Braking in Close Following Platoons: The Law of the Weakest

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Abstract—**This paper is concerned with the realization of semi-autonomous vehicle arrangements as the natural transition towards fully automated traffic. In particular, we are interested in road trains or *platoons*, which involve a group of vehicles at close following distances. This is known to reduce fuel — or energy — consumption due to reduced aerodynamic forces acting on them. Currently, available techniques and technologies allow for inter-vehicle distances close to 5 meters with suboptimal fuel/energy savings. To obtain the most savings from a platoon formation (with even less consumption for the lead vehicle), it has been shown that the inter-vehicle distance needs to be reduced to 2.5 meters or less making braking maneuvers even more dangerous. In this paper, we present the design and analysis of a brake-by-wire system for the above case, whose operation is characterized by the *law of the weakest*. That is, the system automatically adapts braking forces at different platoon members — taking vehicles' load condition, etc. into account — to equalize that of the weakest one, i.e., the one braking at the slowest rate in the platoon. We present simulation results based on an automotive hardware-in-the-loop (HiL) setup with realistic car models. Our experiments shows that the proposed system is safe, enabling for collision-free emergency braking at inter-vehicle distances of 2.5 meters and, hence, paving the way for highly efficient platoons.**

I. Introduction

The maximum throughput of a typical highway lane is about 2000 vehicles/hour at an average inter-vehicle spacing of 35 meters [1]. With the number of vehicles increasing, there is a need to improve this throughput; however, infrastructural measures from the past twenty years has shown little effect on this. One solution to this problem would be to efficiently use the existing road infrastructure by reducing the inter-vehicle distances to as close as 5 meters.

There are also aerodynamic benefits when traveling at such close distances as the magnitude of aerodynamic forces acting on a vehicle is reduced due to the vehicle at front. This is the key idea of platooning where a group of vehicles follow a lead vehicle, usually a truck, for the sake of aerodynamic benefits [2] [3].

The longitudinal and lateral control of following or trail vehicles in a platoon is usually done by control systems [4] [5] and the drivers of following vehicles can indulge in other activities resulting in increased comfort [2]. The driver of the lead vehicle drives manually, however, there are systems that assist him/her in the formation and operation of platoons [6]. The European Commission funding the SARTRE project (Safe Road Trains for the Environment) [2] [7] aims to develop technologies to allow the operation of such platoons on normal public highways.

The SARTRE project conducted experiments with an inter-vehicle distance of 5 to 10 meters [8]. However, at such distances, the benefits are not mutual, i.e., only the following vehicles have reduced fuel/energy consumption and the lead vehicle is devoid of any benefits. Wind tunnel tests have demonstrated that if this inter-vehicle distance is reduced to 1 car length (approximately 5 meters) or lesser, the lead vehicle begins to experience reduced aerodynamic forces [9]. Particularly, when the distance is 0.5 car lengths or lesser the benefits are significant.

Contributions. In this paper, based on the above discussion, we propose to reduce the distance to 0.5 car lengths or 2.5 meters and analyze specifically the different braking capacities of each vehicle in the platoon and their resultant effects in emergency braking situations. Our aim is to avoid collisions between vehicles at such close following.

At inter-vehicle distances of 2.5 meters in braking emergencies, there is always the danger of vehicles crashing into each other. As a solution, assuming that vehicles in the platoon know the maximum deceleration rate achievable by the weakest car and do not brake at higher rates than this, then the platoon would be free of collisions.

Here, the term *weakest car* refers to a vehicle whose braking capacity is affected due to, for example, load conditions, wear-out effects, etc. This means that, when such a car joins the platoon, the maximum deceleration rate possible by the entire platoon is conditioned by this car. Based on this, we present the design and analysis of a brake-by-wire system that adjusts deceleration rates at different vehicles accordingly. For this, we consider the effects of reduced aerodynamic forces during braking, which increases vehicles' stopping distances.

Experiments were conducted simulating a three-vehicle platoon in a braking situation. The inter-vehicle distances logged during this simulation braking indeed confirm a collision-free operation with the proposed approach. In addition, we analyze the process of joining and operating in such a platoon.

Structure of the paper. Related work is presented in Section II. The aerodynamic benefits and general motivation are discussed in Section III. The semantics of joining and operating in such a close following platoon is presented in

Section IV. Our brake-by-wire system design and analysis in shown in Section V. Our experimental setup involving realistic car models on an automotive HiL setup is presented in Section VI. Finally, Section VII concludes the paper.

II. Related Work

Research was carried out as part of the California PATH program [1] for demonstrating the advantages of close following vehicle arrangements. Two-, three- and four-vehicle platoons were considered and fuel savings were logged for different inter-vehicle distances. The average fuel savings for the two-vehicle platoon at close following of 0.6 car length (approximately 3 meters) was observed to be much greater than the average fuel savings for the same two vehicle platoon at inter-vehicle distance of 1.2 car lengths. It was also demonstrated that as the vehicles in the platoon increase, the average fuel savings also increases with more savings at shorter inter-vehicle distances.

The advantages of truck platooning are analyzed in [3]. The longitudinal and lateral control of trucks in platooning with the help of image processing system was demonstrated in [4]. Recently, the SARTRE project [2] outlined a high level description of the modules for the technical implementation of platooning. The inter-vehicle distances was 5 to 10 meters for the tests [8].

Most of the research done so far concentrate on the controller implementation and string stability of such systems. Very little research has been done on the effects of braking scenarios in such close following. The effects of driver reaction times and delay involved in actuating the brakes manually in case of control systems failures was carried out in [10]. A two truck platooning was considered for manual emergency braking and the results show that following vehicle had to brake at a much higher deceleration rate than the lead vehicle if collisions has to be avoided.

The work in [11] used a mathematical model for the expected number of collisions and the typical vehicle velocities at impact during close following. All the work done so far prefer inter-vehicle distances to be in the range of 5 to 10 meters. At such distances, there are no aerodynamic benefits or fuel/energy savings for the lead vehicle. In this paper, as mentioned above, we consider the aerodynamic variations and loading conditions affecting the braking behavior of individual vehicles to allow for a safe braking in close following platoons (with inter-vehicle distances of 2.5 meters).

III. Motivation

There are a number of forces that oppose the motion of a car. The most prominent ones are the rolling resistance, aerodynamic forces and inertia [12]. The power required for a passenger car traveling at speeds higher than 80 km/h to overcome the aerodynamic resistance is greater than the power required to overcome the rolling resistance of the tires and the resistance in the transmission [13]. As a result, a lot of research has been carried out to minimize the effects of aerodynamic forces on the vehicle motion and thereby reduce fuel consumption.

There are two sources generating the aerodynamic forces. First, the airflow over the exterior of the vehicle body, and second, the airflow to the interior of the vehicle through the radiator system, etc. Of these two, the former source accounts for more than 90% of the aerodynamic resistance and comprises the following two components: pressure drag and skin friction [12].

The air mass acting against the motion of the vehicle gives rise to the pressure drag, whereas surface of the vehicle body gives rise to skin friction. The skin friction component is only significant in case of truck trailer combinations and buses. However, for passenger cars, the pressure drag is the major one constituting more than 90% of total external aerodynamic resistance. The aerodynamic resistance is expressed by the following equation [12]:

$$R_a = \frac{\rho}{2} C_D A_f V_r^2 \tag{1}$$

where ρ is the mass density of air, C_D is the coefficient of aerodynamic resistance encapsulating all the factors mentioned above, A_f is the frontal area or the projected area of the vehicle in the direction of travel and V_r is the vehicle's relative speed to the wind [12].

The coefficient of aerodynamic resistance C_D is a function of vehicle design, loading conditions and operational factors like windows open or closed and radiator open or blanked. For passenger cars, the value of C_D is typically between 0.311 to 0.475 [14].

As generally known, the magnitude of aerodynamic forces acting on a vehicle is diminished, if it is following another vehicle at close distances. This is the principle behind existing platoon concepts where several cars or trucks follow a lead vehicle at close distances of 5 to 10 meters [8] [2] [3]. The result is reduced fuel consumption for the following/trail vehicles and due to close following, the traffic throughput also increases on a highway. The lead vehicle is usually a truck so that the following vehicles in the platoon benefit from the reduced aerodynamic forces and show higher savings in fuel consumption [6]. However, all the experiments carried out [8] [2] as a demonstration of platooning concepts employ a distance of 5 to 10 meters between vehicles and only the following vehicles benefit from reduced fuel consumption.

Experiments conducted to increase the capacity of highways by University of California as part of the California PATH program [1] [9], have demonstrated that even the lead vehicle of a platoon will have significantly reduced aerodynamic effects when the distance between lead and following vehicles is reduced to 0.5 car lengths (approximately 2.5 meters) and lesser. In fact, when the distance is reduced to 0.35 car lengths, the following vehicle will experience more aerodynamic drag than the lead vehicle. Intuitively, this can be attributed to the fact that the following vehicle pushes the air mass towards the

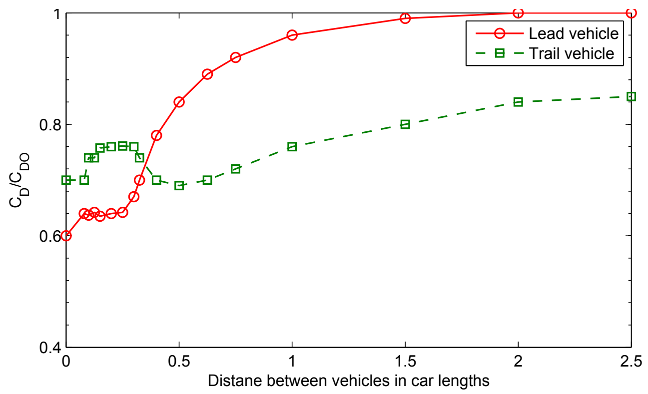

Figure 1. Drag coefficient ratios for two close-following vehicles.

lead vehicle's rear part and hence, this latter experiences a sort of *tailwind*.

The plot in Fig. 1 demonstrates the ratio of coefficient of aerodynamic resistance in a platoon C_D to the coefficient of aerodynamic resistance of the same vehicle in isolation C_{DO} as a function of car lengths [1] [9]. Two vehicles of same height and performance are considered to be part of the platoon and the results of wind tunnel tests are shown [9].

The lead vehicle of the platoon is totally unaware of the following vehicle when this is at a distance of 1 car length or greater. However, the following vehicle experiences measurable decrease in the aerodynamic forces up to a spacing of 10 car lengths. This is termed as *weak interaction regime* because the benefit is one sided and not mutual. When the spacing reduces to less than 1 car length, the lead vehicle of the platoon begins to show a decrease in the coefficient of aerodynamic resistance and this is termed as *strong interaction regime*. At the same time, this coefficient also decreases for the trail vehicle but not so rapidly.

Reducing the distance to 0.5 car lengths and lesser will result in abrupt increase of the coefficient of aerodynamic resistance of the trail vehicle, which crosses that of the lead vehicle at 0.35 car length spacing. This ratio for the trail vehicle will be greater than that of the lead vehicle all the way till zero spacing. At very close spacing of 0.25 car lengths or lesser there is little change in the coefficient of aerodynamic resistance of the lead vehicle. This behavior where the coefficient of aerodynamic resistance of the trail vehicle is greater than that of the lead vehicle is counter-intuitive. However, as stated above, it can be roughly explained by air being pushed by the trail vehicle towards the lead vehicle [1] [9].

An Example: To better understand the graph in Fig. 1, consider a car having a coefficient of aerodynamic resistance of 0.45 when traveling in isolation. Now another car of the same height follows this vehicle at a close distance of 0.5 car lengths, i.e., 2.5 meters. As per the graph in Fig. 1, at such a distance, the value of C_D/C_{DO} is 0.85. As a result, the new coefficient of aerodynamic resistance of the lead vehicle is $0.85 \times 0.45 = 0.3825$.

When these values for C_D are substituted in (1), we find a 15% reduction in the magnitude of aerodynamic forces when traveling in a platoon assuming the velocity is constant in both the cases.

Due to reduced aerodynamic forces, the fuel consumption is also reduced when traveling in a platoon. Experiments conducted as part of the California PATH program demonstrate the same where the lead vehicle exhibited a fuel savings of 5% when the inter-vehicle distance in the platoon was 3 meters [1] [9]. Fuel savings for the trail vehicle are naturally expected and this savings are significant in both cases - following at a distance of 0.5 car length or following at distances greater than 1 car lengths. Now, if a third vehicle joins the platoon with an inter-vehicle distance of 0.35 car lengths, the phenomenon where the aerodynamic coefficient of the second vehicle is more than the lead vehicle does not longer hold. The third vehicle will now have its coefficient of aerodynamic resistance greater than the lead vehicle [1] [9]. If a fourth vehicle joins the platoon this effect replicates and so on. It is also important to note that the average fuel consumption for the entire platoon decreases as the number of vehicles increase. However, it would be impractical to have a large number of vehicles operating in the platoon due to infrastructural issues [8] [15].

The road tests conducted to demonstrate platooning maintain an inter-vehicle distance of 5 to 10 meters (greater than 1 car lengths) [8] [2]. At such distances, as per the graph in Fig. 1, the lead vehicle has no benefit and the average fuel consumption reduces only for the trail vehicles. The proposal in this paper is to reduce the inter-vehicle distance in platoon to 0.5 car lengths so that even the lead vehicle experiences aerodynamic benefits and contributes to average fuel savings of the entire platoon. Naturally, at such short inter-vehicle distances of 2.5 meters, human behavior cannot be relied upon, and as a result control systems are employed for latitudinal and longitudinal control. The semantics of platoon/convoy joining and inter-vehicle communications for operation are explained in the next section.

IV. Convoy Joining and Operation

When traveling in a platoon, particularly in case of braking emergencies, there is always the danger of the trail vehicle crashing into the lead vehicle from behind. Experiments demonstrated by SARTRE project [8] [2] involved a trained professional truck driver driving the lead vehicle of the platoon. The tests were all conducted in controlled environments and the results were logged for inter-vehicle distances of 5 to 10 meters. The packets from the leader of the platoon were broadcasted to all the trail vehicles [16]. It was also demonstrated that placing the antenna at the back of the lead vehicle resulted in benefits like fewer packet loss when compared to placing antenna in the front [16]. The specifications of SARTRE project also agree on disintegrating the platoon in case of braking emergencies.

However, in the approach that we propose, the inter-vehicle distance is reduced to 2.5 meters for aerodynamic benefits also for the lead vehicle resulting in increased average fuel savings for the whole platoon. At such short distances, in braking emergencies, the danger of crashing into the lead vehicle is still more than when compared to following at a distance of 5 to 10 meters. This would also considerably limit the speeds attainable by the platoon.

As discussed above, we propose to restrict the maximum deceleration rate of the platoon to the maximum deceleration rate achievable by the weakest car. The weakest car here refers to a vehicle in the platoon whose maximum deceleration rate is reduced, in particular, due to load condition. The test results provide the confirmation of a collision-free platoon provided the number of packets lost during operation does not cross a threshold, which is a function of the speed of platoon. The theory behind the different maximum deceleration rates achievable by vehicles even though they are of same class in terms of height and performance is explained in the next section.

An Example: Consider a car traveling in isolation which can brake at a maximum deceleration rate of 0.7 g (i.e., $0.7 \times 9.8\,m/s^2 = 6.8\,m/s^2$). Now, a trail vehicle intends to form a platoon and follows up to maintain a distance of 2.5 meters. Even though this trail vehicle is of same height as that of the lead vehicle, it is differently loaded and as a result its maximum deceleration rate achievable is 0.6 g (i.e., $0.6 \times 9.8\,m/s^2 = 5.8\,m/s^2$).

Since this trail vehicle is the weakest of the two in terms of braking, once the platoon is formed, the deceleration rate of the platoon will not exceed more than 0.6 g. In other words, in case of braking scenarios, the lead vehicle calculates and applies the necessary brake force so that its deceleration will not exceed 0.6 g (even though it is capable of braking at more than 0.6 g). All the necessary information is communicated as packets in a timely fashion to the trail vehicle so that it starts braking.

Since the desired deceleration rate in braking situations is achievable by the trail vehicle it will not crash into the rear of the lead vehicle. If a third car joins this two car platoon, considering, it can only achieve a maximum deceleration rate of 0.55 g then the braking capacity of the whole platoon is now restricted to 0.55 g. However, if this third car is capable of achieving a deceleration rate of more than 0.6 g, then in braking situations, it computes the necessary braking force so that its deceleration rate does not exceed 0.6 g.

Whenever a car wants to join an existing platoon it sends a packet as a request to the manager of the platoon with the necessary information like its maximum deceleration rate and maximum speed achievable. The platoon manager or the lead vehicle uses the below algorithm to induce the new car into the platoon. Also, once the vehicle is part of the platoon, it responds or processes packets only from its immediate lead vehicle. This is done to ensure that the trail vehicle will brake only after its immediate lead vehicle has started to brake. The consequence is that the distance between two consecutive vehicles will not be greater than 2.5 meters and the aerodynamic benefits continue.

An Example: Consider a new car that joins an existing platoon and is the last vehicle in this three vehicle platoon. The leader of the platoon broadcasts the necessary information like its current speed and acceleration or deceleration rates to all the platoon vehicles periodically but only the second vehicle in the platoon processes it. As soon as the second vehicle receives the packet it broadcasts the same and only the third vehicle processes it.

Algorithm 1 Algorithm for a new car joining a platoon

Input: Request for platoon joining
Output: New vehicle joins platoon

```
read current max speed of platoon
read current max deceleration rate of platoon
read car's max speed and max deceleration rate
compare platoon's values with car's values
if platoon's values are greater then
    make car's values as platoon's values
    create packet with new values
else
    create packet with platoon values
    inform about new car in packet
end if
broadcast packet to all vehicles and the new car
wait for acknowledgment from all vehicles
if all_acknowledgment_received() then
    create message with needed inter-vehicle distance
    send message to new car
    wait_for_acknowledgment
    if acknowledgment_received() then
        broadcast message about new car in platoon
    end if
end if
```

V. Brake by wire

The rolling resistance of tires, aerodynamic resistance and grade resistance (when traveling uphill) that oppose the motion of a car aid as additional forces during braking. The braking force generated by the mechanical components of a vehicle brake system acting at the tire road interface is the major decelerating force. Thus, the total force acting on a decelerating vehicle can be expressed as the following equation [12]:

$$F_{tot} = F_b + f_r W cos\theta + R_a \pm W sin\theta \qquad (2)$$

where F_{tot} is the resultant total force in Newtons (N), F_b is the force generated by the vehicle's mechanical brake system in Newtons (N), f_r is the coefficient of rolling resistance, W is the weight of the vehicle in Kilograms (kg), θ is the angle of the slope with the horizontal in degrees and R_a is the aerodynamic force on the vehicle in Newtons (N) as represented in (1). It is important to note that the positive term of $Wsin\theta$ has to be used when vehicle is moving uphill and in case of downhill the negative term has to be used [12].

Even though the approach presented in this paper considers cars of the same or lesser height for aerodynamic benefits, their braking capacities will differ because of their loading conditions. The loading conditions is a function of number of occupants in the car, additional loads that are being carried, their distances from the vehicle's center of gravity and hence the forces they exert on the front and rear axles.

The road tire conditions along with the tire pressure also play a role in the maximum deceleration rate that can be achieved. Very similar to the weight transfer from the front to the rear axle during acceleration, there is also a weight transfer from the rear axle to the front during braking situations. That is why, the passengers of a car experience being pushed backwards when the car accelerates and thrown forwards when the car brakes. The weight acting on the front and rear axles during braking are expressed by the respective following equations [12]:

$$W_f = \frac{1}{L}[Wl_2 + h(F_b + f_r W)] \tag{3}$$

$$W_r = \frac{1}{L}[Wl_1 - h(F_b + f_r W)] \tag{4}$$

L represents the vehicle wheel-base in meters, the distance between front axle and vehicle's center of gravity is represented by l_1 in meters, l_2 represents the distance between the vehicle's center of gravity and the rear axle in meters, W represents the total vehicle weight in kilograms, h denotes the height of vehicle's center of gravity from the ground in meters, F_b represents the braking force in Newtons and f_r denotes the coefficient of rolling resistance.

The maximum braking forces sustained by the front and rear axle wheels are a function of coefficient of road adhesion μ and the weight acting on the axle. This maximum braking forces for front and rear axles respectively are expressed by the following equations [12]:

$$F_{bfmax} = \mu W_f \tag{5}$$

$$F_{brmax} = \mu W_r \tag{6}$$

where W_f and W_r are as represented by (3) and (4) respectively. An important aspect of the above two equations is that as long as the braking force supplied to an axle is less than the product of coefficient of road adhesion μ and the weight on that axle, the tires do not lock. When the braking force equals this product, the wheels are on the point of locking. When the wheels of the front and the rear axle are at this point of locking simultaneously, then, the maximum deceleration rate of the vehicle is achieved. If the magnitude of the braking force at any axle exceeds this product then, the corresponding wheels get locked [12].

The braking forces distributed to locked wheels of an axle have no effect on braking and the vehicle slows down only with the help of sliding resistance between the skidding tires and the road. In other words, the locked wheels of an axle indicates the magnitude of braking force distributed to that axle is more than the one it can handle. Thus, the braking forces distribution must be in proportion to that of the normal loads on the axles and this is expressed by the following equation [12]:

$$\frac{K_{bf}}{K_{br}} = \frac{F_{bfmax}}{F_{brmax}} = \frac{l_2 + h(\mu + f_r)}{l_1 - h(\mu + f_r)}, \tag{7}$$

where the proportions of total braking force on the front and rear axles are represented by K_{bf} and K_{br} respectively. It is therefore clear that, a car with fixed braking force distributions will achieve the maximum deceleration rate only for particular loading conditions and for all other cases the achievable deceleration rate is less than the maximum possible. It is indeed difficult to arrive at this fixed braking force distribution ratio as both the range of loaded and unloaded cases have to be considered [12].

The locking of the rear wheels results in loss of directional stability, where the lateral movement of the tires causes the rear end of the vehicle to lead the front. This can be attributed to the fact that locking nullifies the capability of the rear wheels to resist lateral forces and even a slight wind or the angle of the road will trigger this movement. On the other hand, if the front tires lock, then, the vehicle loses directional control and any steering wheel inputs from the driver have no effects on the wheels and the vehicle skids in the direction of the wheel lock [17]. Modern technologies like Antilock Braking System (ABS) prevent locking of the wheels thereby assisting in safe braking [18] [19].

Even though there is proportional distribution of brake forces as per the normal loads on the axles, the deceleration rate of a vehicle is bounded by the coefficient of road adhesion μ [20]. The interaction between vehicle and road happens through the contact patch of the tire and as a result the maximum achievable deceleration rate when normalized as g (acceleration due to gravity) will not exceed μ. This infers that on dry road surfaces where the coefficient of adhesion is 0.85, the maximum deceleration rate achievable would be 0.85 g. Similarly, on icy roads the maximum deceleration achievable would be 0.3 g.

Conventional brake systems have been replaced by brake-by-wire systems [21] eliminating the hydraulic components. The advantage is that the delay of the system is drastically reduced resulting in faster braking systems. The brake pressure generated by the driver is now applied to the wheels by a controller with the help of motor driven electronic actuators. In our approach, we propose to use brake-by-wire systems which performs the necessary calculations taking into account several parameters and generates the required braking force in order to achieve a desired deceleration rate.

Taking all the above factors into consideration, we now use Newton's second law of motion as expressed below to perform the necessary computations.

$$F = ma \tag{8}$$

where F represents the force in Newtons (N), m represents the mass in kilograms and a represents acceleration/deceleration.

Substituting this equation in (2) we get

$$F_{tot} = F_b + f_r W cos\theta + R_a \pm W sin\theta = ma \tag{9}$$

$$F_{tot} = F_b + f_r W cos\theta + R_a \pm W sin\theta = \frac{W}{g} a \tag{10}$$

Therefore, to achieve the required deceleration rate (normalized as g) the brake-by-wire controller has to account for factors like road angle, aerodynamic forces and vehicle total weight and then compute the required braking force F_b. The resultant deceleration rate is then given by the following equation [12]:

$$\frac{F_b + f_r W cos\theta + R_a \pm W sin\theta}{W} = \frac{a}{g} \tag{11}$$

In our proposed approach, during braking, the lead vehicle will achieve a deceleration rate that is below or equal to the maximum achievable by the platoon due to the weakest car. This deceleration rate would be communicated via packets and the following vehicles through the equation in (11) perform necessary computations to achieve this rate. The assumptions here are that the vehicle knows its weight, angle of the road it is currently traveling, and the aerodynamic force acting on it during platoon operation. The aerodynamic drag coefficient is also assumed to be more or less constant with very less variation as the number of vehicles in the platoon changes.

VI. Results

A. Test Setup

A hardware-in-the-loop (HiL) system named SCALEXIO from dSPACE [22] was used in our tests. The tools available with this system help to create a realistic model of a car involving complex mathematical equations for vehicle dynamics, engine, drivetrain, transmission, brake system, wheels, and kinematics. This model of a car can be simulated either using MATLAB/Simulink or using the HiL system. The hardware-in-the-loop (HiL) device that was used is shown in Fig. 2 [23].

As seen in Fig. 2, there are a couple of ECU connectors that help in connecting ECUs to this device. The system to be controlled can be simulated on the HiL device and the control algorithm can be implemented on the ECU. The signal values that are sent and received by the ECU during the control operation can be logged and monitored with the Host PC.

An Example: Consider an application where the wind screen vipers of a car have to be activated when its raining. An ECU with the control algorithm can be connected to the HiL. The model of the wind screen vipers can be simulated on the HiL device and the ECU functionality can be tested.

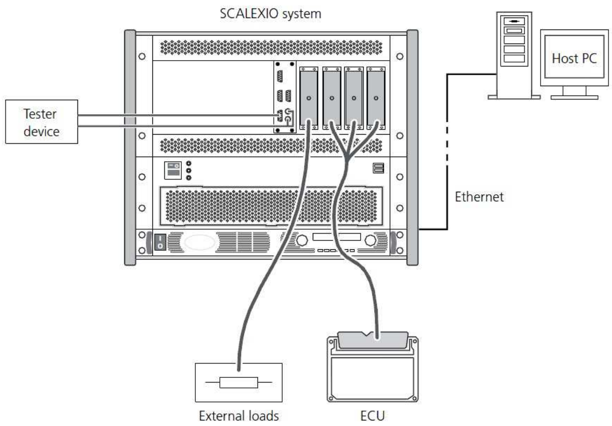

Figure 2. dSPACE SCALEXIO external view

Since our tests involved two platoons, one with two midsize cars, and another with three mid-size cars, we employed libraries from dSPACE for MATLAB/Simulink [24] and constructed the car models. These cars were configured to have different loads and as a result different achievable maximum deceleration rates. The overview of the car model is also shown in Fig. 3 with the components involved in braking maneuvers highlighted. The longitudinal and lateral control systems responsible for platoon operation along with the driver handle the vehicle maneuvers. Roads with different conditions can be constructed and all the related properties are specified by the road model. It is also possible to animate and visualize the car behavior in different situations. For the two platoons tested, we employed a straight road with dry asphalt surface. As a result, the maximum deceleration rate possible was 0.85g.

B. Test Results

1) Inter-Vehicle Distances in Braking: The two vehicle platoon was first considered for measuring the inter-vehicle distances during braking. The results of not considering the different braking capacities vs. the result of considering the same are presented in Fig. 4. The lead vehicle of the platoon was capable of braking at 0.7 g where as the trail vehicle was capable of braking only at 0.6 g. The platoon was simulated to travel at a speed of 80 km/h. Then at this speed, a traffic situation caused the lead vehicle to begin braking and communicate this information via packets. If the braking capacities are not considered, the lead vehicle brakes at 0.7 g and the trail vehicle at 0.6 g resulting in a crash between the two at approximately around 11.3 seconds as seen in the plot. However, if the braking capacities are considered, then, the lead vehicle brakes at only 0.6 g and there would be no collisions. In such cases, the trail vehicle can be seen to follow up close to the lead vehicle and the inter-vehicle distance reduces to 2 meters and

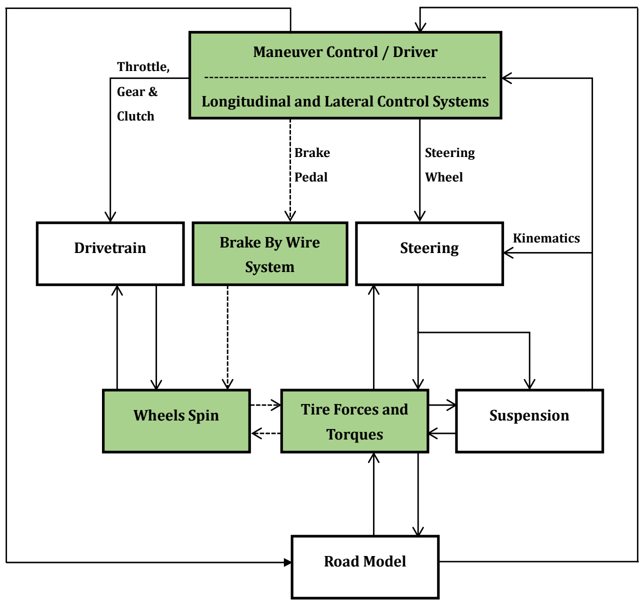

Figure 3. Model of the car used in simulations

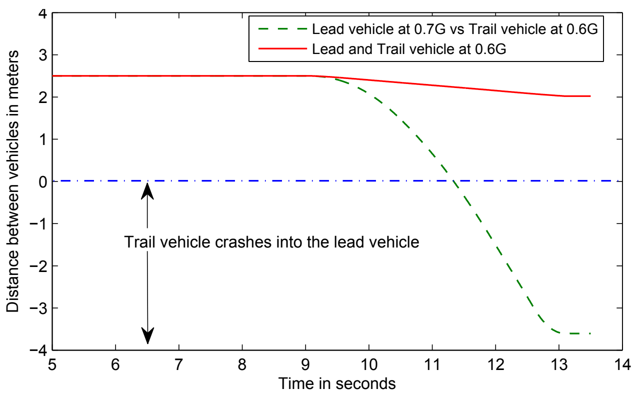

Figure 4. Inter-vehicle distances while braking

then remains constant till the platoon stops completely. This reduction in inter-vehicle distance can be attributed to the delay involved due to transmission and processing of the packet. This time is assumed to be 20 milliseconds.

For the three vehicle platoon, the results are exactly similar. Even the inter-vehicle distances between the second and third are the same. The reason is, the third vehicle processes packets only from the second vehicle. So, when the lead vehicle broadcasts the packet, the second vehicle receives it and would broadcast the same so that the third vehicle processes it.

2) Stopping Distances: The three vehicle platoon is considered for stopping distance calculations. The lead vehicle can brake at 0.7 g, the second vehicle at 0.6 g and the third vehicle at 0.75 g. Therefore, the platoon's maximum deceleration rate

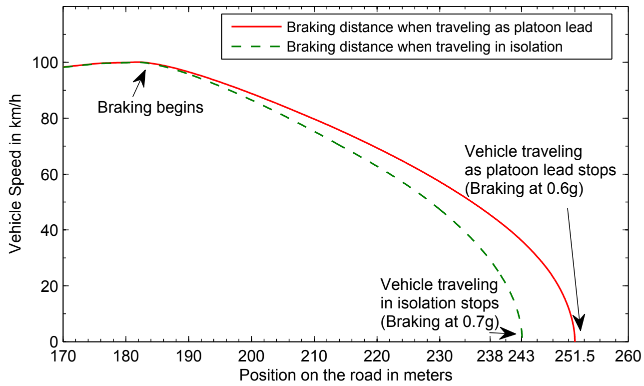

Figure 5. Stopping distances

is only 0.6 g. We log the positions of the lead vehicle on the road during braking and also when it completely stops. Fig. 5 compares the stopping distances for the lead vehicle when traveling in platoon and when traveling in isolation. Please note that when in isolation, the lead car brakes at 0.7 g. From the plot, clearly, the stopping distance is more for the lead car in platoon as compared to isolation and this is approximately around 9 meters. The reasons are lesser deceleration rate and reduced aerodynamic forces. The platoon speed was 100 km/h when the lead vehicle started to brake. For the two-vehicle platoon, the results are again identical.

3) Packet Loss during platoon operation: Since the inter-vehicle distance is at 2.5 meters, the analysis of packet loss in communication is also considered. In this section, we present the allowable number of packets that can be lost during platoon operation and this is a function of platoon speed. That is, higher the platoon speed, the threshold on the number of packets that can be lost consecutively decreases. The analysis is presented as best case and worst case scenarios. The best-case scenario is when the lead vehicle accelerates or maintains the same velocity and communicates data to the trail vehicles, but the packets are lost. On the other hand, the worst-case scenario is when the lead vehicle decelerates. Once the number of consecutive packets that can be lost crosses a threshold, then, in both best and worst cases, the immediate trail vehicle brakes, communicates the same to its following vehicle and completely stops thereby disintegrating the platoon.

An Example: Consider a two vehicle platoon traveling at 50 km/h and the maximum deceleration rate is limited at 0.6 g. A traffic situation causes the lead vehicle to brake. At such low speeds, with packets to be processed every 20 milliseconds, and assuming four consecutive packets are lost, the inter-vehicle distances reduces to $2.5\,m - 1.1\,m = 1.4\,m$. Due to the safety mechanism, the trail vehicle begins braking and this distance further reduces due to time taken for actuation of brakes, however, there is still approximately more than 1 meter inter-vehicle distance as shown in Fig. 6. In scenario of best case, with the lead vehicle cruising, the distance would

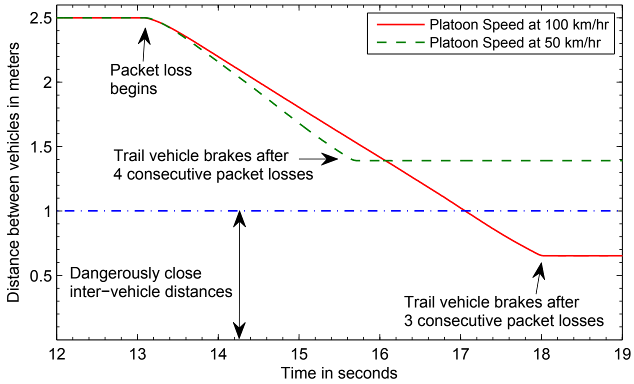

Figure 6. Effect of packet losses during platoon operation

increase to more than 2.5 meters and the platoon would be disintegrated. Thus, at lower speeds this threshold is 4. Now, at much higher speeds of 100 km/h, with every packet loss, the inter-vehicle distance reduces by 0.55 meters. With three consecutive packet losses, there is less than 1 meter distance between the vehicles and by the time braking of the trail vehicle begins, it is dangerously close to the lead vehicle as shown in Fig. 6. The threshold at such higher speeds is now only 2.

VII. Conclusion

The braking process in close following platoons was studied in this paper. Apart from increasing the throughput of vehicles on the road, there are aerodynamic benefits even for the lead vehicle resulting in increased average fuel/energy savings.

A safe operation of platoons in case of braking is demonstrated by considering the deceleration rate of the weakest car and therefore computing the necessary brake forces to be applied through a brake-by-wire systems to achieve a given deceleration rate.

On the other hand, the weakest car dominates the maximum deceleration rate of the whole platoon. Even though there are other vehicles in the platoon with much better braking capacities, their potential is not utilized, resulting in stopping distance that is more than when braking in isolation.

For the above reason, whenever a weak car joins the platoon, the lead vehicle has to take into account the resultant reduced deceleration rate and analyze all traffic situations with utmost safety to initiate a braking maneuver with enough anticipation.

As part of future work, we would like to envisage a technique where the braking potentials of vehicles in a platoon are utilized as much as possible to reduce stopping distances in a close following platoon and, at the same time, guaranteeing a collision-free operation.

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