A Subplatooning Strategy for Safe Braking Maneuvers

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Abstract—**Reducing the inter-vehicle separation in a platoon results in the most benefits in terms of aerodynamic savings and vehicles throughput. However, this makes braking maneuvers dangerous and leads to long stopping distances, in particular, when considering heterogeneous vehicles with different braking capacities. Even though control theoretic approaches exist for the platoon cruise operation, the scenario of sudden braking has to be designed separately as the system reaches saturation, i.e., in order to minimize the stopping distance of the platoon, the application of the maximum possible braking forces is required. This cannot be handled by standard control systems alone, since they rely on varying (control) variables/signals, which is not possible under saturation. In this paper, we are concerned with vehicles of heterogeneous braking capacity and propose a subplatooning strategy that not only guarantees a collision-free braking, but also minimizes the stopping distance. Vehicles within each subplatoon have inter-vehicle separations of below one car length, whereas the inter-subplatoon separation is increased to compensate the differences in decelerations between subplatoons. We evaluate this scheme using a realistic simulation based on complex vehicle dynamics models and a HiL (hardware in the loop) setting.**

I. Introduction

The increasing number of road vehicles demands improvements in the existing infrastructure. However, in the past twenty years, infrastructural improvements have provided very little help in increasing the throughput of highways. At high speeds, an average inter-vehicle spacing of 35 meters is observed leading to a maximum throughput of about 2000 vehicles/hour [1]. The platooning concept helps in increasing the throughput of vehicles and additionally reduces the fuel/energy consumption.

Currently, platooning involves a manually driven truck leading a convoy of several closely following vehicles. The inter-vehicle separations are around 5 to 10 meters. This results in reduced aerodynamic forces on the following vehicles, thereby leading to fuel/energy savings [2][3]. The shorter inter-vehicle separations apart from increasing the traffic throughput also provides increased comfort for drivers as control systems perform the longitudinal and lateral control of vehicles [2][4][5].

At inter-vehicle distances of 5 to 10 meters, there are no fuel/energy savings for the platoon lead. However, wind tunnel experiments demonstrate reduced aerodynamic forces even on the lead when the inter-vehicle distances are reduced to below one car length. Particularly, at 0.5 car lengths (around 2.5 meters), the platoon lead has significant benefits [6].

On the other hand, the braking maneuvers become difficult at distances of 2.5 meters endangering safety of vehicles. Until now, the literature has focused on control theory techniques for designing and improving a platoon's cruise operation [7][8][9].

In contrast, during braking maneuvers, the need to minimize the platoon stopping distance requires the constant application of the maximum possible braking forces, which makes control systems reach saturation. Therefore, the need arises to design this situation separately, independent of cruise control.

Considering vehicle heterogeneity, one solution is to brake the whole platoon as the vehicle with the lowest deceleration rate [10]. Even though this solution guarantees safety, it is coupled with an undesirably long stopping distance.

This drawback can be overcome by an other solution where the vehicle with the highest deceleration rate leads the platoon. The inter-vehicle separations are then determined by the difference in deceleration rates between two consecutive vehicles. A greater difference in deceleration rates leads to greater separations, yielding longer platoons and lesser fuel/energy savings.

The first solution achieves optimum aerodynamic savings and platoon length, whereas, the second solution achieves optimum stopping distance. For the simultaneous optimization of all these three parameters, we propose subplatooning strategy as stated below.

Contributions. We consider vehicles with heterogeneous braking capacity due to, for example, their masses and the corresponding load distribution among the axles, etc. In this context, we propose clustering vehicles into two subplatoons (later we will show that more than two subplatoons decreases performance). Vehicles in each subplatoon maintain inter-vehicle separations at 2.5 meters, whereas the inter-subplatoon separation compensates the difference in deceleration rates between subplatoons. This way, the lead subplatoon can brake at a higher rate than the trail or following subplatoon. Two variants of this strategy are proposed: Subplatoon Scheme and Communication Scheme. These allow guaranteeing safety at braking maneuvers while optimizing aerodynamic benefits, platoon length, and stopping distance. We illustrate this in comparison with the above mentioned, more intuitive solutions based on a set of experiments using an automotive HiL setting.

Structure of the paper. Related work is presented in the next section. The background on platooning, brake-by-wire systems, and the computation of a vehicle's stopping distance are discussed in Section III. Our approach for collision avoidance along with the modified communication strategy for further improvements is presented in Section IV. The experimental results obtained through realistic car models on an automotive HiL setup is presented in Section V. Finally, Section VI concludes the paper.

II. Related Work

The platooning concept in freight transportation yields significant fuel savings as recently shown in [3]. As part of the CHAUFFEUR project [4], image processing was used for achieving the longitudinal and lateral control of trucks in a platoon. However, the first prototypical implementation with inter-vehicle distances of 5 to 10 meters was performed by the SARTRE project [2][11][12].

The benefits of maintaining inter-vehicle distances close to one car length and below was shown by the California PATH program [1]. Two-, three- and four-vehicle platoons with inter-vehicle spacings of 0.6 and 1.2 car lengths were considered and the fuel savings were logged. For all the platoons, the average fuel savings at distances of 0.6 car lengths (approximately 3 meters) was observed to be greater than the savings at distances of 1.2 car lengths. Increasing the number of platoon vehicles and maintaining shorter inter-vehicle distances increased the overall average fuel savings [1].

So far, most works have proposed control strategies for the platoon cruise operation. These strategies emphasize on achieving string stability [13], where the platoon behavior for small variations in the lead vehicle's velocity is observed. A string stable controller ensures that the disturbances in inter-vehicle separations do not to amplify along the platoon. However, a string stable controller does not additionally ensure collision-free operation in braking situations. The need to minimize the platoon stopping distance requires the application of maximum possible braking forces leading to control system saturation. Therefore, such maneuvers have to be designed separately, independent of cruise control.

Among the very few works on platoon braking maneuvers, the significant ones are [14], [15], and [16]. The evaluation of human driver reaction times was performed in [14]. A two truck platoon was considered for the case of manual emergency braking. The necessity of the following vehicle to brake at a higher deceleration rate than the lead in order to avoid collisions was shown.

The minimum possible inter-vehicle distance between two automatically controlled trucks was studied in [15]. The short inter-vehicle separation was shown to be safe and possible only if the following truck was capable of a higher deceleration rate than the lead.

The probability of an inter-vehicular collision, the expected number of collisions, and relative vehicle velocities at impact during close following was analyzed in [16].

To the best of our knowledge, this is the first attempt to study platoon braking maneuvers considering vehicle heterogeneity and operating at separations below one car length.

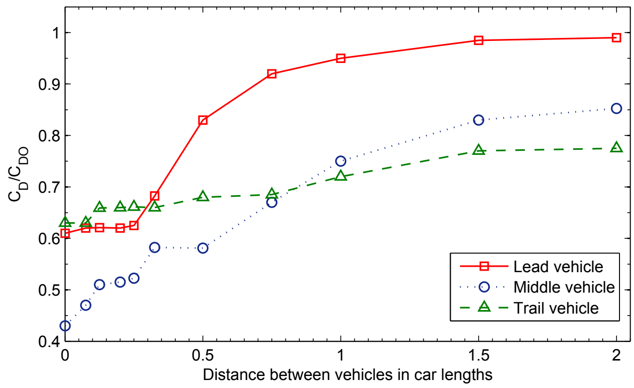

Fig. 1. Drag coefficient ratio for three close-following vehicles

III. Background

A. Aerodynamic Gain

In the existing platoon strategies, several cars/trucks follow a lead truck at close distances of 5 to 10 meters [12][2][3]. This results in reduced aerodynamic forces on the following vehicles, thereby leading to fuel/energy savings.

Experiments conducted as part of the California PATH program [1][6] demonstrated fuel/energy savings even for the platoon lead when the inter-vehicle distance is reduced to below one car length. In fact, significant savings are achieved at distances of 0.5 car lengths (around 2.5 meters).

The aerodynamic resistance on a vehicle/car is determined by its drag coefficient. Fig. 1 shows the ratio of aerodynamic drag coefficient when traveling in a platoon (C_D) to the aerodynamic drag coefficient of the same vehicle traveling in isolation (C_{DO}) as a function of car lengths. The three vehicles considered in the platoon have the same height [1][6].

The lead vehicle is devoid of benefits when the inter-vehicle distances are 1 car length or greater. However, the following vehicles benefit from reduced aerodynamic forces up to a distance of 10 car lengths. This interaction is said to be *weak interaction regime* as only the following vehicles have benefits.

Reducing the inter-vehicle distances to less than 1 car length benefits the lead vehicle as well. This interaction is said to be *strong interaction regime*. In this regime, interestingly, at 0.35 car lengths and below, the lead vehicle experiences lesser aerodynamic drag than the third vehicle. This counter-intuitive behavior is caused by the air mass being pushed to the lead's rear by its following vehicle. The drag coefficient ratio of the trail or third vehicle also decreases but not so rapidly. The middle vehicle has the least drag coefficient ratio as it benefits from both the lead and trail vehicles [1][6].

The following generalizations can be made with respect to large platoons [6]:

- The most fuel savings are achieved by the middle vehicles of a platoon.
- The decrements in the average drag coefficient ratio for the whole platoon would become smaller as the number of vehicles increase.

- The drag coefficient ratio for the lead vehicle and for each of the subsequent vehicles up to the n-th show no dependency on the number of vehicles, provided there are at least *n+1* vehicles.

In the cruise situation, platooning leads to fuel/energy savings. However in braking maneuvers, it leads to longer stopping distances. This is caused by the reduction in the magnitude of motion opposing aerodynamic forces. The vehicle then majorly relies on its brake system to achieve standstill.

B. Brake by Wire

Traditional brake systems have high reaction times and are difficult to automate. In platoon braking situations, the required braking force has to be generated in the shortest possible time. Otherwise, the short inter-vehicle distances leads to collisions. These factors give rise to the need of brake-by-wire systems [17] which are capable of lesser reaction times and easy automation. Particularly, during platoon braking maneuvers, brake-by-wire systems adjust the braking forces such that vehicular collisions do not occur.

Apart from the force generated by the brakes, the vehicle deceleration is also assisted by additional forces like the aerodynamic resistance, rolling resistance of tires, and grade resistance. Therefore, the total force constituted by all these forces is expressed by the following equation [18]:

$$F_{tot} = F_b + f_r W cos\theta + R_a \pm W sin\theta, \tag{1}$$

where F_{tot} denotes the resultant total force in Newtons (N), F_b represents the force in N generated by the vehicle's brake system, the coefficient of rolling resistance is denoted by f_r, W represents the vehicle weight in N, θ denotes the angle of the road with the horizontal in degrees, and the aerodynamic resistance also in N is represented by R_a. When the vehicle is moving uphill, the term $W sin\theta$ takes a positive sign, and when in downhill, it takes a negative sign [18].

Vehicles belonging to the same performance category and equipped with similar brake systems have different braking capacities. This is primarily due to their loading conditions. In other words, the maximum achievable deceleration rate is determined by the number of car passengers and any other additional loads. These exert forces on the front and rear axles depending on their distances to the vehicle's center of gravity.

When the braking forces supplied to the front and rear axles are in proportion to the loads acting on them, the deceleration rate can be maximized. However, if the supplied braking force exceeds the axle load, then the corresponding wheels lock resulting in skidding. A fixed braking force distribution to the front and rear axles coupled with the loading conditions determines the maximum achievable deceleration rate [18].

The road/tire conditions along with the tires' air pressure also play a vital role. In fact, the maximum achievable deceleration rate when normalized by g (acceleration due to gravity) is bounded and cannot exceed the coefficient of road adhesion [18].

The brake-by-wire system relies on the Newton's second law of motion for performing its computations as shown:

$$F_{tot} = ma, \tag{2}$$

where F_{tot} is as represented in (1), the mass in kilograms (kg) is denoted by m, and the acceleration/deceleration in m/s^2 is represented by a.

The sum of forces in (1) can be substituted for F_{tot} as

$$F_b + f_r W cos\theta + R_a \pm W sin\theta = ma. \tag{3}$$

Finally, the vehicle's deceleration rate normalized by g can be obtained by replacing m with W/g and rearranging as [18]:

$$\frac{F_b + f_r W cos\theta + R_a \pm W sin\theta}{W} = \frac{a}{g}. \tag{4}$$

During platoon operation, particularly, the lead vehicle communicates its speed and the acceleration/deceleration rate to all others. This deceleration rate is achieved by the vehicles with the help of their brake by wire systems which compute the required braking forces. However, certain assumptions are made while performing the calculations. These include: knowing the vehicle's weight W, angle of the road θ, and the proportion of braking force distribution. Note that these can be measured/estimated with the sensors already equipped in modern vehicles. Additionally, during platoon operation, the variation in aerodynamic drag coefficient is neglected.

C. Stopping Distance

During braking maneuvers, if the heterogeneous braking capacities of vehicles are not considered, then collisions may happen (depending on the inter-vehicle separation). A vehicle's *stopping distance* S is determined by several parameters as shown in the following equation [18]:

$$S = \frac{\gamma_m W}{2 g C_A} \ln\left(1 + \frac{C_A V^2}{\eta_b \mu W + f_r W \cos\theta \pm W sin\theta}\right), \tag{5}$$

where γ_m is termed as *equivalent mass factor* and denotes the moment of inertia of the rotating parts involved in braking. For passenger cars, it has a value of around 1.03 to 1.05. The weight of the vehicle in Newtons (N) is represented by W, the acceleration due to gravity in m/s^2 is denoted by g, the aerodynamic constant as shown in (6) is represented by C_A, the initial speed of the vehicle in m/s before the application of brakes is denoted by V, the braking efficiency as shown in (7) is represented by η_b, the coefficient of road adhesion is denoted by μ, the coefficient of rolling resistance is represented by f_r, and the angle of the road in degrees is denoted by θ ($W sin\theta$ takes a positive sign in an uphill and a negative sign in a downhill). Additionally, we have [18]:

$$C_A = \frac{\rho}{2} C_D A_f, \tag{6}$$

$$\eta_b = \frac{(\frac{a}{g})}{\mu}, \tag{7}$$

where the air mass density in kg/m^3 is represented by ρ, the aerodynamic drag coefficient is denoted by C_D, the

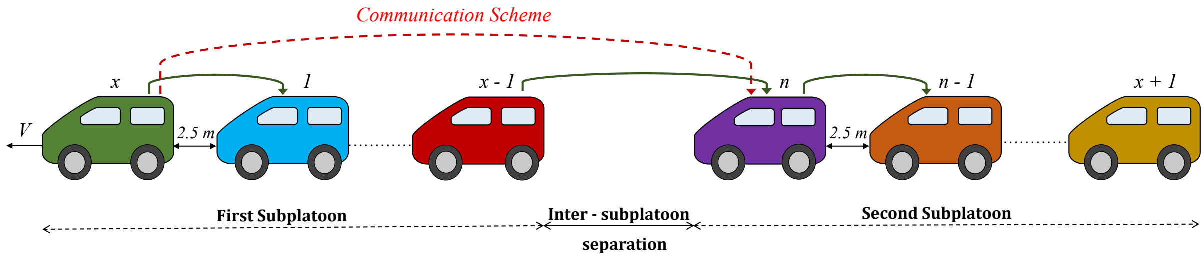

Fig. 2. Suplatooning strategy: Vehicles are clustered into two subplatoons with constant inter-vehicle separation of $2.5m$. The inter-subplatoon separation varies to compensate differences in the deceleration rates between subplatoons. For simplicity, vehicles are assumed to be sorted in the order of decreasing deceleration, i.e., vehicle 1 has a higher deceleration than vehicle x and vehicle x has a higher deceleration than n with $1 < x < n$.

frontal/projected area of the vehicle in m^2 along the direction of travel is represented by A_f, and the maximum achievable deceleration in m/s^2 is denoted by a. Intuitively, for heavy vehicles, and in cases of lower deceleration rates, the achieved stopping distance will be longer. The time taken for the activation of brakes also results in a longer stopping distance. Therefore, in reality, a vehicle's stopping distance will be longer than computed in (5) [18].

The two intuitive solutions presented in the introduction section consider the different stopping distances achieved by the platoon vehicles. They are hereby referred to as *Least Stopping Distance* and *Least Platoon Length*.

The optimum stopping distance is achieved by the Least Stopping Distance approach. The vehicle capable of achieving the shortest stopping distance is chosen to lead the platoon. The vehicle with the second best stopping distance follows the lead and so on until the last vehicle which has the longest stopping distance. The differences in deceleration rates of consecutive vehicles determine the inter-vehicle separations.

On the other hand, the Least Platoon Length approach achieves optimum aerodynamic savings and platoon length by maintaining constant inter-vehicle separation of 2.5 meters. The whole platoon brakes as the vehicle with the worst or longest stopping distance, thereby making it undesirable. Hence, our subplatooning strategy becomes necessary.

IV. Subplatoon Scheme

Clearly, we would like to have a platoon with highest possible aerodynamic benefits, the shortest possible length, and the shortest possible stopping distance. To this end, we introduce our Subplatoon Scheme, which is a hybrid solution based on the above mentioned intuitive approaches. The goal is to maintain the inter-vehicle distance as close to 2.5 meters as possible and, at the same time, minimize the stopping distance.

The overall platoon is divided into 2 subplatoons. The first subplatoon consists of all vehicles that can brake at higher or same deceleration rates as that of the platoon lead and the second subplatoon consists of all vehicles that brake at a lesser rate than the platoon lead. As for Least Platoon Length, the second subplatoon brakes at the rate of the worst vehicle.

Whereas the inter-vehicle separation in each subplatoon is 2.5 meters, the inter-subplatoon separation is a function of the difference in deceleration rates between the first subplatoon lead and the worst car, i.e., the difference in their stopping distances is the inter-subplatoon separation. Even though this might be more than 2.5 meters, the aerodynamic benefits are considerably better than for Least Stopping Distance.

An Example: Consider $1, 2, 3, ...n$ vehicles as part of a platoon. Assuming vehicle *1* has the best and vehicle *n* has the worst braking capacity, the first subplatoon lead will be vehicle *x* that achieves stopping distance, platoon length, and, aerodynamic benefits as close as possible to their respective optimum values. As shown in Fig. 2, the first subplatoon consists of all vehicles capable of braking at deceleration rates that are same or higher than the lead, i.e., *x, 1, 2, .. x-1*. The second subplatoon is led by the slowest/worst braking car consisting of all vehicles capable of lesser deceleration rates than *x*, i.e., *n, n-1, n-2, .. x+1*. The brake-by-wire systems have to be configured such that all vehicles brake as *x* in the first and as *n* in the second subplatoon respectively.

Communication Strategy for Safety: To avoid collisions in such close following platoons, the current speed and acceleration/deceleration values are periodically sent every 20 milliseconds from one vehicle to (and only processed by) its immediately following vehicle — see Fig. 2. This way, each vehicle can detect communication loss (e.g., a number of update packets are not received) and trigger an emergency brake. If one vehicle in the platoon brakes, it also forces all following vehicles to brake, i.e., the platoon breaks off.

Finally, note that Least Stopping Distance is a special case of the Subplatoon Scheme where there is exactly one vehicle per subplatoon, i.e., a total of n subplatoons. There can be any number of subplatoons between 2 and n. However, for a chosen lead vehicle x, it is easy to see that there cannot be any configuration with more than two subplatoons that yields a lesser length for the whole platoon. This is because the stopping distance of the first subplatoon is determined by x and that of the last subplatoon by n. Independent of the number of subplatoons we have, the sum of their inter-subplatoon separations cannot be less than the difference in stopping distance between x and n. On the other hand, having more than two subplatoons might negatively impact aerodynamic gain, since the inter-subplatoon separations are usually larger than 2.5 meters as already discussed.

A. Communication Scheme

As stated before, each vehicle in the platoon will process packets only from its immediate lead vehicle. A slight modification to this communication scheme results in further reducing the inter-subplatoon separation, thereby increasing the overall aerodynamic benefits and reducing platoon length. In other words, the inter-subplatoon separation can be configured to be less than the difference in stopping distances between the lead and the worst braking car.

To this end, as shown in Fig. 2, the lead of the second subplatoon also processes packets from the lead of the first subplatoon and brakes when this latter also does. Now, due to the time involved in propagation and processing of packets sent between vehicles, the consecutive inter-vehicle distances during braking in the first subplatoon will successively become lesser over time. As a result, if the second subplatoon starts braking with the lead of the first subplatoon, the inter-subplatoon distance will increase until the last vehicle of the first subplatoon also starts braking. This effect allows reducing the inter-subplatoon distance configured for the cruise situation, while still ensuring safety.

An Example: Consider 6 vehicles in the first subplatoon and the required inter-subplatoon separation to be 10 meters. The platoon speed is 80 Km/h when the lead of the first subplatoon starts braking. This broadcasts the message that is received and processed by its immediate following vehicle and also the lead of the second subplatoon after 20 ms. During this period, as the following vehicle has not yet started braking, the inter-vehicle distance reduces to $2.5 - 0.44 = 2.06$ meters. After 20 ms further, the third vehicle receives and processes the rebroadcasted message from second vehicle and so on. The consecutive inter-vehicle distances reduces to same 2.06 meters. When the last vehicle of the first subplatoon starts braking (100 ms later), this subplatoon becomes $2.2\,(5 \times 0.44)$ meters shorter than before braking. Since the second subplatoon started braking with the second vehicle, the required inter-subplatoon distance can be reduced by $1.8\,(4 \times 0.44)$ meters to 8.2 meters without compromising safety.

V. Evaluation and Comparison

In this section, an experimental evaluation and comparison of the proposed Subplatoon Scheme and the Communication Scheme with the more intuitive approaches is performed.

A. Test Setup

Fig. 4 shows the realistic car model used with a hardware-in-the-loop (HiL) system from dSPACE named SCALEXIO [19] to carry out the experiments. As shown in Fig. 3, through special connectors, an Electronic Control Unit (ECU) can be connected to the HiL. In our case, the car models were controlled through Host PC and no external ECU was used.

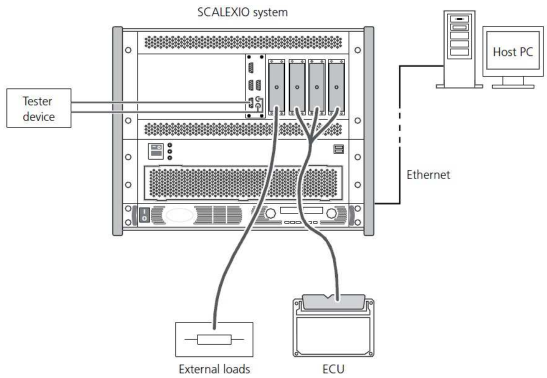

Fig. 3. dSPACE SCALEXIO external view

B. Test Data

There cannot be an infinite number of platoon vehicles due to road infrastructure limitations. As a result, for our experiments, we considered a maximum of 20 cars in a platoon. Their masses m, braking capacities, aerodynamic coefficients C_D, and frontal areas A_f were randomly generated in the range of $1000\,kg - 3500\,kg$, $0.5\,g - 0.8\,g$, $0.311 - 0.475$, and $2 - 2.5\,m^2$ respectively. These 20 cars constitute a dataset. One hundred such datasets were randomly generated. All the cars are of the same height and each car is 5 meters in length. The chosen value of equivalent mass factor γ_m for all cars is 1.05.

The simulated road was a flat and dry asphalt surface. Therefore, the maximum achievable deceleration rate was restricted to 0.85 g. Additionally, there is no impact of road angle force ($W \cdot sin\theta$) on the achieved stopping distance. The value of air mass density ρ is $1.225\,kg/m^3$ and the coefficient of rolling resistance f_r is 0.02.

The aerodynamic benefits, platoon length, and stopping distance achieved by all the approaches were computed as the vehicles of a dataset from 1 to 20 join the platoon. This was repeated for all the datasets and the corresponding averages were calculated.

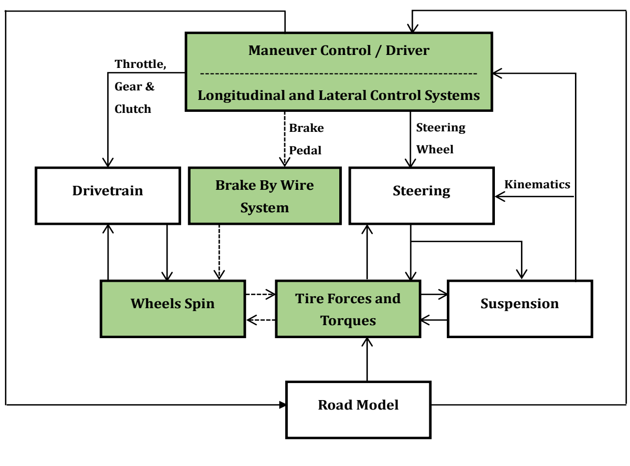

Fig. 4. Model of the car used in simulations

TABLE I

EXAMPLE OF ONE DATASET OF VEHICLES

ID	m (in kg)	a (in g)	C_D	A_f (in m^2)	ID	m (in kg)	a (in g)	C_D	A_f (in m^2)
1	1139	0.77	0.439	2.45	11	2024	0.65	0.346	2.05
2	1620	0.78	0.387	2.06	12	3455	0.69	0.322	2.26
3	1553	0.76	0.334	2.30	13	2400	0.62	0.409	2.29
4	2985	0.79	0.471	2.45	14	1788	0.58	0.438	2.12
5	2621	0.74	0.423	2.38	15	3038	0.63	0.474	2.04
6	1232	0.68	0.324	2.14	16	1477	0.56	0.317	2.37
7	2171	0.71	0.416	2.29	17	1673	0.54	0.438	2.16
8	1883	0.70	0.338	2.28	18	1754	0.51	0.354	2.46
9	2837	0.72	0.320	2.04	19	2133	0.55	0.339	2.06
10	2579	0.66	0.334	2.50	20	2678	0.50	0.327	2.17

An Example: The properties of cars belonging to one of the datsets is shown in Table I. Their order of joining the platoon is represented by *ID*. For the subplatooning strategy, a suitable lead has to be selected that minimizes stopping distance and platoon length on one hand, and, maximizes aerodynamic gain on the other hand. Table II shows the corresponding braking capacities of the selected lead from this dataset as vehicle 1 to 20 join the platoon — again, only the case of two subplatoons is considered. Every time a new vehicle joins, the lead was selected by an exhaustive search, i.e., trying out each and every vehicle as the lead and choosing the one with more benefits. This results in a linear complexity on the number of vehicles joining the platoon.

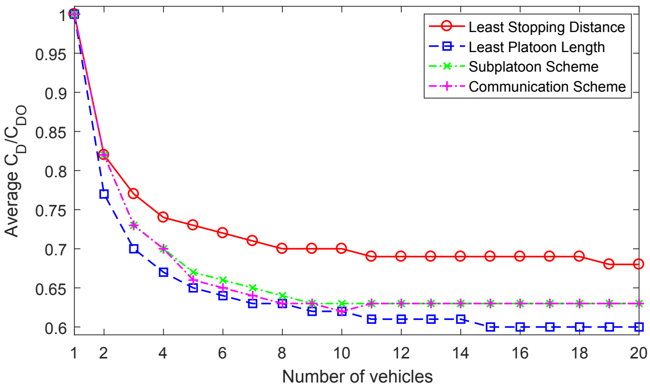

Fig. 5. Average drag coefficient ratio vs. number of vehicles

C. Test Results

In this section, the approaches are initially compared on the basis of achieved aerodynamic savings, platoon length, and stopping distance. Later, the dependency of these parameters on braking capacities is analyzed.

1) Aerodynamic Savings, Platoon Length, and Stopping Distance: The average drag coefficient ratio for the approaches as vehicle 1 to 20 join the platoon is shown in Fig. 5. Clearly, with the Least Stopping Distance approach, the inter-vehicle distances are increased to guarantee safety and, as a result, the overall aerodynamic savings are also less.

In contrast, the Least Platoon Length approach achieves optimum values by maintaining constant inter-vehicle separations of 2.5 meters. It outperforms the Least Stopping Distance approach by around 9% more from 3 vehicles onwards.

TABLE II

SELECTED LEAD FOR SUBPLATOON SCHEME

Vehicle joining	a (in g)	Vehicle joining	a (in g)
1	0.77	11	0.79
2	0.77	12	0.79
3	0.78	13	0.79
4	0.76	14	0.79
5	0.76	15	0.79
6	0.74	16	0.79
7	0.68	17	0.79
8	0.79	18	0.79
9	0.74	19	0.79
10	0.79	20	0.79

The Subplatoon Scheme and Communication Scheme have a maximum difference of around 3% to the optimum for 20 vehicles. In fact, the Communication Scheme achieves more savings than the Subplatoon Scheme upto 10 vehicles. Beyond this, even though shorter inter-subplatoon separations exist, the differences are marginal. The subplatooning strategy achieves 6% more savings than the Least Stopping Distance approach.

As the number of vehicles increase beyond 12, the aerodynamic benefits of all approaches stagnate. As mentioned before, the increments in aerodynamic savings become smaller as the number of vehicles increase.

An Example: Consider a car with mass 2000 kg, coefficient of aerodynamic resistance (C_D) 0.4, and frontal area (A_f) $2\,m^2$ traveling on a flat road with constant velocity V. It travels 200 km consuming 10 liters of fuel. The fraction of liters consumed per kilometer to overcome aerodynamic forces alone is is given by [6]:

$$\frac{[liters/km]_{Aerodyn}}{[liters/km]_{Total}} = \frac{\frac{\rho}{2} C_D A_f V^2}{\frac{\rho}{2} C_D A_f V^2 + f_r W}. \tag{8}$$

There will be a 15% reduction in the aerodynamic forces on the lead, if, another car follows at a separation of 2.5 meters for the whole distance — see again Fig. 1. Assuming a value of 0.015 for the coefficient of rolling resistance (f_r) and a value of $1.225\,kg/m^3$ for the air-mass density (ρ), and substituting these values in (8), the lead now covers the same distance using only 8.2 liters of fuel. From Fig. 5, there is an average 40% reduction in aerodynamic forces for 20 vehicles leading to more fuel savings at each of the vehicles.

Fig. 6 shows the overall platoon length for the different approaches. With constant inter-vehicle separations of 2.5 meters, the shortest length of 147.5 meters for 20 vehicles is achieved by the Least Platoon Length approach. Thus, from the perspective of road occupancy, this approach is ideal.

On the other hand, the large inter-subplatoon separation causes the Subplatoon Scheme to achieve an overall length of 173 meters. With the Communication Scheme, this length shortens to that of the Least Stopping Distance approach around 170 meters.

Fig. 7 shows the stopping distances that can be achieved with these approaches. The platoon cruise speed was 108 Km/h when the lead initiated a braking maneuver. In all the approaches, the distance covered before the activation of brakes is assumed to be 3 meters for all vehicles.

The worst stopping distance of around 95 meters for 20 vehicles is achieved by the Least Platoon Length approach. As expected, the Least Stopping Distance approach achieves the optimum value of around 62 meters.

The Subplatoon Scheme and Communication Scheme achieve the same stopping distance of around 66 meters for 20 vehicles. In fact, the stopping distance stagnates beyond 10 vehicles. The choice of the same vehicle to lead the platoon causes this behavior.

All approaches exhibit a slight increase in stopping distance of the lead when followed by 2 or more vehicles. This is basically due to the reduction of aerodynamic forces.

Clearly, the subplatooning strategy performs the best when all the parameters — stopping distance, platoon length and aerodynamic savings — are to be optimized at the same time.

2) The Impact of Braking Capacities: The dependency of the achieved aerodynamic benefits, platoon length, and stopping distance on the vehicle braking capacities is analyzed in this section. The test data is generated in the same way as mentioned before. Additionally, for each range, keeping the number of vehicles constant at 20, the range of vehicle braking capacities is varied from 0.8 – 0.8 till 0.5 – 0.8 in steps of 0.03.

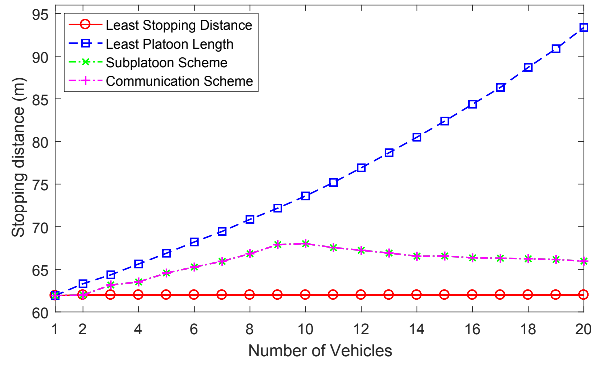

Fig. 7. Stopping distance vs. number of vehicles

The impact of vehicle braking capacities on the aerodynamic benefits is shown in Fig. 8. The Least Platoon Length approach achieves the same optimum values for all ranges of braking capacities.

The Subplatoon Scheme and the Communication Scheme also achieve the optimum until the range of 0.74 g – 0.8 g. This can be attributed to the fact that a small difference in braking capacities ensures the inter-subplatoon separations do not exceed 2.5 meters. As the range of braking capacities widens, their achieved savings have a maximum deviation of approximately 3% from the optimum.

On the other hand, even with homogeneous braking capacities, the Least Stopping Distance approach achieves approximately 6% less savings than the optimum. This can be attributed to the fact that vehicle weights impact stopping distances, thereby requiring varying inter-vehicle separations. For the widest range of braking capacities, the achieved aerodynamic savings are around 10% lesser than the optimum.

Fig. 9 shows the relation between braking capacities and the overall platoon length. Similar to the aerodynamic savings, the Least Platoon Length approach achieves optimum value of 147.5 meters for all ranges. The Communication Scheme also achieves this optimum upto the range of 0.71 g – 0.8 g. Beyond this, as the inter-subplatoon separation increases, it exhibits a linear growth. For the widest range, the overall length is around 170 meters.

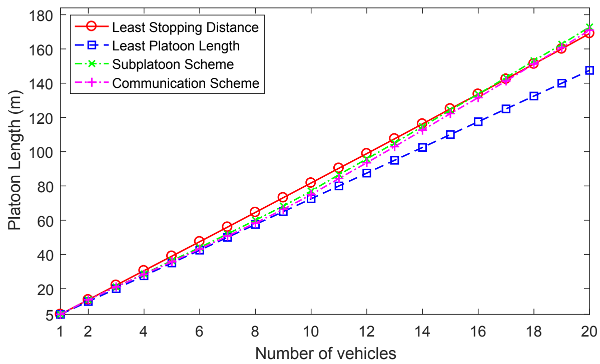

Fig. 6. Platoon length vs. number of vehicles

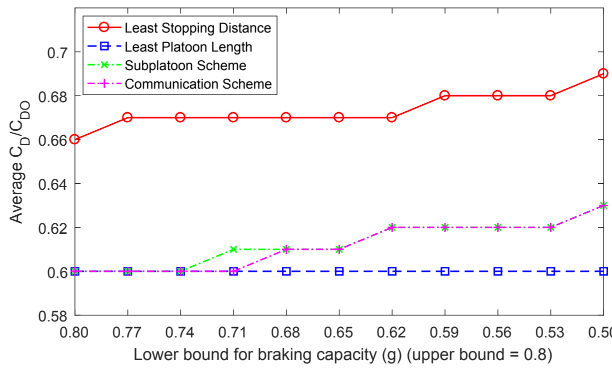

Fig. 8. Average drag coefficient ratio vs. range of braking capacities

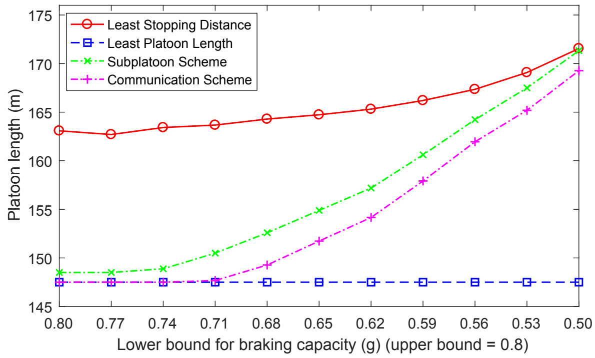

Fig. 9. Platoon length vs. range of braking capacities

The Subplatoon Scheme also demonstrates similar behavior. However, for small differences in braking capacities, the platoon is longer by a maximum of 2 meters than the optimum.

The Least Stopping Distance approach performs the worst even with small differences in braking capacities. For the widest range, both the Least Stopping Distance approach and the Subplatoon Scheme achieve approximately the same length of around 172 meters.

A comparison of the achieved stopping distances for different ranges of braking capacities is presented in Fig. 10. Clearly, the Least Stopping Distance approach outperforms all other approaches for all ranges of braking capacities.

On the other hand, the Least Platoon Length approach performs the worst. However, for homogeneous braking capacities, the achieved stopping distance is only 2 meters longer than the optimum. For the widest range, the stopping distance is around 93 meters.

The same stopping distance is achieved by both the Subplatoon Scheme and the Communication Scheme for all ranges with a difference of approximately 1 to 5 meters to the optimum. In comparison to the Least Platoon Length approach, they achieve around 5 car lengths shorter stopping distance in the widest range of braking capacities.

VI. Conclusion

In this paper, we considered vehicles with heterogeneous braking capacities operating at separations of 2.5 meters in

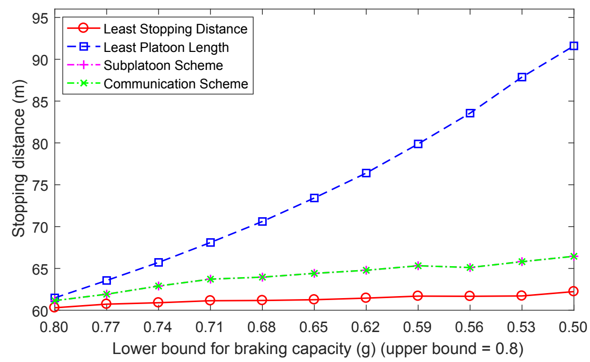

Fig. 10. Stopping distance vs. range of braking capacities

order to have benefits even for the lead. We presented the Subplatoon Scheme with the aim of minimizing stopping distance, and improving aerodynamic benefits and platoon length while ensuring safety. A variation in the communication strategy led to our Communication Scheme with further aerodynamic savings and improved platoon length. These schemes were then compared with the more intuitive approaches such as Least Platoon Length and Least Stopping Distance through experiments on an automotive HiL setup. As future work, we plan to address packet loss effects on safety and elaborate a fail-safe strategy for the case of subplatooning.

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