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RESEARCH ARTICLE

Control of platoons containing diverse vehicles with the consideration of delays and disturbances

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Abstract

The paper focuses on the design of a platoon control system with diverse vehicle formation. After a brief summary of the vehicle model and the control criteria, the paper demonstrates methods for eliminating the longitudinal oscillations caused by the communication and actuator delays and environmental disturbances. The realization and evaluation is done with diverse control strategies. These control methods are demonstrated in a vehicle simulation environment.

Keywords

Platoon · saturation · communication · delay · disturbance · collision

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1 Introduction

The idea behind organizing and controlling vehicles in a platoon during typical traffic situations in which several vehicles travel on the same path for a long distance, is to increase safety and economy with the help of automation. The goal for a vehicle platoon is to achieve the smallest spacing as possible. By means of communication between vehicles enabling nearly simultaneous braking and acceleration, the spacing can be reduced to as small as 0.5-5 meter. For the following vehicles this results in smaller ram, consequently reducing fuel consumption and CO2 emission as well. In addition, the smaller spacing and smoother velocity trajectories can increase the traffic capacity on given distance, accordingly avoiding junctions and its external costs. By the use of automation drivers are greatly relieved, therefore human error related accidents can be avoided, as well as comfort level can be increased. For greater safety, the leader vehicle can be driven by professionally trained driver, and can be equipped with all the available passive and active safety technologies [1, 3, 6, 7] .

The most important requirement within the control of a platoon is to guarantee the safety. During the progress of the platoon the effective and reliable operation of individual vehicles must be guaranteed as well as the safety of the platoon and its environment. Numerous and different kind of traffic situations can endanger the safety of the platoon. Critical traffic situations may occur even under normal running conditions. Coupling or decoupling vehicles, lane changing of the platoon or heavy breaking of the leader vehicle can lead to accident hazards. The inconsistent surface of the path with different traction may cause instabilities in the platoon under extensive breaking. Therefore it is essential to analyse these critical situations during the design of a control system. The platoon also has to be robust for different kind of failures. This can be a puncture or other mechanical breakdown, which forces one of the platoon members to stop abruptly. False data or signal can occur because of a malfunctioning sensor or actuator, which can be eliminated by adding redundancy to the system.

Those control strategies relying on inter-vehicle communication, may suffer from performance degradation due to communi-

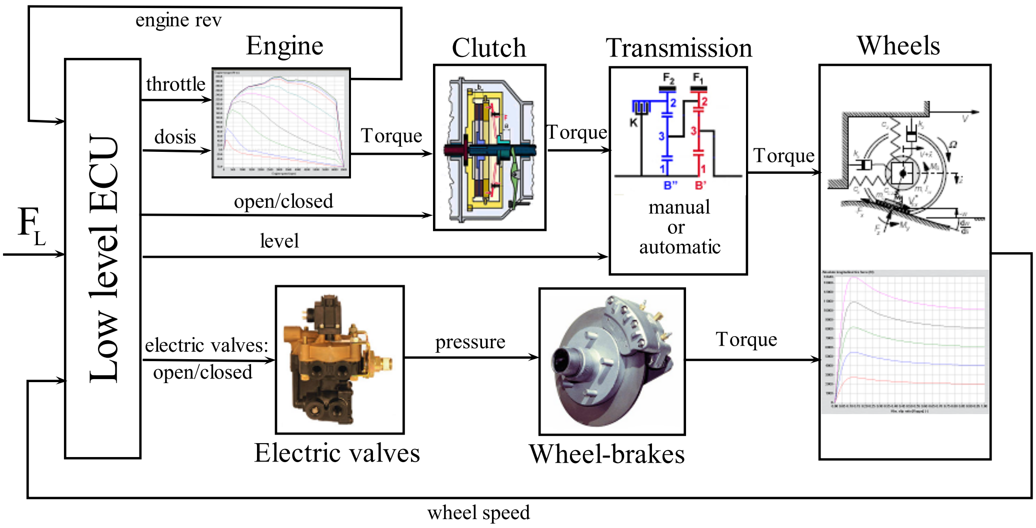


Fig. 1. Vehicle model

cation delays or possible data loss, [2]. It is also very important to handle an accident which already occurred, especially if the leader vehicle is affected in it. In those control strategies using the leader vehicle's or "r" number of preceding vehicles' data for the controller input, the phenomenon of saturation can be dangerous as well. Hereinafter this critical accident hazard will be demonstrated.

2 Platoon controlling

2.1 Vehicle model

For the longitudinal control of vehicles it is practical to introduce a simplified vehicle model. As the output of the control algorithm for a vehicle in the platoon is the acceleration, in the course of controlling the lower level controller the corresponding physical actuators must be addressed (see Figure 1). For the acceleration adjustment the throttle angle of the engine (or in case of diesel operated vehicles the angle of the oil feeder or the opening time of the injector) and the brake pressure must be used. With simplifying assumptions and linearisation the vehicle model enables to punctually define the actuator states necessary for the desired acceleration.

Note that this model is valid even if the vehicles in the platoon are different. Consequently, the controller for stabilizing the platoon can be designed independently of the local dynamics of the vehicles.

2.2 Control

Controlling a platoon two types of stabilization problem has to be solved. For the determination of these problems first the spacing error between vehicles in the platoon has to be defined as follows:

$$e_i = x_i - x_{i-1} + L_{des} \tag{1}$$

where x_i is the position of the actual vehicle, x_{i-1} is the position of the preceding vehicle, L_{des} is the desired inter-vehicular spacing, measured from front bumper to front bumper (see Fig. 2).

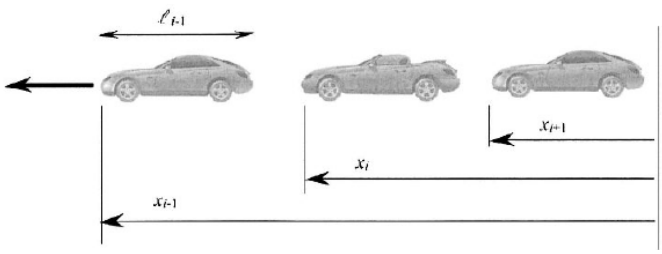


Fig. 2. Vehicle string

Individual vehicle stability is the ability of any vehicle in the platoon to track any bounded acceleration and velocity profile of its predecessor with a bounded spacing and velocity error. The vehicle following control law is said to provide individual vehicle stability if the spacing error of the vehicle converges to zero when the preceding vehicle is operating at constant speed. If the preceding vehicle is accelerating or decelerating, than the spacing error is expected to be non-zero [5].

It is required to ensure that the spacing errors do not amplify upstream from vehicle to vehicle in a platoon. String stability will ensure that a sudden braking that causes a spacing error between the first two vehicles does not propagate in an unstable manner so as to result in a larger spacing error between vehicles at the back of the string. A spacing control algorithm that is not string stable is not only at best likely to provide poor ride quality but also could result in collisions [4]. String stability says that if an interconnected system starts such that all initial system states are within some bound, δ, of the origin, then for all time each state of the system will remain within some other bound, γ, of the origin. Asymptotic string stability says that an interconnected system is string stable and all system states asymptotically approach 0. For providing mathematical conditions ensuring string stability ($\|e_i\| \leq \|e_{i-1}\|_\infty$), the transfer function H(s) must be defined, which relates spacing errors of consecutive vehicles in a string:

$$H(s) = \frac{e_i}{e_{i-1}} \tag{2}$$

The system is string stable if the following two conditions are satisfied. The transfer function H(s) should satisfy:

$$\|H(s)\|_\infty \leq 1 \tag{3}$$

The impulse response function $h(t)$ corresponding to $H(s)$ should not change sign:

$$h(t) > 0 \quad \forall t > 0 \tag{4}$$

2.3 One possible control strategy

The control of a platoon can be realized along diverse strategies. The two main method for this is the constant spacing and the constant headway time strategy. In the former strategy the spacing among vehicles is irrespective of the velocity of the platoon. In the latter strategy the tracking time is a constant, therefore the spacing is a function of the velocity. The control strategy also defines the inputs of the controller. The controller examined below uses the leader and the preceding vehicles' position, velocity and acceleration information for keeping a constant spacing among vehicles [1]. Accordingly the onboard sensors are not sufficient for this strategy, communication between vehicles is necessary. The control algorithm is given by:

$$\begin{aligned} u_{isl} = \frac{1}{1+q_3}[\ddot{x}_{i-1} + q_3\ddot{x}_l - (q_1+\lambda)\dot{e}_i - q_1\lambda e_i - \\ -(q_4+\lambda q_3)(\dot{x}_i - \dot{x}_l) - \lambda q_4(x_i - x_l + \sum_{j=1}^{i} L_j)] \end{aligned} \tag{5}$$

where u_{isl} is the prescribed acceleration of the controlled vehicle, x_l, $\dot{x}_l$, $\ddot{x}_l$ is the position, velocity and acceleration of the leader vehicle, respectively.

3 Considering disturbances and delays in the design

Hereinafter a 60 seconds long simulation is demonstrated, where the sampling time within the communication of the vehicles is 100ms, consequently the signal transfer time is significant. During the breaking process a 30ms delay for the vehicles air brake system is considered, while the gear shifting time during acceleration is around 20-30ms. These delays and the time delay for the engine to build up the sufficient revolution to match the acceleration prescribed by the controller can cause longitudinal oscillations in the platoon. The stability of the platoon is also harmfully affected by the elevation and inclination of the path (see Figure 3)

The elevation angle in the simulation exceeds 4 percent at some sections of the path, which means serious resistance for heavy duty trucks. In the simulation the vehicles in the platoon have different mass, size and performance figures. The mass of

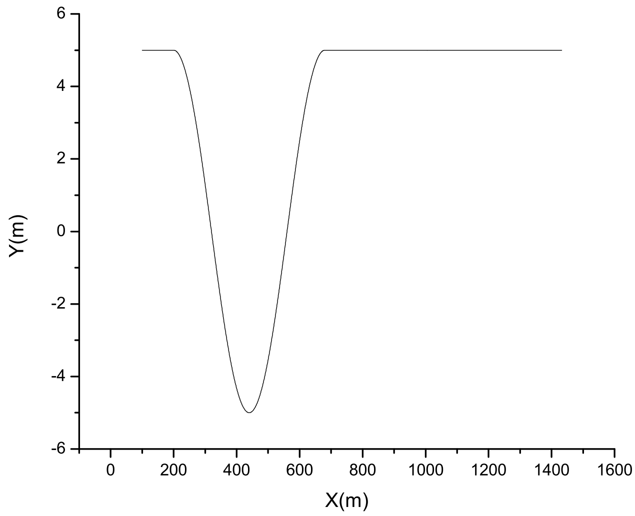


Fig. 3. The elevation and inclination of the road

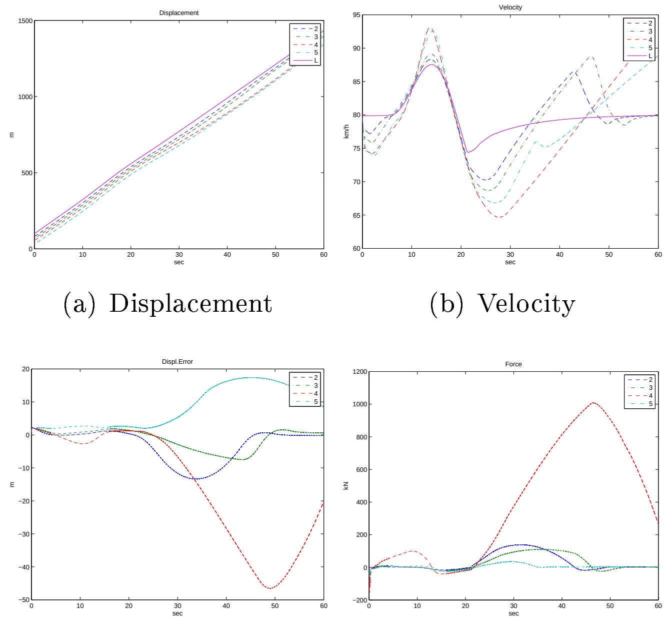
the leader vehicle is 13332 kg, its length is 12,1m, the maximum output of its engine is 330 kW, and it is coupled with a six speed manual transmission. The second and third vehicles are similar, their masses are 12551 kg, their lengths are 5 m, and the maximum performances of their engines are 175 kW. The mass of the fourth vehicle is 26019 kg, its length is 15,356 m, and its engine has a maximum output of 300 kW. The mass of the fifth vehicle is 10690 kg, its length is 4,49 m and the maximum performance of its engine is 175 kW. Except for the leader all of the vehicles in the platoon have a seven speed automatic gearbox. The desired spacing between the vehicles in the platoon is 7,9 m.

In the case of this platoon organized with dynamically different vehicles and with the presence of the actuator and signal processing delays saturation occurred within the following vehicles, while the leader vehicle followed the target velocity of 80 km/h adjusted by the onboard cruise control. Vehicles in the platoon having worse mass/performance figures are not able to match the acceleration prescribed by their controller during uphill or heavy acceleration therefore they cannot keep the desired spacing. Because of the splitting off the following vehicle prescribes bigger acceleration than necessary (due to the growing distance from the leader vehicle), hence the following vehicle can interfere with the saturating vehicle. Fig. 4/d shows that because if it's notable mass, the desired force related to the prescribed acceleration is too big. Hence saturation occurs at this vehicle, consequently it cannot match the prescribed acceleration and in this manner it splits off from the platoon. The significantly big spacing error with a negative sign shows the split off (see Figure 4/c). Due to this, the fifth vehicle prescribes bigger acceleration than it is necessary, hence it runs into the fourth vehicle.

4 Methods for collision avoidance

4.1 Avoiding collision by grading vehicles

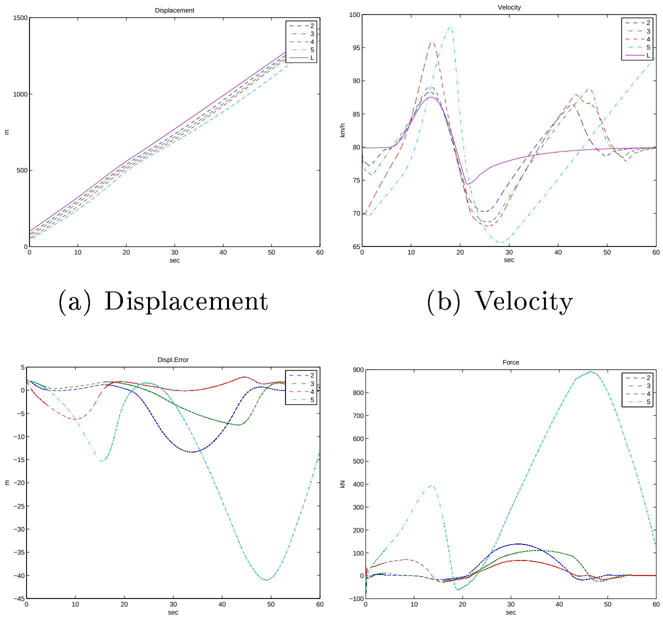
As it has been shown, even a string stable controller is not able to carry out the phenomenon of saturation caused by the diverse



(a) Displacement (b) Velocity

(c) Displacement error (d) Desired force

Fig. 4. Simulation results with diverse vehicles



(a) Displacement (b) Velocity

(c) Displacement error (d) Desired force

Fig. 5. Simulation results with vehicle grading

vehicle formation of the platoon and the delays and environmental disturbances. One possible way to handle saturation is to grade vehicles in the platoon in order of their dynamical ability. If the very heavy and consequently splitting off fourth vehicle is changed with the fifth during the simulation, in that case collision can be avoided despite the split off from the leader.

As Fig. 5 shows collision can be avoided by putting the dynamically worst vehicle at the end of the platoon, although the split off is still significant. One of the drawbacks of this strategy is that the grading of the vehicles is not feasible in all cases. For instant, depending on the vehicles' carriage the dynamical order might change, as the road geometry and velocity of the leader vehicle can affect the actual dynamics as well. The other major drawback is that the strategy does not ensure the cohesion of the platoon, which can lead to accident hazards and badly effects the well known advantages of the platoon. On the other hand, the advantage of this strategy is that the controller algorithm does not need to be changed.

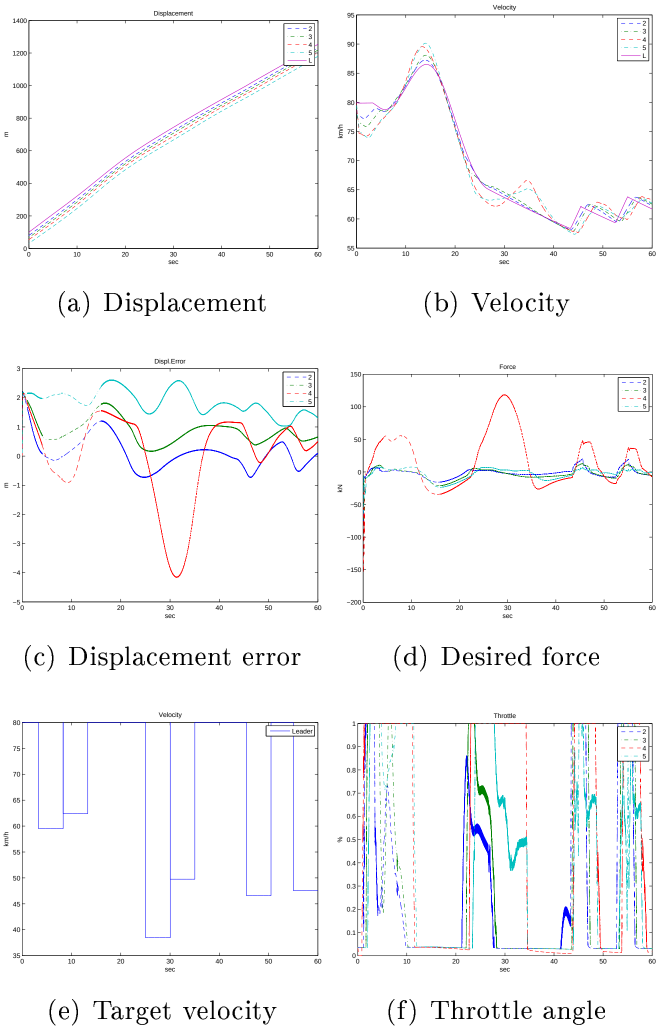
4.2 Avoiding collision by modifying the velocity of the leader vehicle

Inter-vehicular communication methods play a fundamental roll in the problem of a platoon control. For gathering information GPS receiver, WiFi module and CAN communication channel is used. In the design of a platoon control it is required to consider the delays of the communication network and possible losses of data. The greater the sampling time of the communication channel is (in this case 100 ms), the bigger the inter-vehicular spacing must be chosen. In the following strategy the communication with the leader vehicle is bidirectional. To avoid the saturation and the consequent split off of the following vehicles the velocity of the leader vehicle is moderated.

In the simulation example the throttle angle serves as the indicator for saturation. If one of the following vehicles travels with full throttle for more than two seconds than it sends an automatic message to the leader vehicle to moderate the velocity of the leader. Consequently the newly adjusted velocity of the leader vehicle is determined by the saturating vehicle with a proper weighting of its actual acceleration and velocity state (see Figure 6/e). The leader vehicle follows the modified velocity target for five seconds, and in case the saturation cease among the following vehicles, it restores the original velocity target set by the cruise control.

Fig. 6/d shows that properly modifying the velocity of the leader vehicle the maximum prescribed force for the saturating fourth vehicle is nearly one order of a magnitude smaller, hence the saturation time and extent is significantly smaller. Due to this effect the split off is one order of a magnitude smaller, therefore the fifth vehicle does not interfere with the fourth vehicle. It is clearly shown in Figure 6/c that the maximum split off of the fourth vehicle is 4 m, while the fifth vehicle gets closer to it than desired. Meantime the platoon velocity decreases from the adjusted 80 km/h to under 60 km/h, and saturation can be seen during extensive accelerations even on a horizontal path.

One of the biggest advantages of this strategy is that it succeeds to avoid collision without the need to break up the platoon. For this reason all of the platoon advantages remain, and by avoiding the break up the problem of remerging the platoon is unknown. The disadvantage of this scheme is it needs bidirectional communication, which somewhat complicates the realization of the control system. The driver of the leader vehicle may feel insecure because of the external velocity correction.



(a) Displacement (b) Velocity

(c) Displacement error (d) Desired force

(e) Target velocity (f) Throttle angle

Fig. 6. Simulation results with modified velocity

4.3 Avoiding collision by breaking up the platoon

The following control strategy is based on the so-called mini-platoon structure [7]. In this lay-out the platoon dissolves into several platoons following each other, where the last vehicle of the preceding platoon serves as the reference vehicle for the following platoon (see Figure 7)

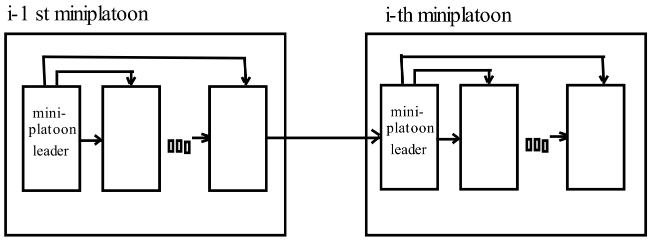
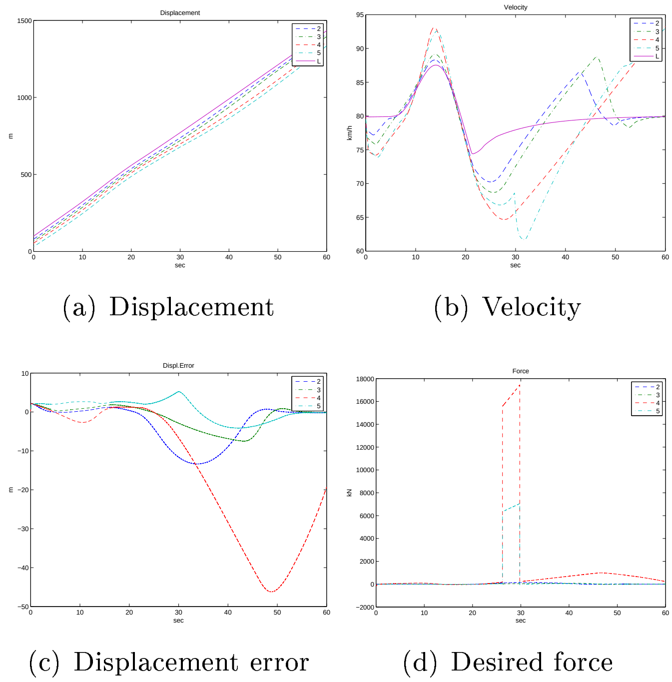


Fig. 7. Mini-platoon information structure

In this simulation example the magnitude of the spacing error serves for saturation detection. If the split off from the desired spacing exceeds three meters for more than two seconds, than saturation is considered. The saturating vehicle consequently falls behind and scales off from the original platoon, creating a new platoon.

In this case according to the above specified mini-platoon strategy the saturating vehicle regards the preceding vehicle as the leader, while the following vehicles regard the saturating vehicle as the new leader vehicle. As it can be seen in this simulation problem, at first the second vehicle saturates and forms a new platoon at 27,4 seconds on the uphill path. Not much time later the fourth vehicle scales off and creates a new platoon as well at 31,1 seconds, therefore at the end of the uphill the original platoon splits into three.

As Fig. 8 shows, in accordance with the original platoon the spacing errors are quite big, but with the use of the mini-platoon strategy collisions can be avoided. The drawback of this scheme is that it cannot ensure the cohesion of the original platoon, but on the other hand it does not require bidirectional communication, hence the realization is simple.



(a) Displacement (b) Velocity

(c) Displacement error (d) Desired force

Fig. 8. Simulation results with platoon break up

5 Summary

In this paper three control strategies were demonstrated dealing with the harmful and dangerous longitudinal oscillations of a platoon containing diverse vehicles. By the grading of the vehicles in the platoon or by applying mini-platoon control strategy collisions can be avoided regardless of the split off, but the separation of the platoon raises countless new safety issues. Therefore the safest strategy to avoid saturation and the consequent collision is to modify the speed of the leader vehicle.

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