Exploiting Space Buffers for Emergency Braking in Highly Efficient Platoons

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***Abstract*—With the advent of autonomous driving, road trains or platoons are regaining importance as a meaningful way of improving traffic efficiency and economizing on fuel/energy. It has been shown that reducing inter-vehicle separations to less than one car length results in the most benefits for the whole platoon; however, this poses a number of challenges. In particular, it becomes difficult to guarantee a collision-free braking in an emergency situation considering that individual vehicles may have different braking capacities in real-life settings — due to, for example, different load conditions, etc. Although control-theoretic approaches can be used to design a platoon's cruise operation, emergency braking leads to saturation, i.e., the maximum possible braking force is applied so as to stop the platoon in the shortest possible time and needs to be designed separately. In this paper, we address this issue and introduce a cyber-physical approach that guarantees a collision-free braking in emergency situations. The proposed approach exploits space buffers contained in between vehicles and can be configured to reduce stopping distance and platoon length, while maximizing aerodynamic benefits. We evaluate our approach based on realistic simulations with vehicle dynamics models typically used in the automotive industry for hardware-in-the-loop (HiL) testing. The effects of communication loss during platoon operation are also considered and fail-safe mechanisms are proposed and investigated.**

I. Introduction

There is an increasing number of vehicles around the globe, which inevitably leads to congestion and traffic jams on roads and highways. To alleviate this situation, normally, infrastructural improvements need to be undertaken. However, these are costly and have a limited effect.[1]

Currently, a standard highway allows a maximum throughput of about 2000 vehicles/hour at an average inter-vehicle spacing of 35 meters [1]. In order to increase this throughput and, at the same time, reduce energy/fuel consumption, platooning comes into picture.

At the moment, platooning involves several vehicles closely following each other at inter-vehicle distances of 5 to 10 meters. The lead vehicle, being manually driven, is usually a truck, resulting in reduced aerodynamic forces on the following vehicles [2] [3]. However, the platoon lead is devoid of any benefits.

On the other hand, when inter-vehicle distances are reduced to below one car length, wind tunnel experiments not only demonstrate improved aerodynamic benefits for trail vehicles, but also for the lead. Benefits stagnate, however, at 0.20 car lengths (i.e., around 1 meter) [4].

At such close inter-vehicle distances, it is difficult to guarantee safety, in particular, during emergency braking. So far, most approaches from the literature focus on designing and improving a platoon's cruise operation, for which techniques based on control theory have been effectively used [5] [6] [7].

However, during emergency braking, control systems attain saturation, i.e., the maximum possible braking force is constantly applied until standstill, and needs to be designed independent of cruise control.

To this end, when considering heterogeneous platoons, one possibility is to make the whole platoon brake as the vehicle with the least achievable deceleration rate [8]. This approach results in a generally undesirable long stopping distance.

A second possibility is to let the vehicle with the best deceleration rate lead the platoon resulting in a shorter stopping distance. However, inter-vehicle separations are then a function of the difference in deceleration rates between consecutive vehicles. The greater this difference, greater their separations will be resulting in longer platoons and lesser fuel/energy savings.

These two, rather intuitive, approaches achieve optimum values either with respect to aerodynamic benefits and platoon length in the first case, or stopping distance in the second case.

Contributions. In this paper, we consider heterogeneous platoons with vehicles of different braking capacities — due to, for example, load conditions, etc. — and analyze emergency braking. Based on this, we propose a cyber-physical approach that exploits space buffers in between vehicles and can be configured to minimize both stopping distance and platoon length while maximizing aerodynamic benefits. We show that the proposed approach guarantees safety, i.e., it prevents vehicle collisions while braking. A comparison with the above mentioned, more intuitive, approaches is performed on the basis of aerodynamic savings, platoon length, and stopping distance showing that the proposed scheme allows for improvements in all these parameters. The effects of communication loss are also analyzed and a fail-safe behavior is outlined for the case where the number of consecutive packets lost crosses a critical threshold.

[1]In particular, the road network cannot be improved/extended at the same pace with which vehicles are sold.

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Structure of the paper. Related work is presented in the next section. Section III discusses basic background knowledge on platooning, brake-by-wire systems and the computation of a vehicle's stopping distance. Our safety-preserving approach exploiting space buffers is presented in Section IV. The experimental setup involving realistic car models on an automotive HiL setting and the corresponding results are presented in Section V. Finally, Section VI concludes the paper.

II. Related Work

Platooning provides comfort for drivers as the following vehicles are controlled automatically [3] [9] [10]. The benefits are probably more prominent in the context of trucks as recently shown [11] [12] [13]. The longitudinal and lateral control of trucks in a platoon with the aid of image processing was demonstrated in [9]. However, the SARTRE project [3] [14] was the first in performing a prototypical implementation with 5 to 10 meters separation between vehicles [15].

The California PATH program [1] showed the benefits of maintaining inter-vehicle distances at around 0.6 car lengths [4]. Fuel/energy savings were logged for other inter-vehicle distances considering two-, three- and four-vehicle platoons. In the two-vehicle platoon case, the average fuel savings at close following of 0.6 car lengths (approximately 3 meters) was observed to be much greater than the average savings for the same two-vehicle platoon at a spacing of 1.2 car lengths. Increasing the number of vehicles in platoon, increased the overall average fuel savings with more savings at shorter inter-vehicle distances [1].

So far, most works have focused on control strategies. The emphasis is particularly on ensuring string stability [16] [17] [18], where a small disturbance in the inter-vehicle separations between any pair of consecutive vehicles is guaranteed not to amplify towards the end of the platoon. However, a string stable platoon does not ensure collision free operation during emergency braking. In such scenarios, the system attains saturation, i.e., the maximum possible braking force is constantly applied until standstill, and needs to be designed and analyzed independent of cruise control.

There is little work on emergency braking within a platoon. Notable exceptions to this are [19], [20] and [21]. The probability and number of inter-vehicular collisions along with relative velocities at impact while operating in platoons were analyzed in [19].

The effects of driver reaction times and delays involved in manual actuation of brakes considering control system failures was carried out in [20]. A two truck platoon was considered for manual emergency braking and the results demonstrate the necessity of the following vehicle to brake at a much higher deceleration rate than the lead so as to avoid collisions.

The minimum inter-vehicle separations to guarantee collision free braking for heavy duty vehicle platoon was considered in [21]. However, packet losses were not considered and the following vehicle was required to brake at a higher deceleration rate than the lead.

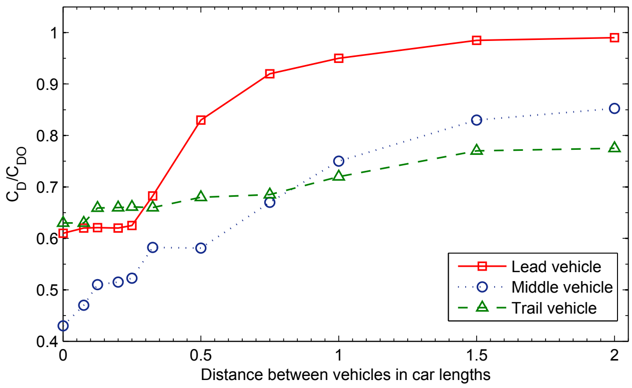

Fig. 1. Drag coefficient ratio for three close-following vehicles

To the best of our knowledge, this is the first attempt to study this problem, considering heterogeneous vehicles operating at inter-vehicle separations below one car length.

III. Background

A. Aerodynamic Gain

A vehicle closely following another vehicle will have reduced aerodynamic forces acting on it. This is the principle behind existing platoon strategies where several cars or trucks follow a lead vehicle at distances of 5 to 10 meters [15] [3] [2]. The lead vehicle will usually be a truck so that the following/trail vehicles benefit the most from reduced aerodynamic forces.

The University of California along with the United States Department of Transportation conducted several experiments as part of the California PATH program [1] [4]. These experiments considered platoons with different number of vehicles and demonstrated that even the lead vehicle experiences fuel/energy savings when the inter-vehicle distance is reduced to less than one car length. Interestingly, reducing the inter-vehicle distances to 0.35 car lengths and lesser, resulted in the lead vehicle experiencing lesser aerodynamic drag than the trail vehicle. The air mass pushed to the lead's rear by its following vehicle can be reasoned for this counter-intuitive behavior.

The ratio of aerodynamic drag coefficient when traveling in a platoon C_D, to the aerodynamic drag coefficient of the same vehicle in isolation C_{DO}, is plotted in Fig. 1 for a three-vehicle platoon as a function of car lengths. Here, vehicles are assumed to have the same height [1] [4]. Note that the aerodynamic resistance on a vehicle/car depends proportionally on its drag coefficient.

At inter-vehicle distances of 1 car length or greater, the lead vehicle is unaware of the following vehicles and has almost no benefits. The two following vehicles experience reduced aerodynamic forces up to a distance of 10 car lengths. Since only the following vehicles benefit at such inter-vehicle distances, this is said to be a *weak interaction regime*. The lead vehicle begins to experience significantly less aerodynamic forces only when the inter-vehicle distance reduces to less than 1 car length. This is said to be a *strong interaction regime* as the benefits are mutual. In this case, the drag coefficient ratio for the trail vehicle also decreases but not so rapidly — see Fig. 1.

There will be a reduction in the drag coefficient ratio for the lead vehicle up to a spacing of 0.20 car lengths. Further until zero spacing, it is more or less constant. The middle or the second vehicle's drag coefficient ratio is constituted by two plateau regions — from 0.1 to 0.2 and from 0.3 to 0.5 car lengths. At 0.35 car lengths and lesser, interestingly, the drag coefficient ratio of the lead is less than that of the trail and continues the same until zero spacing. As stated before, this behavior is due to the wind being pushed towards the rear of the lead by the following vehicles [1] [4]. Due to combined effects stemming from the lead and trail vehicles, the middle vehicle benefits the most and has lowest drag coefficient ratio.

For platoons with large numbers of vehicles, the following generalizations can be made [4]:

- The drag coefficient ratio for the lead vehicle and for each of the subsequent vehicles up to the n-th is independent of the number of vehicles given that there are at least *n+1* vehicles.
- The middle vehicles of a platoon experience least drag coefficients thereby having the most fuel/energy savings.
- Adding vehicles to a platoon reduces the average drag coefficient ratio for the whole platoon, however, this asymptotically approaches a value of around 0.5 as per Fig. 1 (considering that inter-vehicle separations are reduced to zero, which is not achievable in practice).

Even though a reduction in the magnitude of aerodynamic forces implies fuel/energy savings, it also results in longer stopping distances for vehicles during braking. This behavior can be attributed to the fact that aerodynamic forces oppose motion and contribute to deceleration. Reducing their magnitudes causes vehicles to majorly rely on the forces generated by brakes leading to longer stopping distance before standstill.

B. Brake by Wire

Since, in a platoon, vehicles travel at close distances, brake-by-wire systems need to be used [22] that have less reaction time and can be automated more easily. In particular, these allow adjusting braking forces to compensate for differences between vehicles as explained below. Among the decelerating forces acting on a vehicle, the braking force generated by vehicle's brakes is the major one. However, aerodynamic resistance, rolling resistance of tires and grade resistance also aid in braking. The total force then being the summation of all these forces is stated by the following equation [23]:

$$F_{tot} = F_b + f_r \cdot W \cdot cos\theta + R_a \pm W \cdot sin\theta, \qquad (1)$$

where F_{tot} is the resultant total force in Newtons (N), the force generated by vehicle's brakes in N is F_b, f_r is the coefficient of rolling resistance, the vehicle weight in N is W, θ is the angle of the road with the horizontal in degrees, and R_a is the aerodynamic resistance on the vehicle also in N. $W \cdot sin\theta$ takes a positive sign when the vehicle is moving uphill and a negative sign when downhill [23].

Vehicles belonging to the same category and performance range have different braking capacities. Even though equipped with similar brakes, their loading conditions may differ. In other words, the number of occupants and additional loads exert forces on the front and rear axles — depending on their distances to the vehicle's center of gravity — and affect the maximum achievable deceleration rate.

Another important parameter is the road/tire conditions along with the tires' air pressure. Physically, a vehicle's deceleration rate when normalized by g (acceleration due to gravity) cannot exceed the coefficient of road adhesion [24].

The maximum braking forces that can be sustained by the front and rear axles are a function of both loads or weights acting on them and the coefficient of road adhesion. The front and rear axles should not be supplied with braking forces greater than expressed by the following equations [23]:

$$\hat{F}_{b,f} = \mu \cdot W_f, \qquad (2)$$

$$\hat{F}_{b,r} = \mu \cdot W_r, \qquad (3)$$

where W_f and W_r are weights on front and rear axle respectively in Newtons (N). The coefficient of road adhesion is denoted by μ, $\hat{F}_{b,f}$ represents the maximum braking force in N the front axle can sustain and, similarly, $\hat{F}_{b,r}$ denotes this maximum braking force in N for the rear axle.

When the braking forces at the front and rear axle reach the values in (2) and (3) respectively, wheels are at the point of locking and the vehicle achieves its maximum deceleration rate. If the braking forces supplied exceeds these bounds, wheels lock resulting in skidding, but not increasing deceleration rate. Therefore, given a fixed braking force distribution to the front and rear wheels, the vehicle loading conditions affect the maximum achievable deceleration rate [23].

The computations done by the brake-by-wire system rely on the Newton's second law of motion as expressed below:

$$F_{tot} = m \cdot a, \qquad (4)$$

where m represents the mass in kilograms (kg) and acceleration/deceleration in m/s^2 is denoted by a. Substituting F_{tot} by the sum of forces in (1) we get:

$$F_b + f_r \cdot W \cdot cos\theta + R_a \pm W \cdot sin\theta = m \cdot a, \qquad (5)$$

replacing m by W/g and reshaping, we finally obtain the vehicle's deceleration normalized by g [23]:

$$\frac{F_b + f_r \cdot W \cdot cos\theta + R_a \pm W \cdot sin\theta}{W} = \frac{a}{g}. \qquad (6)$$

During platoon operation, braking forces required to achieve a desired deceleration rate will be computed individually for each vehicle by their respective brake-by-wire systems. To this end, the proportion of brake force distribution to the front and rear axles, the vehicle's weight W, along with the angle of the road θ need to be known — note that modern vehicles are already equipped with sensors that allow measuring/estimating these values. In addition, the aerodynamic drag coefficient during platoon operation does not have to undergo drastic variations, which can be guaranteed by maintaining inter-vehicle separations (almost) constant.

C. Stopping Distance

Due to different load conditions, the individual braking capacities of vehicles may be different. As a result, if one vehicle brakes at a deceleration rate that cannot be achieved by its immediately following vehicle in the platoon, there may be a collision (depending on the inter-vehicle separation).

The *stopping distance* S achieved by a vehicle is a function of various parameters as shown in the following equation [23]:

$$S = \frac{\gamma_m W}{2gC_A} \ln\left(1 + \frac{C_A V^2}{\eta_b \mu W + f_r W \cos\theta \pm W sin\theta}\right). \quad (7)$$

In (7), W is the weight of the vehicle in N, g denotes the acceleration due to gravity in m/s^2, C_A is the aerodynamic constant as shown in (8), V is the initial speed of the vehicle in m/s, η_b is the braking efficiency as per (9), μ is the coefficient of road adhesion, f_r is the coefficient of rolling resistance, θ is the angle of the road in degrees ($W \cdot sin\theta$ takes a positive sign in an uphill and a negative sign in a downhill situation), the moment of inertia of the rotating parts involved in braking is denoted by γ_m and termed *equivalent mass factor* (usually around 1.03 - 1.05 for passenger cars) [12]. In addition, we have [23]:

$$C_A = \frac{\rho}{2} \cdot C_D \cdot A_f, \quad (8)$$

$$\eta_b = \frac{\left(\frac{a}{g}\right)}{\mu}, \quad (9)$$

where ρ is the air mass density in kg/m^3, C_D is the drag coefficient, A_f is the vehicle's frontal/projected area in m^2 along the direction of travel, and a is the maximum achievable deceleration in m/s^2. Clearly, the stopping distance will be longer in case of heavy vehicles and lower deceleration rates. Note that the time taken to activate brakes is not considered in (7) and might effectively lead to longer stopping distance [23].

On the basis of stopping distances, during emergency braking, the two intuitive approaches from the introduction — referred to as *Least Stopping Distance* and *Least Platoon Length* — can be used.

The Least Stopping Distance approach achieves optimum stopping distance by allowing the vehicle with the best, i.e., the shortest, stopping distance to lead the platoon. This is then followed by the vehicle with the second best stopping distance and so on until reaching the last vehicle which brakes the worst.

The inter-vehicle separations vary as function of the difference in stopping distances between consecutive vehicles. The greater this difference, greater their separations will be. Additionally, this separation is then increased by one-meter *safeguard* to account for communication losses during platoon operation as discussed later.

Inter-vehicle separations in the Least Platoon Length approach are all equal to this one-meter safeguard. In this case, the whole platoon brakes as the vehicle with the worst, i.e., the longest, stopping distance. Even though the aerodynamic benefits and platoon lengths are optimum for this second approach, the longer stopping distance is undesirable making our proposed approach necessary.

IV. Space-Buffer Scheme

Similar to the Least Platoon Length, inter-vehicle separations are the same for all vehicles and kept constant. However, now these not only include the aforementioned safeguard but also an additional *space buffer*.

As a result, this scheme also has a reduced length and high aerodynamic benefits. The difference to Least Platoon Length is that vehicles in this approach make use of the space buffer contained in the inter-vehicle separation to allow for a shorter stopping distance of the whole platoon. In other words, the lead vehicle is allowed to brake at a higher deceleration rate than the following vehicles.

As in the Least Stopping Distance, let us again assume that vehicles are sorted in the order of increasing stopping distances. That is, for the stopping distances of any two vehicles i and j denoted by S_i and S_j respectively, it holds that $S_i \leq S_j$ if $i < j$ holds.

Now, for each vehicle, if we utilize the space buffers contained in all the inter-vehicle separations towards the lead and subtract them from the corresponding vehicle stopping distance, there exists a vehicle for which this value will be the maximum. This scheme then allows an overall stopping distance given by:

$$S_{SB} = \max_{1 \leq i \leq n} \left(S_i - (i-1)B\right), \quad (10)$$

where B denotes the space buffer and n is the number of vehicles in the platoon and — by the assumed order — the index of the vehicle with the lowest deceleration rate. Clearly, B must be less than or equal to the inter-vehicle separation. Later, in our experiments we assign B a value of 1, 2 and 3 meters thereby resulting in total inter-vehicle separations of 2, 3 and 4 meters respectively when adding the one-meter safeguard discussed above.

Let us assume that $S_i - (i-1)B$ is maximum for $i = x$. Now, $S_{SB} = S_x - (x-1)B$. So, we allow the lead vehicle to have a stopping distance equal to S_{SB} that is $(x-1)B$ shorter than that of a vehicle x in the platoon. In other words, we make use of all space buffers between the lead and the vehicle x to compensate for the difference in stopping distance in the worst case, i.e., $S_x - S_{SB}$.

The next step is to configure the brake-by-wire systems of all vehicles to guarantee that no collision occur. To this end, we make use of (7) for each vehicle i in the platoon:

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

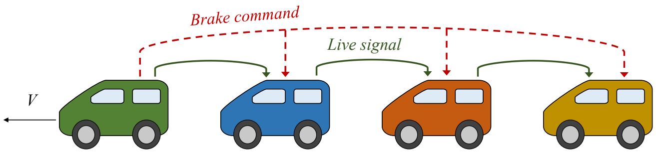

Fig. 2. Intra-platoon communication: live signal and brake command

i.e., we make the stopping distance of vehicle i equal to the selected stopping distance of the lead (i.e., S_{SB}) plus all space buffers in between the lead and vehicle i. For simplicity, we have made following replacements $K_1 = \frac{\gamma_m W}{2gC_A}$, $K_2 = C_A V^2$, and $K_3 = f_r W \cos\theta \pm W sin\theta$. Next, we need to solve for η_b, i.e., the braking efficiency of vehicle i, so we proceed as follows:

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

and then:

$$\eta_b = \frac{\frac{K_2}{\left(e^{\frac{S_{SB}+(i-1)B}{K_1}} - 1\right)} - K_3}{\mu W}. \tag{11}$$

Finally, we can use (9) to compute the necessary deceleration rate a of vehicle i and (5) to compute the necessary braking force F_b to be exerted.

It can be easily observed that the space buffers in the inter-vehicle separations are embedded between vehicles. It is therefore necessary to ensure that the displacements of any two consecutive vehicles during braking guarantees safety, i.e., no inter-vehicle collisions. A mathematical proof of the same is presented in the appendix.

Intra-Platoon Communication: The communication between vehicles constitutes the backbone of platoon operation both in cruise and emergency braking. As a result, we consider two types of messages that are sent (via wireless communication) between platoon vehicles: *live signal* and *brake command*.

As illustrated in Fig. 2, live signals are sent periodically from every — except for the trail — vehicle to its immediately following vehicle. These messages contain the current values of speed, acceleration, and steering angle of the sender.[2] The receiver then checks the plausibility of the live signal from its preceding vehicle, in particular, whether the difference to its own values of speed, acceleration, and steering angle is within an acceptable range.

If one vehicle receives a non-plausible live signal or this is not received at all for a specified period of time (i.e., packet losses are experienced), it performs an emergency brake by communicating the same to its following vehicles and the platoon disperses. In other words, if there is a problem with the live signal received, a vehicle assumes the worst-case situation to preserve safety, namely, that its preceding vehicle might be already braking.

[2]Clearly, live signals can and probably should be combined with control messages in the platoon; however, as already mentioned, we are concerned with emergency braking and not with cruise control.

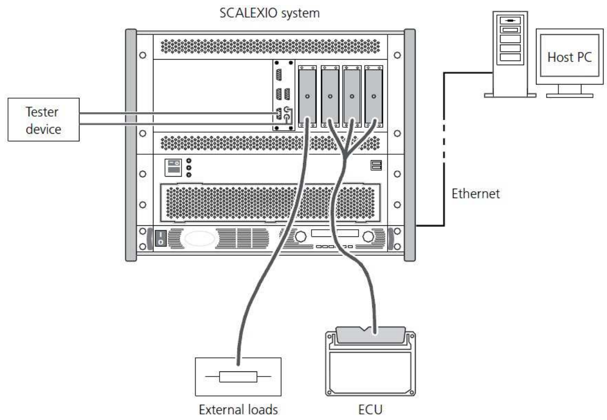

Fig. 3. dSPACE SCALEXIO external view

The frequency with which live signals are sent depends clearly on the cruise speed V. In this paper, we assume that live signals are sent every $20\,ms$ between any two vehicles in the platoon. This is sufficient to guarantee a safe behavior for up to $100\,Km/h$, considering that some packets may be lost on the communication channel and, hence, that there should be sufficient time to react in this extreme situation. Note that this frequency is considerably higher than that specified in Car-to-Car communication standards in Europe [25] with a maximum frequency of $0.1\,Hz$, i.e., $100\,ms$. However, as discussed later, $100\,ms$ does not suffice for a safe platoon operation.

During an emergency situation, the lead vehicle sends a brake command, i.e., a multicast message to all the following vehicles. In this paper, we consider that the lead will not initiate braking immediately, but $20\,ms$ later. In other words, all the vehicles start braking simultaneously $20\,ms$ after the lead sends a brake command. This behavior simplifies our analysis of the space-buffer scheme and, in addition, a $20\,ms$ delay does not significantly increase the platoon's stopping distances. Note that our analysis can be otherwise extended to the case of non-simultaneous braking, if required, i.e., when the lead starts braking $20\,ms$ before its following vehicles.

The emergency braking is normally initiated by the lead — see illustration in Fig. 2. Any other vehicle in between can initiate an emergency brake causing the platoon to disintegrate, only if it detects problems with its live signal.

V. Evaluation and Comparison

In this section, an experimental evaluation and comparison of the proposed Space-Buffer Scheme is performed.

A. Test Setup

We carry out experiments using a hardware-in-the-loop (HiL) system from dSPACE named SCALEXIO. A realistic model of a car involving complex models for vehicle dynamics, engine, drivetrain, transmission, brake system, wheels, and kinematics as shown in Fig. 4 is used for simulations.

An Electronic Control Unit (ECU) can be connected to the HiL through a special connector as shown in Fig. 3. The

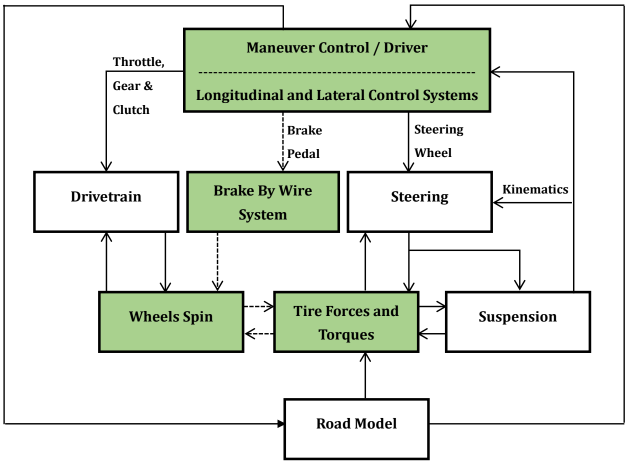

Fig. 4. Model of the car used in simulations

system to be controlled is simulated on the HiL. The Host PC monitors and logs the ECU signals during control operation. In our case, we run the whole simulation on the HiL and did not make use of an external ECU.

B. Test Data

For our experiments, we generated 100 datasets of 20 cars each. The cars in each dataset were randomly selected with their masses m in the range of $1000\,kg$ – $3500\,kg$. The braking capacities a, aerodynamic coefficients C_D, and frontal areas A_f, were also randomly selected in the range $0.5\,g$ – $0.8\,g$, $0.311 - 0.475$, and $2 - 2.5\,m^2$ respectively. The equivalent mass factor of all cars γ_m, is assumed to be 1.05. All cars are assumed to be 5 meters in length and of the same height.[3]

For the simulation we considered a flat and dry asphalt surface, thereby, restricting the maximum achievable deceleration rate to $0.85\,g$. Additionally, this nullifies the impact of road angle forces ($W \cdot sin\theta$), on the achieved stopping distances. The value considered for the coefficient of rolling resistance is 0.02 and for the air mass density is $1.225\,kg/m^3$.

Three different inter-vehicle separations of 2, 3, and 4 meters are considered for the Space-Buffer scheme. They are then compared with the Least Stopping Distance and the Least Platoon Length approaches on the basis of aerodynamic savings, platoon length, and stopping distance.

For each dataset, as vehicles from 1 to 20 join the platoon, we computed aerodynamic savings, platoon length, and stopping distances achieved by all approaches. Once the computations are done for all 100 datasets, the corresponding averages are calculated.

An Example: Table I shows the details of cars belonging to one of the one hundred datasets. The order in which they join the platoon is represented by *ID*.

[3]Note that we use m for mass as well as for the unit meter. However, these can be easily differentiated depending on the context.

C. Test Results

In this section, initially, we compare the approaches with respect to aerodynamic savings, platoon length, and stopping distance. Later, the impact of braking capacities on these parameters is analyzed. Finally, we analyze packet loss and propose a fail-safe behavior in such situations.

1) Aerodynamic Savings, Platoon Length, and Stopping Distance: Fig. 5 shows the average drag coefficient ratio for the approaches as the number of vehicles increases (i.e., as vehicle 1 to 20) join the platoon. Clearly, at large separations of 4 meters (B=3), the overall aerodynamic savings for the Space-Buffer Scheme are less.

In contrast, the Least Platoon Length approach maintains constant inter-vehicle separations of 1 meter and achieves optimum values by around 20% when compared to the Space-Buffer Scheme for 4 meters (B=3) from 3 vehicles onwards.

At inter-vehicle separations of 2 meters (B=1), the Space-Buffer scheme has a maximum deviation of 7% when compared to the optimum. For 3 meters (B=2) separations, this deviation increases to 12%. The Least Stopping Distance approach also achieves approximately the same benefits.

Interestingly, all approaches' aerodynamic savings stagnate for more than 12 vehicles. As stated before, these savings become smaller as the number of vehicles increase.

An Example: Consider a car with constant velocity V on a flat road. Its mass m is 2000 kg, coefficient of aerodynamic resistance C_D is 0.4, frontal area of the vehicle A_f is $2\,m^2$ and, coefficient of rolling resistance f_r is 0.015 and the air-mass density ρ is $1.225\,kg/m^3$. The ratio of liters consumed per kilometer to overcome aerodynamic forces to the total liters consumed per kilometer by the vehicle is given by [4]:

$$\frac{[liters/km]_{Aerodyn}}{[liters/km]_{Total}} = \frac{\frac{\rho}{2} C_D A_f V^2}{\frac{\rho}{2} C_D A_f V^2 + f_r W}. \quad (12)$$

Assume a distance of 200 km is covered in isolation consuming 10 liters of fuel. If, another car follows at separation of 1 meter for the whole distance, then, there is a reduction of 36% in the aerodynamic forces for the lead

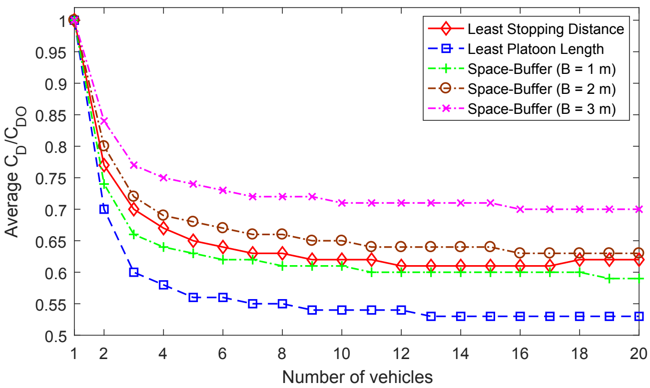

Fig. 5. Average drag coefficient ratio vs. number of vehicles

TABLE I
EXAMPLE OF ONE DATASET OF VEHICLES

ID	m (in kg)	a (in g)	C_D	A_f (in m^2)
1	1794	0.78	0.469	2.35
2	3390	0.79	0.398	2.13
3	1866	0.77	0.386	2.27
4	2319	0.76	0.365	2.22
5	2895	0.74	0.419	2.03
6	3117	0.73	0.314	2.50
7	3078	0.70	0.398	2.10
8	3044	0.69	0.465	2.26
9	2092	0.68	0.414	2.19
10	1630	0.67	0.475	2.40

ID	m (in kg)	a (in g)	C_D	A_f (in m^2)
11	1352	0.65	0.375	2.32
12	2575	0.64	0.389	2.09
13	2518	0.63	0.436	2.41
14	1343	0.61	0.359	2.44
15	2815	0.62	0.341	2.23
16	2704	0.58	0.321	2.29
17	3234	0.57	0.369	2.26
18	3020	0.56	0.387	2.32
19	1398	0.51	0.342	2.27
20	2300	0.50	0.373	2.02

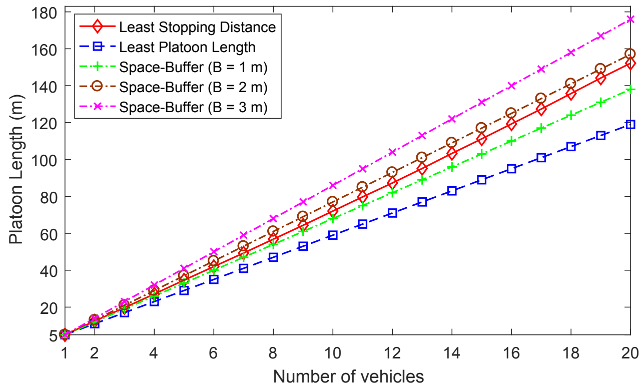

Fig. 6. Platoon length vs. number of vehicles

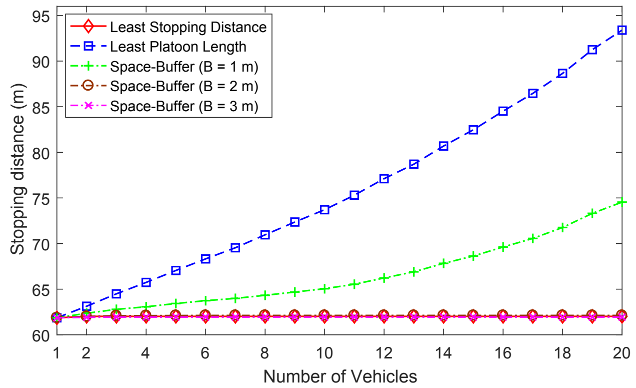

Fig. 7. Stopping distance vs. number of vehicles

— see again Fig. 1. Substituting these values in (12), the lead now requires less than 7 liters of fuel to cover the same distance. From Fig. 5, for 20 vehicles, there is an average 48% reduction in aerodynamic forces leading to more fuel savings at each of the vehicles.

Fig. 6 shows the resulting platoon length for the different approaches. With constant inter-vehicle separations of 1 meter, the Least Platoon Length approach achieves the shortest length of 119 meters for 20 vehicles making it ideal for coexistence with other road users. The next best platoon length of 138 meters is achieved by the Space-Buffer Scheme at inter-vehicle separations of 2 meters (B=1).

Contrarily, at large separations of 4 meters (B=3), it results in the longest platoon with around 178 meters. The Least Stopping Distance approach is approximately 4 car lengths (i.e., 20 meters) shorter than this longest platoon. However, at separations of 3 meters (B=2), the Space-Buffer Scheme is around 0.5 car lengths (i.e., 2.5 meters) longer than the Least Stopping Distance approach.

Fig. 7 shows the stopping distances that can be achieved with these approaches. The platoon cruise speed was 108 km/h when the emergency braking was initiated. Note that the vehicles brake simultaneously in all the approaches. The distance covered before activation of brakes is assumed to be 3 meters for all vehicles in all the approaches.

The Least Platoon Length approach achieves the worst stopping distance of around 95 meters for 20 vehicles and is thereby unsuitable for emergency situations. Note that this value is greater than the stopping distance of any of the vehicles in isolation. The reduction of aerodynamic forces causes this behavior.

Contrarily, the optimum value of around 62 meters is achieved by the Least Stopping Distance approach and also by the Space-Buffer Scheme for separations of 3 (B=2) and 4 (B=3) meters. More precisely, at separations of 4 (B=3) meters, the Space-Buffer Scheme outperforms the Least Stopping Distance approach marginally by 0.05 meters. The stopping distances exhibit stagnation for both these values of B. This can be reasoned by the same choice of vehicle x leading to the same S_{SB}.

These stopping distances are marginally greater than that of the lead vehicle in isolation. In general, the lesser the separation between the lead and its immediate following vehicle, greater is the increase in stopping distance.

Even at $B = 1$ meter, the Space-Buffer scheme outperforms the Least Platoon Length approach and achieves a stopping distance that is 20 meters shorter. Clearly, the Space-Buffer Scheme approach performs best when all the parameters are considered i.e., when we need to optimize stopping distance, aerodynamic savings and platoon length at the same time.

2) The Impact of Braking Capacities: In this section, different ranges of vehicle braking capacities are considered and their impact on the achieved aerodynamic benefits, platoon length, and stopping distances are analyzed.

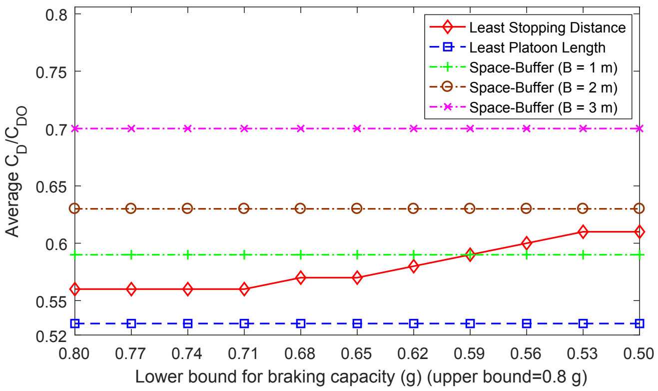

Fig. 8. Average drag coefficient ratio vs. range of braking capacities

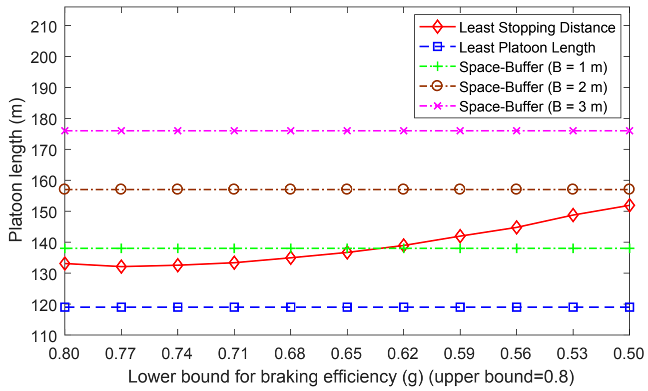

Fig. 9. Platoon length vs. range of braking capacities

The method used for generating test data is the same as mentioned before. Additionally, we vary the range of vehicle braking capacities from $0.8-0.8$ till $0.5-0.8$ in steps of 0.03 keeping the number of vehicles constant at 20 for each range.

Fig. 8 shows the impact of vehicle braking capacities on the aerodynamic benefits. Only the Least Stopping Distance approach shows a dependency on the range of braking capacities with higher benefits at identical braking capacities.

However, the aerodynamic benefits are not optimum. It is approximately 4% lesser and this difference can be attributed to the fact that vehicle weights impact stopping distances, thereby resulting in varying inter-vehicle separations. As the range increases, the benefits decrease. For the widest range of braking capacities, the ratio is around 0.62 and is slightly lesser than $B=2$ by around 1%.

Clearly, with separations of only a meter, optimum benefits are achieved by the Least Platoon Length for all ranges. The Space-Buffer Scheme with $B=1$, differs by only 7% from the optimum. At $B=2$, this difference increases to 11%.

For $B=3$, the Space-Buffer Scheme performs the worst since it does not adapt its B to the range of braking capacity. In other words, the proposed scheme is suitable for the, more common, case where vehicles do not brake the same. If all vehicles brake the same, the Least Platoon Length approach is the most suitable.

Fig. 9 shows the relation between braking capacities and the overall platoon length. Similar to the aerodynamic benefits, only the Least Stopping Distance exhibits a dependency.

With homogeneous capacities, the platoon length differs by only 15 meters to the optimum. Shorter, but varying inter-vehicle separations can be reasoned for this. This length happens to even be lesser than that of the Space-Buffer Scheme with $B=1$.

However, the platoon length increases linearly as the range of braking capacity gets wider. For the widest range, the length is approximately 153 meters and this is longer than for the proposed scheme with $B=1$ but slightly shorter than $B=2$.

The longest platoon is around 178 meters with the proposed scheme for $B=3$ and, on the other hand, the shortest platoon of 119 meters is achieved by the Least Platoon Length.

A comparison of the achieved stopping distances for different ranges of braking capacities is presented in Fig. 10. The Least Stopping Distance approach and the Space-Buffer Scheme with separations of 4 (B=3) meters, achieve optimum values for all ranges of braking capacities.

Contrarily, the Least Platoon Length achieves the longest stopping distance. For homogeneous capacities, the achieved stopping distance is around 62 meters when compared to the optimum of around 60 meters.

As the range increases, the difference between the best and worst stopping distances also increases. For the widest range, there exists a difference of approximately 30 meters.

For $B=2$, the Space-Buffer Scheme achieves stopping distances closer to the optimum. The difference is approximately same when all vehicles brake the same. Even in the widest range, this difference is only 0.2 meters.

When $B=1$, for similar braking behaviors of vehicles, the difference to the optimum is approximately 1 meter and remains the same until the range 0.65 to 0.8. However, as the range further increases, the Space-Buffer Scheme with $B=1$ becomes worse. For the maximum range considered in Fig. 10, $B=1$ leads to a stopping distance that is around 20 meters away from the worst (by Least Platoon Length) and 12 meters from the best case (by Least Stopping Distance).

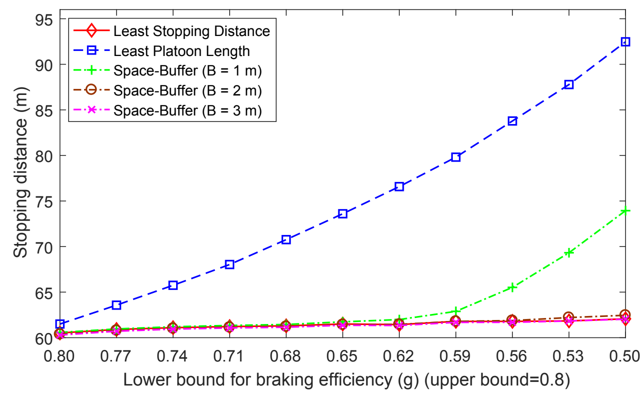

Fig. 10. Stopping distance vs. range of braking capacities

3) Effects of Packet Loss: The packet loss can be analyzed from the perspectives of brake command and live signal. These individual losses can be viewed as overlapping subsets with the overlapping region representing the worst-case situation, where both the live signal and brake command are lost. We consider this worst case for our analysis.

Whenever a vehicle experiences communication problems, it assumes the worst-case scenario — the immediate lead vehicle is already braking — and initiates an emergency braking communicating the same to all of its following vehicles. The platoon then disintegrates ensuring safety. This behavior is initiated immediately after the number of consecutive packets lost crosses a threshold.

This threshold is a function of the platoon cruise speed. As discussed below, a higher number of packets can be lost at low cruise speeds compared to high speeds. All the approaches exhibit this behavior. In our analysis, we consider high and low speeds of $90\,Km/h$ and $50\,Km/h$ respectively.

Fig. 11 shows the effect of packet losses on inter-vehicle separations at high platoon speeds. Note that, in Fig. 11, we use a 20 ms scale from 14 s up to 14.060 s (region enclosed by vertical dotted lines). From then onwards we change to a 2 s scale (to be able to show the points in time at which the inter-vehicle separation of all schemes reduces to zero). In all the approaches, an emergency situation caused the lead vehicle to broadcast the brake command, initiating a simultaneous braking 20 ms later. The two consecutive vehicles under test neither received this brake command nor the appropriate live signals.

In the Least Stopping Distance approach, the necessary separation including the safeguard between two vehicles under test was 8.8 meters. When the second consecutive live signal after the brake command is lost, the following vehicle initiates emergency braking. The inter-vehicle separation gradually reduces to zero at standstill.

At high speeds, including the brake command loss, a packet loss threshold of 3 packets can be observed. This generally applies to all pairs of consecutive vehicles because the separations account for the difference in their respective stopping distances and packet loss has to be dealt only with safeguard.

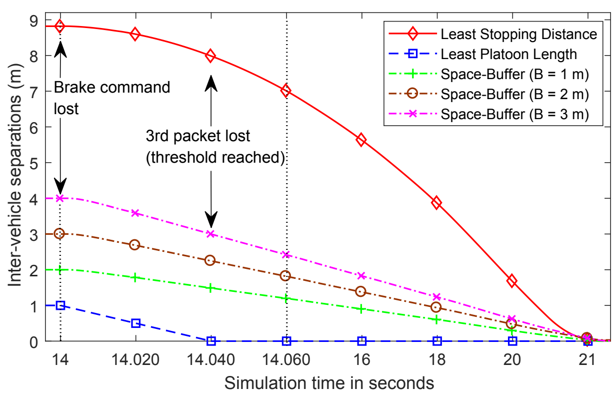

Fig. 11. Effect of packet losses on inter-vehicle separation

The threshold is the same for the Least Platoon Length as well. However, as soon as the third packet is lost, the separation reduces to zero and remains the same until standstill. This implies the following vehicle's front bumper is in contact with its immediate lead's rear bumper. Such an undesirable scenario, in particular, because there is no margin for errors, can be eliminated by choosing the safeguard slightly greater than 1 meter.

For the Space-Buffer Scheme, the difference in stopping distances between any two consecutive vehicles differs by B and their separation is the sum of the safeguard and B. As a result, again, only the safeguard can account for packet loss and, hence, the above mentioned threshold of 3 packets does not change. Unlike Least Platoon Length and similar to Least Stopping Distance, the inter-vehicle separation gradually reduces to zero at standstill.

At speeds of $90\,Km/h$, assuming the lead vehicle is braking, the inter-vehicle distance reduces by 0.5 meters per packet lost. Increasing the safeguard allows for more packet lost threshold, however, this also negatively impacts platoon length and aerodynamic savings, in particular.

On the other hand, keeping the safeguard constant, provided the platoon cruises at low speeds, the allowable number of packet losses is slightly more. More precisely at $50\,Km/h$, the threshold increases to 4 consecutive packets including loss of brake command, as the reduction in separation is 0.28 meters per packet loss. Additionally, note that in this case, non-zero inter-vehicle separations result at standstill for all approaches.

VI. Conclusion

In this paper, in order to minimize stopping distance and platoon length while maximizing fuel/energy savings of the platoon, the Space-Buffer Scheme was proposed. The approach was compared with two other more intuitive approaches (Least Platoon Length and Least Stopping Distance) on the basis of three parameters — aerodynamic gain, stopping distance and overall platoon length. The impact of the range of braking capacity on these parameters was also analyzed showing that the proposed approach is more suitable when considering heterogeneous vehicles. When all vehicles brake the same, the Least Platoon Length approach outperforms all others, however, this condition might not always hold in practice. Finally, the effect of packet loss was investigated by realistic simulations based on an automotive HiL setting. A suitable behavior in such situations ensuring safety for all platoon participants was outlined. As future work, we plan to investigate the effects of different road profiles with different inclination angles, leading to cases where vehicles are not capable of braking at the required deceleration rates. Fail-operational and or fail-safe strategies have to be envisaged for such platoons. In addition, we believe that hybrid approaches combining Least Platoon Length with space buffers are worth investigating to provide safety in highly efficient platoons.

APPENDIX

Now we present, a mathematical proof of collision-free braking when utilizing the space buffers. For ease of exposition, we rely on the displacement formula given below for the i-th vehicle in our Space-Buffer Scheme. Note that, in contrast to (7), this does not consider any forces apart from those exerted by a vehicle's brakes, which results in a longer stopping distance:

$$S_i = Vt - \frac{1}{2}a_i t^2, \tag{13}$$

where S_i represents the displacement or stopping distance in m, V represents the initial velocity in m/s when braking was initiated. The time in s required to achieve standstill is represented by t, and a_i denotes deceleration in m/s^2. Since we consider deceleration, a minus sign exists in the equation.

Note that vehicle i comes to standstill after some time $t = \frac{V}{a_i}$ and that its $S_i = S_{SB} + (i-1)B$ where B is the space buffer. Substituting these in (13) we obtain:

$$a_i = \frac{V^2}{2\left(S_{SB} + (i-1)B\right)}, \tag{14}$$

Similarly, the difference in deceleration rates between any two consecutive vehicles, i and $i+1$, denoted by $\Delta a_{i,i+1}$, is given by:

$$\Delta a_{i,i+1} = \frac{V^2}{2}\left[\frac{B}{\left(S_{SB} + (i-1)B\right)\left(S_{SB} + iB\right)}\right]. \tag{15}$$

Now, the time required for vehicle $i+1$ to fully consume the space buffer to vehicle i can be obtained by substituting $\Delta a_{i,i+1}$ in (13) and solving for t:

$$t = \frac{V + \sqrt{V^2 - \left(2 \cdot \Delta a_{i,i+1} \cdot B\right)}}{\Delta a_{i,i+1}}. \tag{16}$$

A collision-free braking exists between any two consecutive vehicles i and $i+1$ provided the time required to consume the space buffer B between them is greater than or equal to the time required to stop the $i+1$-th vehicle. Therefore,

$$\frac{V}{a_i} \leq \frac{V + \sqrt{V^2 - \left(2 \cdot \Delta a_{i,i+1} \cdot B\right)}}{\Delta a_{i,i+1}}, \tag{17}$$

has to be ensured. B is lesser when compared to S_{SB} (e.g., 3 m and 62 m respectively). This also results in $\Delta a_{i,i+1} < 1$ and also $\frac{\Delta a_{i,i+1}}{a_i} < 1$. With this, (17) holds if the following holds:

$$V^2 \geq \left(2 \cdot \Delta a_{i,i+1} \cdot B\right). \tag{18}$$

The worst case is when $i = 1$. Substituting (15) in (18),

$$1 \geq \frac{B^2}{S_{SB}^2 + \left(S_{SB} \cdot B\right)}, \tag{19}$$

is required. Rearranging (19), since $B < S_{SB}$, it is clear that,

$$B \leq \left(\frac{S_{SB}^2}{B} + S_{SB}\right). \tag{20}$$

This proves that vehicle $i+1$ stops before fully consuming its space buffer B to the next vehicle, independent of the value of i.

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