceeds the steady-state value.	Since the controller almost reaches the saturation brake force, designing for an overshoot other than 0% is going to cause saturation resulting in a nonlinear behavior that is difficult to deal with.
Settling time	$\leq 400ms$	The time required to achieve a deceleration that remains within ±2% of the reference.	Since no overshoot is required, a feasible controller needs a longer time to settle.
Steady-state error	$\approx 0\%$	The difference between reference and achieved deceleration in the steady state.	A non-negligible steady-state error accumulates over time potentially leading to intra-platoon collisions.
Feedback delay	$20ms$	Delay incurred in the feedback loop.	The delay due to data processing by sensor and to communicate the same back to the controller.

following state-space representation:[5]

$$\dot{x}_i = 0 \cdot x_i + \frac{1}{\gamma_m \cdot \mathrm{m}_i} \cdot u_i + z_i, \tag{12}$$

and

$$y_i = 1 \cdot x_i, \tag{13}$$

where the only state is the vehicle i's velocity in m/s denoted by x_i. Similarly, its deceleration in m/s^2 is $\dot{x}_i$, its mass in kilograms (kg) is m_i, and its equivalent mass factor is again denoted as γ_m.

Note that (12) states Newton's second law, i.e., the resultant deceleration is equal to the (input) brake force u_i divided by the mass times the equivalent mass factor. The disturbance force z_i (i.e., grade resistance in our case) affects the resultant deceleration and, hence, it is also present in the expression. Since the deceleration magnitude linearly increases with an increase in brake force (until a maximum limit is reached at saturation) and it does not depend on time, this constitutes an LTI system as mentioned above.

Clearly, the brake-by-wire controller requires the vehicle's deceleration rather than its velocity for reference tracking, which can be obtained by differentiating the output velocity from the model. In reality, vehicles are equipped with accelerometers which directly measure acceleration/deceleration.

The brake-by-wire controllers present at each vehicle have to meet the performance specifications in Table 1. These were chosen considering the mechanical, hydraulic, and/or electrical components of a brake-by-wire system apart from the associated lag, the magnitude of the generated brake force, and the implications of braking at short inter-vehicle separations.

In this paper, we choose the proportional integral derivative (PID) technique for designing our controllers. Note that even techniques based on optimal control like linear quadratic regulator (LQR) or model predictive control (MPC) can be used. However, our focus is to demonstrate that even a simple control technique like PID does the job. Therefore, the controller gains to meet the specifications in Table 1 can be obtained using standard techniques such as Root Locus or Pole Placement [22] and, hence, we do not elaborate on this any further.

[5]The standard state-space representation of a LTI system is: $\dot{x}_i = Ax_i + Bu_i + z_i$ and $y_i = Cx_i + Du_i$, where A, B, C, and D are the system, input, output, and feed-forward matrices respectively, u_i is the input vector, x_i is the state vector, z_i is the disturbance vector, and y_i is the output vector. However, note that we have one-element vectors x_i, u_i, and z_i and, as a result, matrices A, B, C, and D become scalars. Further, to be consistent with the standard representation, we explicitly make the output y_i equal to our only state x_i.

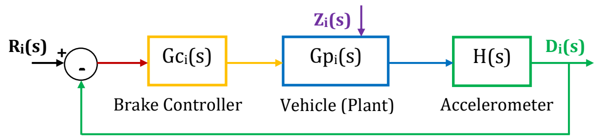

Fig. 3. Closed-loop control system

Now that we have a vehicle model and the controller specifications, we can obtain the vehicle's stopping distance under controller action as shown in the next section. To this end and for the sake of simplicity, we first obtain a transfer function (in the frequency domain s) of both the vehicle model and the controller.

4.2 Brake-by-Wire Stopping Distance

We first derive the transfer functions $G_{p_i}(s)$ from the state-space model represented by (12) and (13), and $G_{c_i}(s)$ from the controller used. As mentioned before, for reference tracking, we require the vehicle's deceleration, which is provided by an accelerometer described by $H(s)$.

Let us assume that there are no disturbances (i.e., $Z_i(s) = 0$) implying no grade force and, hence, road grade/inclination $\theta = 0$. We then reduce the closed-loop system shown in Fig. 3 to a single-input/single-output system, where the input is the reference deceleration $R_i(s)$ and the output is the vehicle's achieved deceleration $D_i(s)$. The overall transfer function is:

$$G_i(s) = \frac{Gc_i(s)Gp_i(s)H(s)}{1 + Gc_i(s)Gp_i(s)H(s)}. \tag{14}$$

Multiplying the input $R_i(s)$ by $G_i(s)$ yields $D_i(s)$ (a 4^{th} order transfer function), which can be expressed by decomposing it into partial fractions:

$$D_i(s) = R_i(s)G_i(s) = \frac{R_1}{s - p_1} + \frac{R_2}{s - p_2} + \frac{R_3}{s - p_3} + \frac{R_4}{s - p_4}, \tag{15}$$

where R_1 to R_4 are residues and p_1 to p_4 are poles. Then, applying the inverse Laplace transform, we obtain an expression for the output deceleration in the time domain t as:

$$d_i(t) = R_1e^{p_1t} + R_2e^{p_2t} + R_3e^{p_3t} + R_4e^{p_4t}. \tag{16}$$

Integrating (16), we obtain the expression of velocity:

$$\int d_i(t)\,\mathrm{d}t = v_i(t) = \frac{R_1e^{p_1t}}{p_1} + \frac{R_2e^{p_2t}}{p_2} + \frac{R_3e^{p_3t}}{p_3} + \frac{R_4e^{p_4t}}{p_4} + V_{init} + C_1, \tag{17}$$

where $V_{init} + C_1$ is a constant of integration with V_{init} being the initial velocity in *m/s* at the moment of braking. Thus, C_1 is chosen such that $v_i(t) = V_{init}$ at time $t = 0$, i.e., when braking begins (17) should be equal to V_{init}. Therefore, we substitute $t = 0$ and choose $C_1 = -\left(\frac{R_1}{p_1} + \frac{R_2}{p_2} + \frac{R_3}{p_3} + \frac{R_4}{p_4}\right)$.

Finally, integrating (17) yields the expression of stopping distance:

$$\int v_i(t)\,\mathrm{d}t = s_i(t) = \frac{R_1e^{p_1t}}{p_1^2} + \frac{R_2e^{p_2t}}{p_2^2} + \frac{R_3e^{p_3t}}{p_3^2} + \frac{R_4e^{p_4t}}{p_4^2} + V_{init}t + C_1t + S_{init} + C_2, \tag{18}$$

where $S_{init} + C_2$ is a second constant of integration with S_{init} being the vehicle's position in m at the moment of braking. Similar to before, C_2 is chosen such that (18) is equal to S_{init} at $t = 0$. Hence, we substitute $t = 0$ and choose $C_2 = -\left(\frac{R_1}{p_1^2} + \frac{R_2}{p_2^2} + \frac{R_3}{p_3^2} + \frac{R_4}{p_4^2}\right)$. Note that since we are interested in the vehicle's stopping distance and not in its absolute position, we assume $S_{init} = 0$, i.e., we *measure* the vehicle's (longitudinal) displacement relative to S_{init}.

In order to compute the stopping distance as per (18), apart from the residues, poles, and the initial velocity, we need the *stopping time* t, for which $v_i(t) = 0$ in (17). This can be obtained analytically using Taylor series or numerically. For simplicity, we opt for a numerical solution.

An example. Consider a vehicle with m = $3265kg$. Due to its loading conditions and considering $\gamma_m = 1.05$, its maximum achievable deceleration has a magnitude of $d = 4.76m/s^2$. Similarly, $V_{init} = 30m/s$, $A_f = 2.02m^2$, $C_A = 0.315$, $\rho = 1.225kg/m^3$, $g = 9.8m/s^2$, $f_r = 0.015$, and $\mu = 0.85$. In addition, we assume a *dead time* of $0.1s$ to activate the brakes, hence, the vehicle travels $3m$ ($30m/s \cdot 0.1s$) before beginning to decelerate. Substituting these parameters in (2), and appending the distance traveled due to dead time, yields a stopping distance of $93.71m$ considering a constant deceleration by neglecting all controller-related effects.

Now, using the same parameters, we obtain the vehicle's transfer function $G_{p_i}(s)$ and design a PID-based brake-by-wire controller (using Matlab/Simulink) to meet the performance specifications of Table 1. The resulting integral gain $Ki = 34282.5$, whereas both the proportional and derivative gains are 0. Therefore, $G_{c_i}(s) = \frac{Ki}{s}$, while $H(s)$ was chosen as $\frac{s}{s+1}$.

For the decomposition as per (15), the poles and residues are [−10, -1, 0, 0] and [4.77, 0, -4.77, 0] respectively and we obtain (16) using the inverse Laplace transform. However, for these residues and poles, (16) simplifies to:[6]

$$d_i(t) = R_1 e^{p_1 t} + R_3. \tag{19}$$

Integrating (19), we derive a corresponding expression of velocity as:

$$\int d_i(t)\,\mathrm{d}t = v_i(t) = \frac{R_1 e^{p_1 t}}{p_1} + R_3 t + V_{init} + C_1, \tag{20}$$

which we numerically solve to obtain the stopping time $t = 6.4s$. Note that we have $C_1 = 0.477$. Integrating (20) results in:

$$\int v_i(t)\,\mathrm{d}t = s_i(t) = \frac{R_1 e^{p_1 t}}{p_1^2} + \frac{R_3 t^2}{2} + V_{init} t + C_1 t + S_{init} + C_2, \tag{21}$$

where we now have $C_2 = 0.0477$. Substituting $t = 6.4s$ and $S_{init} = 0$ in (21) yields the brake-by-wire stopping distance of $97.32m$, i.e., after the dead time of brake activation elapses and the brake force reaches the actuators, the vehicle needs $6.4s$ to reach a standstill under controller action, thereby, covering a distance of $97.32m$. If we also include the dead time ($0.1s$) and the distance traveled in that time ($3m$), it results in an overall stopping time and distance of $6.5s$ and $100.32m$ respectively.

The braking dynamics of the vehicle (i.e., all the forces shown in Fig. 1) along with its brake-by-wire controller was modeled and simulated in Matlab/Simulink. The resulting brake-by-wire stopping distance was $100.28m$ (from $V_{init} = 30m/s$), which is similar to the analytically computed

[6]Note that $d_i(t)$ has a negative value for $t = 0$ onwards, i.e., the vehicle decelerates.

Table 2. Computed and simulated vehicle positions. After actuators' dead time elapses, the time is counted. However, the positions here do include the distance traveled due to dead time.

Time (s)	**Position as per** (21) (m)	**Simulated position** (m)
1	30.53	30.52
2	53.95	53.93
3	72.59	72.56
4	86.47	86.43
5	95.58	95.54
6.4	100.32	100.28

value from this example. Table 2 shows the analytically computed values of vehicle position as per (21) in comparison to the actual values during simulation. Note that in contrast to our analytical (LTI) model, the performed simulation considers both aerodynamic and rolling resistances which are nonlinear.[7]

Computing space buffers. Once controller gains have been selected to meet the aforementioned performance specifications, every vehicle can compute its shortest possible stopping distance on a flat road using (18). Vehicles communicate their stopping distances computed this way, when joining a platoon. The platoon lead then computes the deceleration magnitudes to be tracked by individual vehicles in an emergency and communicates them back to all vehicles. Thus, apart from using (18) instead of (2) to compute S_{SB} in Section 3.3, this procedure remains unchanged.

Considering disturbances. So far, we considered that vehicles brake on a flat road (i.e., $\theta = 0$) and designed brake-by-wire controllers as explained above. These controllers can easily track their assigned decelerations on an uphill as well, as the (disturbing) grade force aids braking. However, a downhill presents the most challenging conditions for emergency braking and, hence, constitutes the worst case as explained below.

If vehicles enter a downhill, the brake-by-wire controllers still attempt to compensate the (disturbing) grade force by applying a greater brake force. Now, if the necessary increase in brake force does not exceed the maximum possible, our brake-by-wire controllers will be able to maintain the desired deceleration they were designed for. Hence, the vehicles' stopping distances continue to be those of the flat road, i.e., the whole platoon can safely brake in the downhill too.

On the other hand, if the required increase in brake force exceeds the maximum possible by any vehicle dis with $1 \leq dis \leq n$, for example, in a pronounced downhill, the corresponding brake-by-wire controller saturates and will be unable to reach its desired deceleration, yielding a longer stopping distance for the affected vehicle. As a result, it cannot be guaranteed that the whole platoon brakes in a safe manner anymore. We refer to this as a *distress situation*. Note that, when vehicles are sorted in the order of their non-decreasing stopping distances, this usually affects all vehicles towards the end of the platoon, i.e., all vehicles in $dis \leq i \leq n$.

On the other hand, even if vehicles are sorted in the above order, it may occur that a vehicle dis incurs a distress situation, without its following vehicles being also under distress. There are two possible options to preserve safety under these circumstances: 1) every leading vehicle i with $1 \leq i < dis$ adapts to vehicle dis and 2) all vehicles (i.e., $1 \leq i \leq n$) adapt to vehicle dis. In case 1), the platoon splits into two sub-platoons. The first $1 \leq i \leq dis$ vehicles brake as one driven by vehicle dis's current deceleration. The last $dis < i \leq n$ vehicles brake as originally planned. In case 2), the platoon is kept together with vehicles $dis < i \leq n$ also adapting their decelerations to dis.

In the case that multiple vehicles are under distress, the above vehicle dis represents the most distressed one. Note that the trail sub-platoon in case 1) might need to be further subdivided/split to avoid collisions, if some vehicle in $dis < i \leq n$ is also under distress (even if it is less distressed than dis).

In the next section, we discuss how the different vehicles cooperate in such a distress situation. Note that, for the following analysis, we basically assume case 1), i.e., only the leading vehicles adapt their decelerations. However, the proposed procedure can be straightforwardly extended to case 2) as well.

[7] Their magnitudes $C_A V_{init}^2$ and $f_r W \cos(\theta)$ respectively (as per (2)) were not included in our LTI car model.

5 COOPERATIVE BEHAVIOR FOR EMERGENCY BRAKING

In a distress situation, the necessary actions to be performed by the vehicles can be separated into two different categories. The first category comprises vehicle(s) that cannot track their assigned reference deceleration(s), which are henceforth referred to as *distressed vehicle(s)*. As mentioned before, in case of more than one vehicle in distress, the most distressed vehicle has to be considered simply disregarding all others. The other category includes less or non-distressed vehicles that can no longer continue braking at their originally assigned decelerations and have to adapt according to the most distressed vehicle as explained next.

5.1 Actions by distressed vehicles

Every vehicle in the platoon checks for its current deceleration after the settling time has elapsed (400ms as per our specifications) and, if there is a deviation with respect to its desired deceleration, it broadcasts a distress message as detailed below. Recall that, independent of whether a distress message is sent or not, every vehicle has to send an *asynchronous* live signal to its immediately following vehicle (with an update of its deceleration, velocity, separation to its immediately leading vehicle, etc.) as discussed above.

The contents of the distress message are the distressed vehicle's index dis, the minimum remaining space buffer B_{min}, and the maximum stopping distance S_{max} that results from vehicle dis being under distress, based on which the most distressed vehicle can be identified.

With the information provided in the live signal from its immediately leading vehicle, a distressed vehicle can compute B_{dis} as per (11). B_{min} is then computed as follows:

$$B_{min} = B_{dis} - \left\{ \left[V_{dis} - (V_{dis-1} - |d_{dis-1}| \cdot (t_{dis} - t_{dis-1})) \right] \cdot 0.02 - \frac{1}{2} \cdot (|d_{dis-1}| - |d_{dis}|) \cdot 0.02^2 \right\}, \quad (22)$$

that is, B_{dis} minus the expected amount of space buffer that is consumed between vehicles dis and $dis - 1$ in 20ms. This is because other vehicles start adapting to the distress situation with a delay of 20ms, i.e., one sample period, which needs to be accounted for as explained later in more detail. Note that other delays can be considered as well. For the sake of simplicity, however, we decided not to introduce further nomenclature and use the concrete delay value of 20ms instead. Note that vehicle $dis - 1$'s speed is given by $V_{dis-1} - |d_{dis-1}| \cdot (t_{dis} - t_{dis-1})$, at time t_{dis}, at which vehicle dis computes B_{min}. Further, B_{min} is a conservative measure that considers the minimum remaining space buffer up to vehicle dis, which might not necessarily be between $dis - 1$ and dis, and reduces it by the greatest possible amount that results from dis being the most distressed vehicle.

Finally, the stopping distance (or final position at standstill) of the vehicle dis denoted as S_{dis} is computed using (2),[8] from which we calculate S_{max} as:

$$S_{max} = S_{dis} - \left(V_{dis} \cdot 0.02 - \frac{1}{2} \cdot |d_{dis}| \cdot 0.02^2 \right), \quad (23)$$

that is, S_{dis} is reduced during the 20ms delay required by other vehicles to start adapting to the distress situation and this is considered by S_{max}.

Apart from multiple vehicles broadcasting their distress messages, cascaded distress messages from the same vehicle are also possible. This might happen when a vehicle that had previously broadcast a distress message has entered another downhill that is much steeper. For example, when the vehicle was initially distressed due to a 4° downhill and, it then entered a much steeper downhill of 8°. In such a scenario, the vehicle is more distressed in the steeper downhill and, hence, its

[8] It should be noted that (18) is not valid when the controller is saturated and, hence, unable to track its assigned deceleration. However, since its (saturated) deceleration remains constant, we can still use the standard expression of (2) to compute its stopping distance.

stopping distance S_{dis} will be longer. Therefore, the vehicle has to broadcast a separate distress message with the updated information.

On the contrary, if a previously distressed vehicle enters a flat road (instead of entering a steeper downhill), it can broadcast a *de-distress message* indicating that it is no longer under distress. All the other vehicles can then switch back to tracking their originally assigned decelerations (computed for a flat road) and the overall stopping distance of the platoon can be reduced.

5.2 Actions by less or non-distressed vehicles

Once a distress message is broadcast at t_{dis}, all vehicles receive it (recall that we assume a negligible propagation delay). The above mentioned contents of the distress message are processed by all less or non-distressed vehicles that need to start adapting by computing their new deceleration values within a $20ms$ delay (i.e., one sample period) and begin tracking the same.

Considering S_{max} and B_{min} from the distress message, a vehicle i with $1 \leq i < dis$ first computes a stopping distance S_i^{new} in m that has to be covered from the point in time of beginning to track its new deceleration:

$$S_i^{new} = S_{max} - (dis - i)B_{min}. \tag{24}$$

Let us first assume an instantaneous deceleration switching. As a result, we can compute the constant deceleration d_i^{new} that brings the vehicle to standstill in a distance S_i^{new}:

$$V_i^2 + 2|d_i^{new}|S_i^{new} = 0, \tag{25}$$

where V_i is vehicle i's velocity at $t_{dis} + 0.02$, i.e., the point in time of starting to track its new deceleration, which is an amount $|d_i| \cdot 0.02$ smaller than the speed at t_{dis}. In other words, from receiving the distress message until switching to the new deceleration d_i^{new}, vehicle i continues braking at its originally assigned deceleration d_i for the duration of $20ms$.

However, the brake-by-wire controller cannot switch instantaneously to d_i^{new}, but it rather undergoes a transition until it settles after $400ms$ as per our specifications, which needs to be considered to avoid collisions. To this end, we proceed similar to before letting $\Delta D_i(s)$ denote the difference between $|d_i|$ and $|d_i^{new}|$ in the frequency domain s with $|d_i| > |d_i^{new}|$.

Multiplying $\Delta D_i(s)$ with the closed-loop transfer function of (14), the expression of the output, i.e., the transition from one deceleration to the other, can be obtained by decomposing into partial fractions similar to (15). Applying the inverse Laplace transform, we obtain an expression in the time domain t denoted by $\Delta d_i(t)$.

On the other hand, the vehicle is undergoing a transition from its current to the new deceleration. Hence, the current deceleration $d_i(t)$ and the deceleration difference $\Delta d_i(t)$ need to be superposed from $t \geq t_{dis} + 0.02$ onwards. This is possible for a LTI system like ours [22]:

$$\begin{aligned} d_i(t) + \Delta d_i(t) = {} & R_1 e^{p_1 t} + R_2 e^{p_2 t} + R_3 e^{p_3 t} + R_4 e^{p_4 t} + \tilde{R}_1 e^{p_1 (t-(t_{dis}+0.02))} \\ & + \tilde{R}_2 e^{p_2 (t-(t_{dis}+0.02))} + \tilde{R}_3 e^{p_3 (t-(t_{dis}+0.02))} + \tilde{R}_4 e^{p_4 (t-(t_{dis}+0.02))}. \end{aligned} \tag{26}$$

Although it is not evident from (26), note that the expression of $\Delta d_i(t)$ represents the decrease in deceleration, i.e., it diminishes function $d_i(t)$'s value from the initial d_i at $t_{dis} + 0.02$ to d_i^{new} at $t_{dis} + 0.42$ (from which it remains constant). Integrating (26), we obtain the expression of velocity as:

$$\begin{aligned} v_i(t) + \Delta v_i(t) = {} & \frac{R_1 e^{p_1 t}}{p_1} + \frac{R_2 e^{p_2 t}}{p_2} + \frac{R_3 e^{p_3 t}}{p_3} + \frac{R_4 e^{p_4 t}}{p_4} + \frac{\tilde{R}_1 e^{p_1 (t-(t_{dis}+0.02))}}{p_1} + \frac{\tilde{R}_2 e^{p_2 (t-(t_{dis}+0.02))}}{p_2} \\ & + \frac{\tilde{R}_3 e^{p_3 (t-(t_{dis}+0.02))}}{p_3} + \frac{\tilde{R}_4 e^{p_4 (t-(t_{dis}+0.02))}}{p_4} + V_i + C_3, \end{aligned} \tag{27}$$

where $V_i + C_3$ is an integration constant similar to before and V_i is again the vehicle i's speed at time $t_{dis} + 0.02$. Further, integrating (27), we obtain the expression of distance as:

$$\begin{aligned} s_i(t) + \Delta s_i(t) = &\frac{R_1 e^{p_1 t}}{p_1^2} + \frac{R_2 e^{p_2 t}}{p_2^2} + \frac{R_3 e^{p_3 t}}{p_3^2} + \frac{R_4 e^{p_4 t}}{p_4^2} + \frac{\tilde{R}_1 e^{p_1(t-(t_{dis}+0.02))}}{p_1^2} + \frac{\tilde{R}_2 e^{p_2(t-(t_{dis}+0.02))}}{p_2^2} \\ &+ \frac{\tilde{R}_3 e^{p_3(t-(t_{dis}+0.02))}}{p_3^2} + \frac{\tilde{R}_4 e^{p_4(t-(t_{dis}+0.02))}}{p_4^2} + V_i t + C_3 t + S_i + C_4, \end{aligned} \tag{28}$$

where again $S_i + C_4$ is a constant of integration with S_i representing vehicle i's position in m at $t_{dis} + 0.02$ relative to its position at the moment of braking.

Now, vehicle i has to cover a distance of S_i^{new} from time $t_{dis} + 0.02$ until it reaches standstill. If we calculate the time at which the vehicle reaches standstill and evaluate (28) between the two limits, the distance covered can be obtained. The time to reach standstill when transitioning to d_i^{new} can either be obtained analytically from (27) or computed numerically. For the sake of simplicity, we opt to use a numerical approach.

That is, we begin by substituting $t = t_{dis} + 0.02$ in (27) and iterate in steps of $20ms$, i.e., the brake controller's sampling time, until the value of (27) becomes zero (or slightly less than zero). This stopping time when substituted in (28) yields the stopping distance covered by the vehicle.

However, transitioning from $|d_i|$ to settling at $|d_i^{new}|$ yields a trajectory that is shorter than the intended S_i^{new}, since the vehicle continues braking at a higher magnitude than $|d_i^{new}|$ for some time.

In order to make vehicle i cover a distance of S_i^{new}, we have to reduce the magnitude of d_i^{new} computed initially as per (25), i.e., the vehicle has to transition to a deceleration that is of a lower magnitude than $|d_i^{new}|$. For simplicity, we again opt for a numerical approach. So we reduce the magnitude of d_i^{new} in steps of 0.01.[9] Let $|d_{i,k}^{new}|$ denote the reduced magnitude where k is the iteration and takes a value $\{1, 2, 3, \ldots\}$. Then, we compute the difference between $|d_i|$ and $|d_{i,k}^{new}|$ in the frequency domain s, multiply the difference with the closed-loop transfer function of (14) and obtain the corresponding residues as per (15).

Through inverse Laplace transform, we obtain the deceleration transition in the time domain and, similar to before using (27) and (28) respectively, we compute the new stopping time of the vehicle and the corresponding distance covered. Let $S_{i,k}^{new}$ denote the distance covered by transitioning to the corresponding reduced magnitude of deceleration. If $S_{i,k}^{new} \geq S_i^{new}$, we stop the numerical iteration and the vehicle transitions to the corresponding $d_{i,k}^{new}$ rather than to the initially computed d_i^{new}. On the contrary, if $S_{i,k}^{new} < S_i^{new}$, we repeat the process by reducing the magnitude from the previous iteration until $S_{i,k}^{new} \geq S_i^{new}$.

Note that even though the computations are iterative, the numerical solution space to be explored to arrive at the deceleration value is bounded between $|d_i^{new}|$ and a value close to $|d_{dis}|$. This is because any of the less or non-distressed vehicles will never decelerate at a magnitude that is much less than that of the most distressed vehicle. As a result, the numerical solution can be computed well within $20ms$ (as shown later with an example).

Finally, it is not possible for all the less or non-distressed vehicles to cover a distance of exactly S_i^{new}. There will be minor differences between the achieved stopping distance $S_{i,k}^{new}$ and the required S_i^{new}. This is because we iteratively reduce the deceleration value in steps of 0.01 (until $S_{i,k}^{new} \geq S_i^{new}$) and, hence, quantization error might be incurred.

[9]Recall that as per our assumptions our brake-by-wire controllers can track a deceleration accurately up to two-decimal places. Hence, the value of 0.01 is chosen.

An example. Consider a 10-vehicle platoon with $2m$ ($B = 1m$) inter-vehicle separations on a downhill slope of 4°. Assume that the last 2 vehicles (trail and its immediately leading vehicle) are unable to track their respective reference decelerations due to their actuators' saturation and that the trail vehicle is the most distressed one. As a result, its distress message broadcast after $400ms$ of initiating an emergency brake maneuver is considered by all other vehicles. This distress message has all the necessary details. For example, assume S_{max} is $95.42m$, and B_{min} is $0.99m$ (from the initial $1m$). Note that there is a difference of only $0.01m$ due to downhill grade of only 4° and early broadcast of distress message (i.e., after $400ms$). For road profiles steeper than 4° or if distress situation arises much later, i.e., braking on flat road and then entering a downhill, more space buffer will be consumed and, hence, B_{min} would be lesser.

All the other vehicles process data in the distress message and adapt their decelerations. As an example, we consider the computations done by the 8th vehicle in the platoon. This vehicle has to achieve S_i^{new} of $93.44m$ from time $420ms$ ($20ms$ after distress message broadcast) onwards and, as a result, the corresponding $|d_i^{new}|$ is $4.37m/s^2$. The vehicle has to switch from its current deceleration $|d_i|$ of $4.82m/s^2$ to $|d_i^{new}|$. This difference of $0.45m/s^2$ corresponds to Δd_i. From (27), the vehicle reaches standstill at time $6.96s$ after it begins transitioning to the new deceleration magnitude of $4.37m/s^2$ at time $420ms$. Substituting these two time limits in (28) yields a shorter stopping distance of $93.15m$ rather than the required $93.44m$.

Hence, we reduce the magnitude of d_i^{new} from $4.37m/s^2$ to $4.36m/s^2$ as explained above. This new magnitude $|d_{i,1}^{new}|$ produces a corresponding $S_{i,1}^{new}$ of $93.36m$. Since $S_{i,1}^{new} < S_i^{new}$, we proceed further and reduce the magnitude to $4.35m/s^2$. This new magnitude $|d_{i,2}^{new}|$ produces a corresponding $S_{i,2}^{new}$ of $93.56m$. Since $S_{i,2}^{new} > S_i^{new}$, we stop the numerical computations. Therefore, the vehicle switches to a deceleration magnitude of $4.35m/s^2$ (from the originally assigned magnitude of $4.82m/s^2$) such that collisions are avoided and a safe brake maneuver is guaranteed. Note that the vehicle covers a stopping distance that is only $0.12m$ ($93.56m - 93.44m$) longer than the required value and the corresponding deceleration magnitude was computed with just two iterations.

The above such computations are performed similarly at each individual vehicle requiring only two iterations as for the shown case. Similar to the 8th vehicle, all up to the 7th vehicle cover distances that are longer than their intended ones by $0.02m$, $0.03m$, $0.16m$, $0.12m$, $0.04m$, $0.04m$, and $0.15m$ respectively. Also the 9th vehicle covers a distance that is $0.12m$ longer than intended. Note that this difference in the resulting stopping distance has to be compensated by the safeguard (SG). However, this is not much and only varies from $1cm$ between the lead and its immediately following vehicle to $13cm$ between the 2nd and 3rd vehicle.

The actual deceleration transition by the 8th vehicle (as simulated in Matlab/Simulink) and its analytically computed counterpart as per (26) (until it settles to the new deceleration) can be seen in Fig. 4. Note again that the controller settles much faster in simulation than the analytically computed trajectory. This is because in the simulation aerodynamic and rolling resistances are also acting on the vehicle, whereas the analytical expression considers that only the brake force is acting on the vehicle.

6 SIMULATION RESULTS

In this section, we present an extensive evaluation of our Space-Buffer approach along with the cooperative scheme on different road profiles.

6.1 Test Data

The following vehicle data was randomly generated. Similar to our previous work in [9], the vehicle masses m are in the range of $1000kg - 3500kg$, and the frontal areas A_f are in the range of

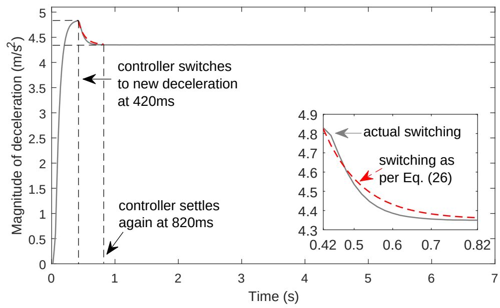

Fig. 4. Vehicle 8's deceleration switching from a $4.82m/s^2$ to a $4.35m/s^2$ magnitude during a distress situation

$2m^2 - 2.5m^2$, i.e., we consider passenger and utility vehicles. Since the aerodynamic coefficients C_D of production cars are in the range of $0.311 - 0.475$ [16], the same was chosen.

We consider a dry asphalt surface and, hence, the coefficient of road adhesion μ is 0.85 [16]. This also implies that vehicles can achieve a maximum deceleration magnitude of 0.85g (under optimal brake-force distribution). As a result, we chose the vehicles' magnitude of maximum deceleration capabilities in the 0.5g – 0.8g range. Note that due to the equivalent mass factor γ_m, with a common value of 1.05, the corresponding maximum deceleration magnitudes would be lesser [9].

Other parameters common to all vehicles are the coefficient of rolling resistance $f_r = 0.015$, the air mass density $\rho = 1.225kg/m^3$, acceleration due to gravity $g = 9.8m/s^2$, and vehicle length of $5m$. Additionally, before the braking maneuver is initiated, vehicles are assumed to be traveling at a common cruise velocity of $30m/s$. A common dead time of $0.1s$ is considered for their brake-by-wire systems. Therefore, all vehicles cover a distance of $3m$ before actually starting to decelerate.

6.2 Test Results

In the following, we present our simulation results. We first dedicate some space to analyze the use of space buffers and then discuss braking under a distress situation.

Effectiveness of space buffers. We consider 100 datasets generated as explained before and log the stopping distances as the number of vehicles increase from 1 to 20. Fig. 5 shows the average of such stopping distances over the 100 datasets.

We compare our Space-Buffer approach with $B = 1m$, $B = 2m$, and $B = 3m$, thereby, leading to inter-vehicle separations of $2m$, $3m$, and $4m$ respectively, with the intuitive approaches — Least Platoon Length and Least Stopping Distance — discussed before. Recall that Least Platoon Length

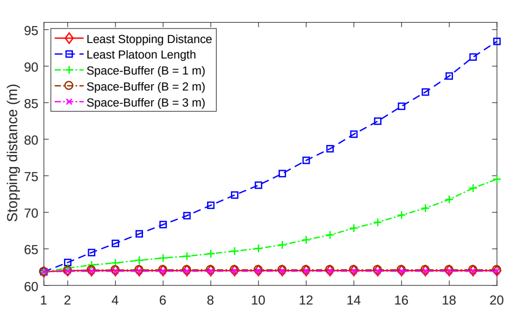

Fig. 5. Stopping distance vs. number of vehicles

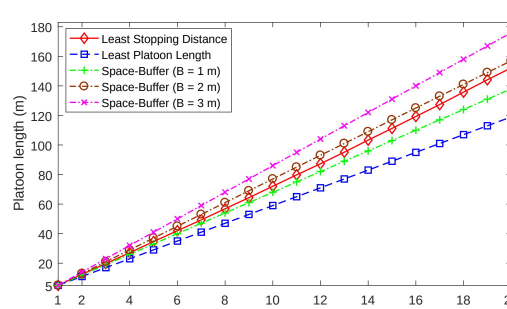

Fig. 6. Platoon length vs. number of vehicles

consists in making every vehicle brake as the worst-braking vehicle in the platoon. As a result, the inter-vehicle separations can just be the $1m$ SG accounting for packet losses. Hence, this approach results in the shortest possible platoon length and optimum fuel/energy savings, but at the cost of longest possible stopping distance [9].

On the contrary, the optimum stopping distance is achieved by the Least Stopping Distance approach as the vehicles are sorted as per their braking capabilities starting with the best decelerating vehicle. As mentioned before, the separations vary to avoid intra-platoon collisions. Further, they are increased by the $1m$ SG leading to longer platoons and lesser fuel/energy savings [9].

In Fig. 5, as expected, the Least Platoon Length approach yields the worst stopping distance of around 95 meters for 20 vehicles. Even with $B = 1m$, our Space-Buffer approach achieves a stopping distance that is around 20 meters shorter than that. The optimum stopping distance of around 62 meters is achieved by the Least Stopping Distance approach and also by our Space-Buffer approach with $B = 2m$ and $B = 3m$ [9]. It can be concluded that further increasing B (beyond $3m$) does not considerably reduce the stopping distance.[10]

Fig. 6 shows the resulting platoon length for the different approaches. With constant inter-vehicle separations of $1m$, the Least Platoon Length approach achieves the shortest length of $119m$ for 20 vehicles. The next best platoon length of $138m$ is achieved by the Space-Buffer approach at inter-vehicle separations of $2m$ (i.e., $B = 1m$). Contrarily, for greater values of B, the proposed Space-Buffer approach leads to platoon lengths that are even longer than that of the Least Stopping Distance approach (with around $157m$ for 20 vehicles). This is because the inter-vehicle separations are adapted in Least Stopping Distance as per the braking capabilities of the consecutive vehicles, whereas in the Space-Buffer approach they remain constant [9].

As a consequence of this comparison, we conclude that $B = 1m$ results in the most benefits, obtaining the best trade-off between stopping distance and platoon length. Therefore, for the following experiments, we mainly focus on $B = 1m$, but also include $B = 2m$ where meaningful. Since $B = 3m$ results in platoons that are too long compared to the other approaches, we exclude it from further consideration. A thorough discussion about the aerodynamic benefits of these approaches can be found in [9].

Braking on a flat road. We now consider a smaller platoon consisting of 10 average vehicles,

[10]There is, however, an almost negligible deduction of the stopping distance due to an increase of the aerodynamic force acting on the lead vehicle as the inter-vehicle separations are increased by B (for an explanation of this see [20] [21]).

Table 3. Dataset of vehicles used in the simulation (d and S respectively stand for deceleration and stopping distance, where we omit indexes for simplicity. Further, the equivalent mass factor γ_m is also considered in the d's shown in the 3rd column from the left.).

ID	m (in kg)	max. $\lvert d \rvert$ (in g)	C_D	A_f (in m^2)	Controller's integral gain (Ki)	Original S (in m)	Required S at $B = 1$ (m)	Desired $\lvert d \rvert$ (in g)	Simulated S (in m)
1	3284	0.7430	0.289	2.02	34482	67.78	91.32	0.5377	91.29
2	1317	0.7188	0.273	2.14	13828.5	69.88	92.32	0.5314	92.27
3	1243	0.6927	0.195	2.41	13051.5	72.24	93.32	0.5253	93.28
4	1696	0.6885	0.221	2.35	17808	72.63	94.32	0.5192	94.31
5	2581	0.6701	0.257	2.05	27100.5	74.46	95.32	0.5130	95.39
6	3394	0.6635	0.257	2.48	35637	75.20	96.32	0.5067	96.51
7	3037	0.6635	0.196	2.35	31888.5	75.20	97.32	0.5005	97.63
8	2367	0.5883	0.269	2.16	24853.5	83.96	98.32	0.4922	98.69
9	3413	0.5251	0.273	2.02	35836.5	93.35	99.32	0.4903	99.53
10	3265	0.4864	0.315	2.02	34282.5	100.32	100.32	0.4864	100.28

which we simulate in Matlab/Simulink. To this end, we use the non-linear model of Section 3.2 parametrized as per Table 3. For each corresponding brake-by-wire controller, we considered a sampling time of $20ms$. To meet the specifications in Table. 1, we obtained the corresponding gains using Matlab's PID Tuner, which returned non-zero integral gains as shown in Table 3, whereas both the proportional and derivative gains were zero. Additionally, to prevent integral windup, *clamping* was used. Further details on how we designed the brake-by-wire controller along with our vehicle and platoon models (in Simulink) can be found in [8].

Fig. 7 shows the trajectories of individual vehicles based on the proposed design technique of Section 4.2, during an emergency braking on a flat road. Trajectories are represented by ribbon-like plots that account for the vehicle length (in our case $5m$).

Overall, it can be observed from Fig. 7 that all vehicles in the platoon brake to complete standstill without collisions, i.e., ribbons do not overlap, while reducing the overall stopping distance from $100.28m$ (i.e., that of the worst braking vehicle) to $91.29m$. Note that all vehicles travel $3m$ (due to the actuation's dead time as discussed above) before beginning to decelerate. This is why the 10$^{\text{th}}$ vehicle's ribbon does not start exactly at (but rather at $3m$ from) the origin in Fig. 7.

Vehicles' individual stopping distances after complete standstill — also presented in the last column of Table 3 — differ by few centimeters from the required stopping distance (8$^{\text{th}}$ column from the left). This is mainly due to rounding errors and can be easily fixed by rounding up the original stopping distances (7$^{\text{th}}$ column from the left) before computing space buffers or slightly increasing the safeguard as discussed in Section 3.3.

Similarly, Fig. 8 shows the results for $B = 2m$ with an overall stopping distance of around $82m$. Interestingly, the overall stopping distance in this case is around $9m$ shorter than for $B = 1m$. This is due to the greater value of B, but also partly due to increased aerodynamic force on the lead as a consequence of the larger inter-vehicle separations (which is in line with results in [20] [21]).

Braking in a downhill. We now demonstrate how certain vehicles fail to track their reference decelerations in a downhill and, as a result, collisions happen. Fig. 9 shows that even a 4° slope downhill results in vehicle collisions for $B = 1m$, i.e., ribbons overlap. In this test, all vehicles remain on the same 4° slope for the whole brake maneuver. Similarly, the inter-vehicular collisions happen for $B = 2m$ (and 4° slope) as well and, hence, the figure is not included for this case.

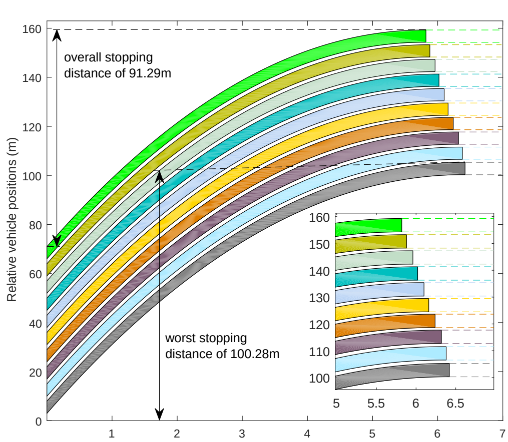

Fig. 7. Braking on a flat road ($B = 1m$)

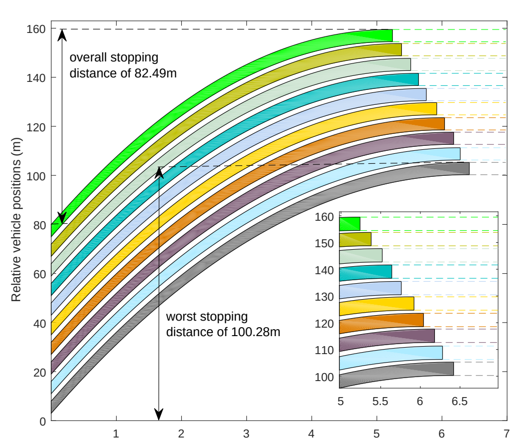

Fig. 8. Braking on a flat road ($B = 2m$)

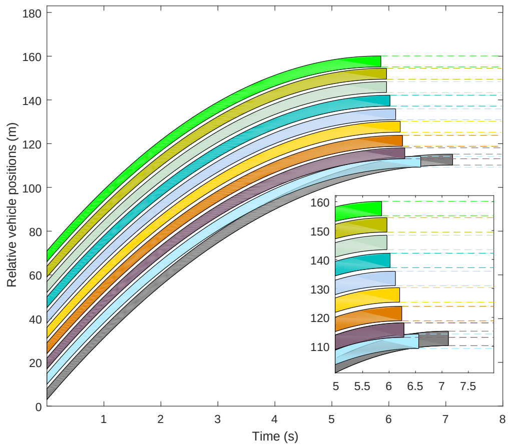

Fig. 9. Braking on 4° slope downhill without distress message ($B = 1m$)

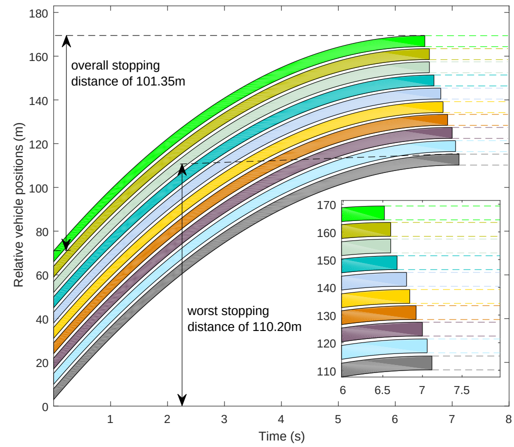

Fig. 10. Braking on 4° slope downhill with distress message ($B = 1m$)

From Table 3, we see that the 9th and 10th vehicle are already required to brake close to/at their maximum decelerations on a flat road. In downhill, they simply cannot counter the disturbing grade force. As a result, they consume the space buffers to their respective immediately leading vehicles, finally, colliding into each other and into the 8th vehicle. These simulated collisions can be more catastrophic in reality as they may also lead to collisions with the 7th vehicle and beyond.

Avoiding collisions by distress messages. The above collisions can be avoided by a distress message broadcast. Upon an emergency, once the settling time of $400ms$ has elapsed, vehicles 9 and 10 know that they fail to track their references. As a result, they broadcast a distress message with all vehicles adjusting their decelerations to the weakest vehicle under distress as described in Section 5. This leads to a safe brake maneuver, clearly, at the cost of a longer stopping distance of $101.35m$ — see Fig. 10. For $B = 2m$, the achieved overall stopping distance is $92.33m$.

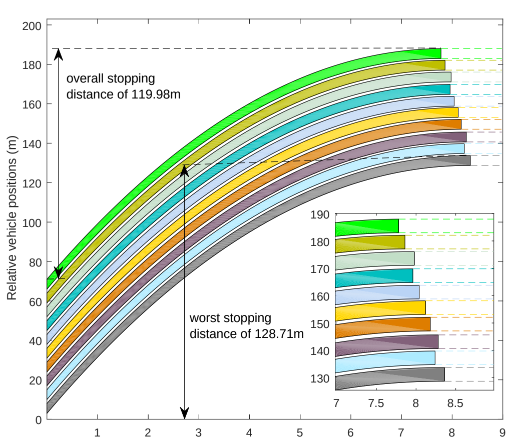

Fig. 11. Braking on 8° slope downhill with distress message ($B = 1m$)

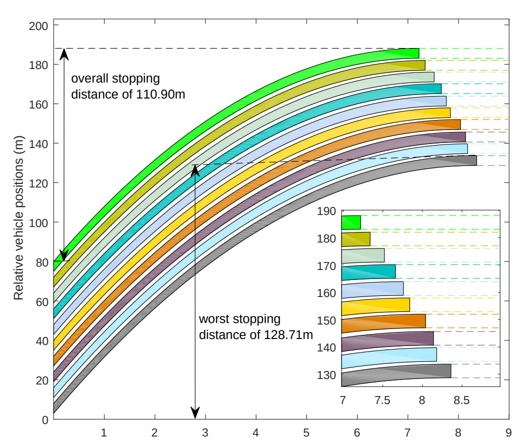

Fig. 12. Braking on 8° slope downhill with distress message ($B = 2m$)

Braking in a steep downhill. We now simulate the platoon on a steep downhill of 8°, i.e., the maximum allowed on European highways as explained before. Similar to previous results, all vehicles are on this same grade for the whole brake maneuver. Due to the steeper downhill, now even the 8^{th} vehicle is under distress. The distressed vehicles now need a longer stopping distance than that achieved on a 4° slope. This impacts the overall stopping distance as shown in Fig. 11 for $B = 1m$, which now amounts to around $119m$ as opposed to the $101m$ on the 4° slope. For $B = 2m$, the achieved overall stopping distance is around $110m$, but again at the cost of a longer platoon length — see Fig. 12.

7 POTENTIAL HAZARDS

In this section, we discuss the impact of communication loss, nonlinear effects at braking, and arbitrary order of vehicles on the proposed approach.

7.1 Communication loss

IEEE 802.11p is robust up to distances of $250m$ to $300m$ [3] and our platoon length, even with 20 vehicles, is below 200m. However, in this section, we do consider the possibility of communication loss. As mentioned above, the safeguard SG is provisioned in between any two vehicles of a platoon to compensate for communication loss. In particular, note that space buffers should never be affected by this (but these are rather exclusively used to compensate for differences in the stopping distances of individual vehicles).

Now, if a brake command is lost, since this is also replicated through live signals, the platoon vehicles can still guarantee a fail-operational behavior. This is because all the vehicles begin braking simultaneously $20ms$ after the brake command is broadcast. Clearly, vehicles receiving the brake command through live signals must start braking without delay.

On the other hand, if a maximum number of packets from a live signal are lost in a row, which depends on the selected cruise speed and SG, a fail-safe operation must be enforced. Affected vehicles must then assume the worst case, i.e., that the platoon is already braking, and start braking themselves to dissolve the platoon without any accidents.

The loss of distress messages is more difficult to handle. Similar to live signals, there can only be a maximum number of distress messages lost, which again depends on SG. However, this time, affected vehicles are already braking (when a distress message is sent) and, hence, their speed is being constantly reduced. As a result, potentially more distress messages can be lost than packets from live signals. However, in contrast to live signals, if this threshold is exceeded, there is no way of guaranteeing safety — recall that vehicles under distress are already braking at their fullest capacity. The only solution is to provision sufficient redundancy to guarantee that distress messages are not lost or engineer intra-platoon collisions to minimize damage [10].

To illustrate how communication loss affects inter-vehicle separations, in Fig. 13, we consider a 2-vehicle platoon based on the approaches from before. The two vehicles in this experiment are supposed to simultaneously initiate an emergency braking at time $0s$. However, the trail vehicle does neither receive the brake command nor the corresponding packets from the live signal and, hence, it does not begin to brake, but until a threshold of three consecutive packets are lost, which corresponds to $SG = 1m$ and a speed of $30m/s$ (i.e., around $100km/h$). Note that, in Fig. 13, the inter-vehicle separation is plotted from the perspective of the trail vehicle, which reaches standstill at $6.42s$ independent of the approach.

Note that the threshold of three packets lost in a row does not consider controller-related effects, i.e., it assumes that vehicles can instantaneously reach their deceleration. However, the lead vehicle settles at its deceleration $400ms$ after initiating the emergency brake maneuver (at $0s$), whereas the trail vehicle takes longer as it does not initiate braking but $40ms$ later, settling at its deceleration

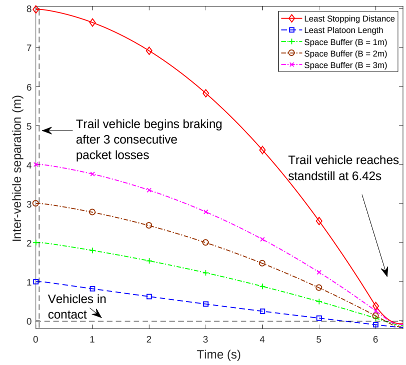

Fig. 13. Effect of packet losses on inter-vehicle separation

at 440ms. As a consequence, vehicles collide, which translates into an inter-vehicle separation at standstill that is (slightly) less than zero, ranging from $-0.08m$ for Least Stopping Distance to $-0.16m$ for Least Platoon Length. Our Space-Buffer approach is in between these values.

This difference in the final inter-vehicle separation can be explained by the fact that the larger initial separation of $7.97m$ (at $0s$) for Least Stopping Distance results in an increased aerodynamic force on the trail vehicle in comparison to the other approaches. This aids the trail vehicle reaching standstill in a shorter distance. On the contrary, this aerodynamic force is smaller for Least Platoon Length because of the initial separation of just $1m$, thereby leading to a larger non-zero separation at standstill.

Clearly vehicles collide towards the end of the brake maneuver since there is no margin for errors. This situation can be solved by choosing an SG slightly greater than $1m$. However, this also negatively impacts the platoon length and aerodynamic savings. As an alternative approach, keeping the SG constant at $1m$, the platoon's maximum speed can be restricted to $25m/s$ (i.e., $90km/h$).

Finally, note that the above analysis applies to any pair of consecutive vehicles in a platoon with more than 2 vehicles. This is because packet loss is only dealt by the safeguard SG, which must be provisioned in between any two vehicles.

7.2 Nonlinear effects at braking

In this paper, we assume that each vehicle estimates its maximum brake force and, thus, its deceleration capability. However, in case of nonlinearities at braking, for example, suboptimal air pressure in tires, worn out profiles or brake actuators, etc., the applied brake force is underutilized resulting in more reduced deceleration magnitudes than originally estimated. Such nonlinearities lead to the corresponding vehicle failing to track its assigned deceleration even on a flat road especially, if it is operating at its limit, potentially causing already a distress situation as discussed in Section 5.

Clearly, distress situations are supposed to be an exception and should not happen on a flat road. On the other hand, nonlinear effects at braking are difficult to model and, in particular, change over time (as, for example, tires lose pressure or age). As a result, if a distress situation occurs on a flat road, the platoon lead should recompute and re-assign decelerations to vehicles to avoid this from happening again. Further analysis on this issue is out of the scope of this paper.

7.3 Arbitrary order of vehicles

In this section, we discuss the impact of an arbitrary order of vehicles on the proposed Space-Buffer approach. To that end, let us consider a 3-vehicle platoon, with stopping distances of $60m$,

$65m$, and $70m$ as well as $B = 1m$. Excluding the arrangement where vehicles are sorted as per their non-decreasing stopping distances, which we have assumed so far, all other possible vehicle arrangements are: $[65m, 60m, \mathbf{70m}]$, $[65m, \mathbf{70m}, 60m]$, $[\mathbf{70m}, 60m, 65m]$, $[\mathbf{70m}, 65m, 60m]$, and $[60m, \mathbf{70m}, 65m]$. The vehicle's stopping distance that dominates S_{SB} in each of the corresponding arrangement has been highlighted in boldface, i.e., these vehicles have the longest stopping distance in spite of using all the space buffers as discussed in Section 3.3.

It can be observed that the last vehicle does not necessarily decide S_{SB} when the vehicles are not ordered as per their non-decreasing stopping distances. For example, in the arrangement $[70m, 65m, 60m]$, the lead vehicle itself decides S_{SB} and, thus, the vehicles have to achieve stopping distances of $[70m, 71m, 72m]$ respectively. In fact, the last two vehicles can even brake at the rate of the (weaker) lead vehicle allowing to reduce the inter-vehicle separations. In this case, since all vehicles have a stopping distance of $70m$, $B = 0m$ can be selected, i.e., only SG can be used as for Least Platoon Length. Based on this example, we conclude that the space-buffer computations as per Section 3.3 still apply even when vehicles are not arranged as per their non-decreasing stopping distances. However, it should be noted that the overall stopping distance that results from an arbitrary order of vehicles is not as short as it can be with the proposed Space-Buffer approach.

8 CONCLUDING REMARKS

In this work, we considered vehicles with heterogeneous braking capabilities operating in a platoon with separations below $5m$ (to maximize benefits), particularly, $3m$ and $2m$. We analyzed the case of braking in an emergency and proposed an approach that provisions space buffers in between any two vehicles. This way, leading vehicles can decelerate at higher magnitudes than their following vehicles without compromising safety. As a result, we are able to considerably reduce the overall stopping distance and simultaneously the platoon length compared to intuitive approaches one can follow. Reducing a platoon's stopping distance and its length is paramount for a safe operation on open roads.

As an extension to space buffers introduced previously in our work [9], we showed an example of how to design the corresponding brake-by-wire controllers that can easily track their assigned decelerations on a flat road as well as on uphill road profiles. However, in downhill situations, certain controllers particularly in vehicles towards the end of the platoon cannot continue tracking their assigned decelerations due to saturation by their brake actuators. This is because they are already braking at their limit on a flat road (to reduce the overall stopping distance as much as possible) and in a downhill they simply cannot negate the effect of the disturbing grade force. As a result, it cannot be guaranteed that the whole platoon brakes in a safe manner anymore. To overcome this problem, we proposed a cooperative behavior among vehicles based on inter-vehicle communication. The idea is that a vehicle sends a distress message, if it is unable to track its assigned deceleration. As a result, other vehicles can adapt their originally assigned decelerations (computed for a flat road) to avoid collisions within the platoon.

As future work, we plan to extend our approach to anomalous road conditions like glaze, wet or snowy surfaces. In such cases, vehicles in the front or in the middle of the platoon may incur distress. In contrast to this, in the downhill situation, only vehicles towards the platoon end are affected. As a result, considering anomalous road conditions implies defining more complex emergency procedures.

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