Traffic-based Control of Truck Platoons on Freeways

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Abstract

This abstract deals with the control of truck platoons traveling in freeways. In order to improve their travel performance, in terms of travelling times and comfort and to guarantee safety, a hierarchical control scheme is proposed for each platoon. At the high level, the reference speed is computed according to a PI-based control rule with the main aim of reducing the time spent by the platoon in the congested area. This reference speed is communicated to the low control level which implements a Linear Quadratic Tracking policy and determines the optimal speed for each truck in the platoon. The application of these hierarchical controllers to a case study shows the effectiveness of the proposed scheme.

Keywords: autonomous, connected, control, freeway, platoons

1 Introduction

Connected and autonomous vehicles (CAVs) offer a chance to change the world by introducing new ways to move people and goods. Increasing safety and efficiency [Dia15], reducing pollution, fuel consumption and congestion and creating the possibility of transporting very young and old people are all promised benefits of introducing this type of vehicles into traffic. Different studies are being conducted nowadays to learn what will be the true impact of autonomous vehicles.

Currently, one of the most promising applications of CAVs is the implementation of truck platooning, which consists of creating a group of at least two trucks that can travel very closely together, safely at high speeds. Cooperative adaptive cruise control (CACC) technologies, radar equipment and wireless communication systems allow the vehicles to travel less than one second apart and to communicate with each other. As mentioned before, truck platooning can reduce the fuel consumption by reducing the air drag of the trucks driving within the platoon [Jan15].

Although fuel consumption is strongly related to the traffic conditions encountered during the route, only a few works in the literature include traffic state in defining planning and control scheme for platoons. This paper studies the control of truck platoons in freeways to improve their performance, as in travelling time, comfort and safety. For this purpose, a hierarchical two-level control scheme is proposed for each platoon, but unlike previous works [Pas18; Sac21], the control depends on the individual vehicles composing the platoons in addition to the surrounding traffic conditions.

2 Methodology

In this work, traffic conditions and the presence of platoons in the mainstream are represented by the Micro-Macro METANET (M3-net model) model previously introduced in [Pas18] and derived from the well-known METANET model [Kot02]. Here, the model is applied to a highway stretch, which is divided into sections and discretized in time, and the presence of platoons traveling on the freeway is explicitly considered. The model has been designed to track the presence of platoons on the freeway in order to understand what traffic conditions they will encounter on their route and how to adjust their speed accordingly.

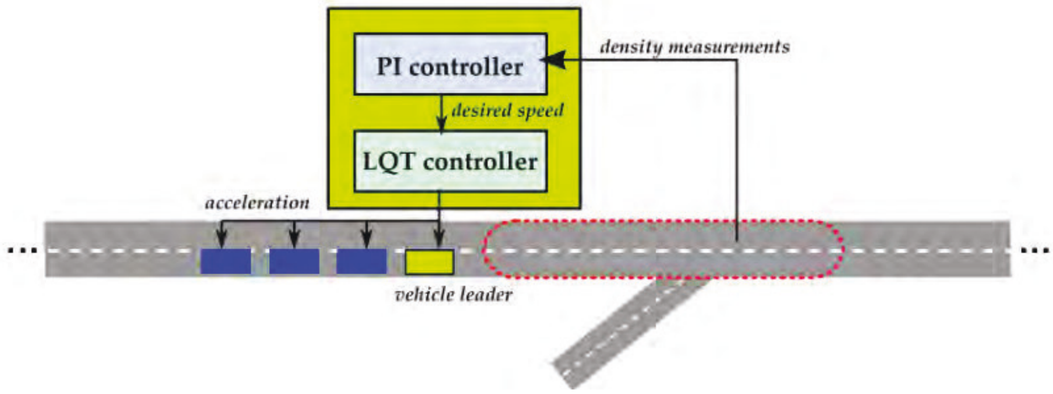


Figure 1: Sketch of the proposed control scheme.

Platoons require specific control techniques because the optimality of the control regards the whole set rather than the individual truck. Analysing the traffic flow from the microscopic point of view, platoons represent the main bottleneck of the system. This happens due to the higher number of constraints that involve many vehicles at a time. The control of each platoon is implemented by means of a two-level control architecture located in the leader vehicle of each platoon. At the high level, the reference speed is computed according to a PI-based control rule to reduce the time spent by the platoon in the congested area. The PI controller defines this speed based on the traffic conditions detected in a portion of freeway downstream of the considered platoon. Then, the low-level controller, which is a Linear Quadratic Tracking (LQT) controller, receives this reference speed profile and defines the accelerations that each vehicle in the platoon must actuate in order to reach the desired speed, while keeping the defined inter-vehicular distances for safety conditions. Each element must continuously monitor the distance from its neighbours and adapt its behaviour consequently. Without these constraints, the control of the platoon translates into a control of the individual vehicle.

To achieve all the above, the control scheme takes advantage of smart communication technologies and the capabilities of CAVs to receive real-time traffic information to define the speed that platoons should take in order to reach the defined objectives.

3 Results and Discussion

The freeway stretch adopted to test the control framework, that is depicted in Figure 2, is 20 km long and is divided into $N = 40$ sections each of which has a length of 0.5 km. The stretch has three on-ramps, located respectively at kilometers 11, 13 and 15, and an exit ramp at kilometer 14. The stretch under consideration has three lanes except for one kilometer where only two lanes are present. Specifically, the narrowing is located from kilometer 11.5 to kilometer 12.5. The presence of four platoons, composed of 5 trucks each, is considered. The arrival of the platoons at the freeway is scheduled at minutes 75, 97, 107 and 117 respectively.

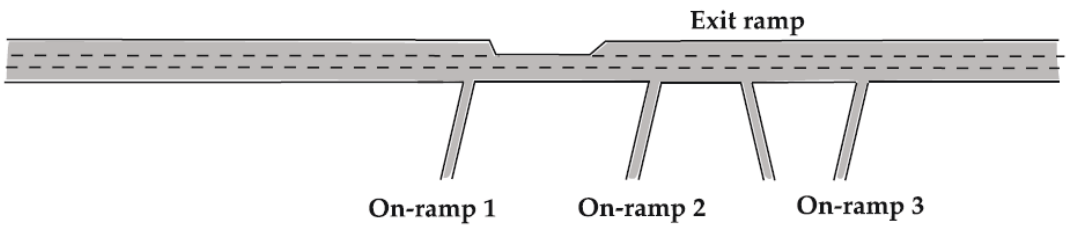
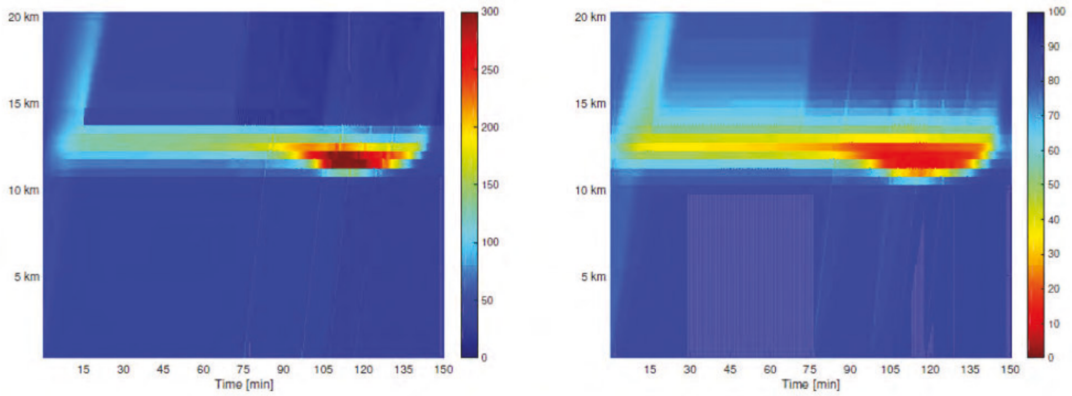


Figure 2: Sketch of the freeway network adopted for this study case.

The simulation has been conducted over a time horizon of two and a half hours. The sample time adopted for the traffic simulation model and to compute the reference value of speed of each platoon has been set equal to 10 s, which gives a total of 900 time steps. By using the simulation model, it is possible to reproduce the traffic behavior in the stretch. As it is possible to observe in Figure 3, which shows the time and space evolution of traffic density and speed, the platoons encounter a state of congestion mainly due to the lane drop at kilometer 11.5.

As for the microscopic representation of platoons, there is the need of a shorter sampling time, taken to be 50 ms, to ensure the responsiveness of vehicles to unexpected events. This allows the platoons to evolve coherently between two consecutive Micro-Macro METANET time intervals and allows the low-level controller to work with a reasonable control horizon, which is 5 in this case study, to pursue the desired speed. At the end of a Micro-Macro METANET sampling time interval, the average speed of the leader within the 10 seconds is provided to the Micro-Macro METANET and the new state of the platoon, considering



(a) (b)

Figure 3: Traffic density (3a) and speed (3b) in the freeway stretch.

the evolution of the traffic, is retrieved to start again the LQT control algorithm. Moreover, the following values of the traffic model parameters have been adopted: the maximum speed a platoon can take is 85 km/h, the free-flow speed is 100 km/h, the jam density is 200 veh/km/lane, the critical density is 50 veh/km/lane, the maximum traffic volume entering section 1 from the mainstream during one sample time is 6000 veh/h, and the maximum on-ramp traffic volume entering a section during one sample time is 1800 veh/h for all on-ramps.

Figures 4 – 7 show the evolution of each platoon overtime, with respect to their entrance and exit time in the main flow. In the above chart it can be noted that the optimal intervehicle distances are broadly maintained through the whole time of simulation without endangering passengers' safety. In other words, the inter-distances do not become too low with respect to the optimal one. Moreover, the desired speed is well-followed even in case of abrupt changes. The zoom in the speed profile denotes the slight differences among elements of the platoon. This suits the expectation of having a set of vehicles moving at a similar speed.

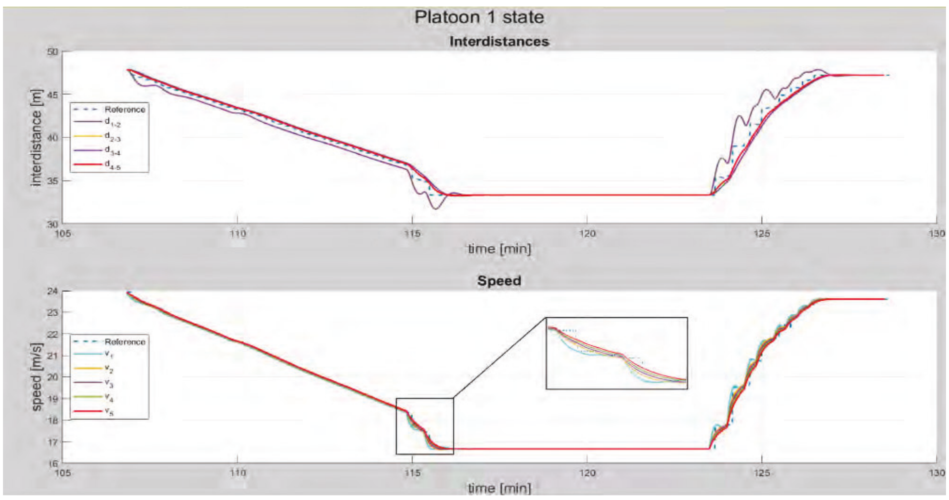


Figure 4: Evolution over time of platoon #1.

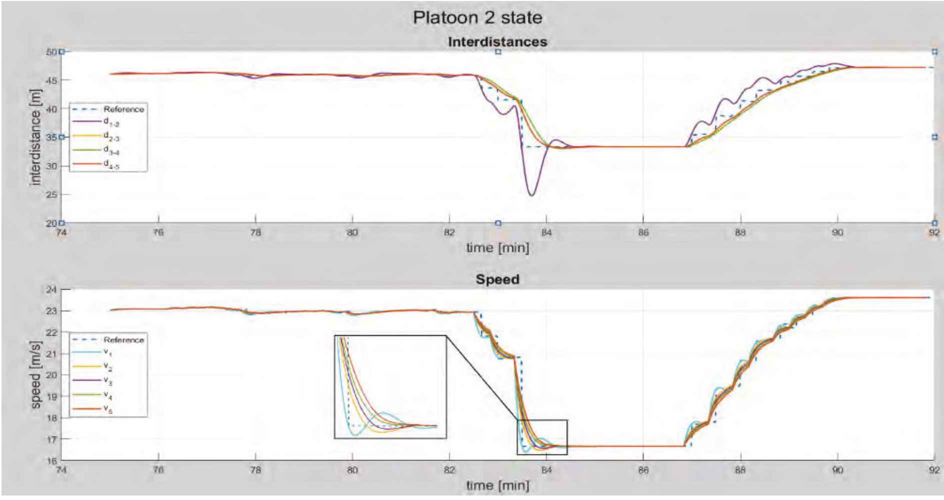


Figure 5: Evolution over time of platoon #2.

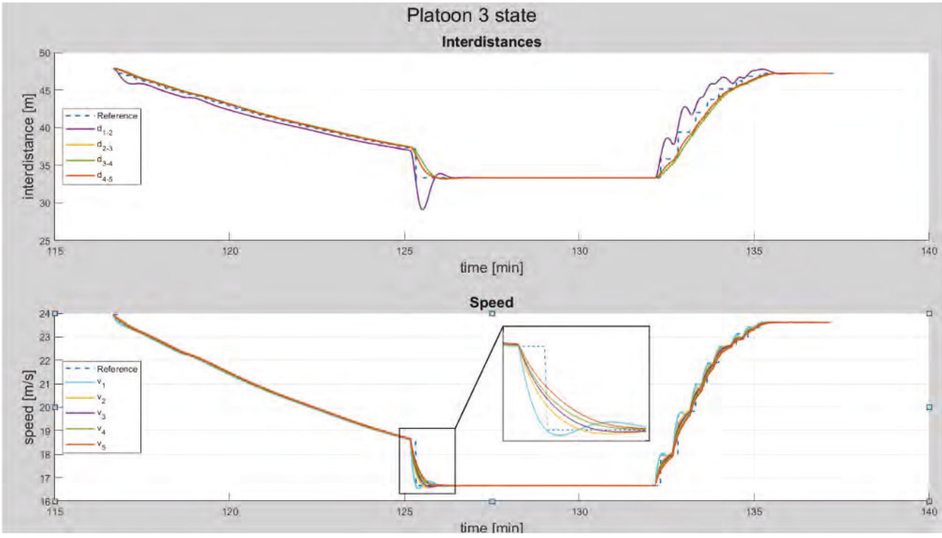


Figure 6: Evolution over time of platoon #3.

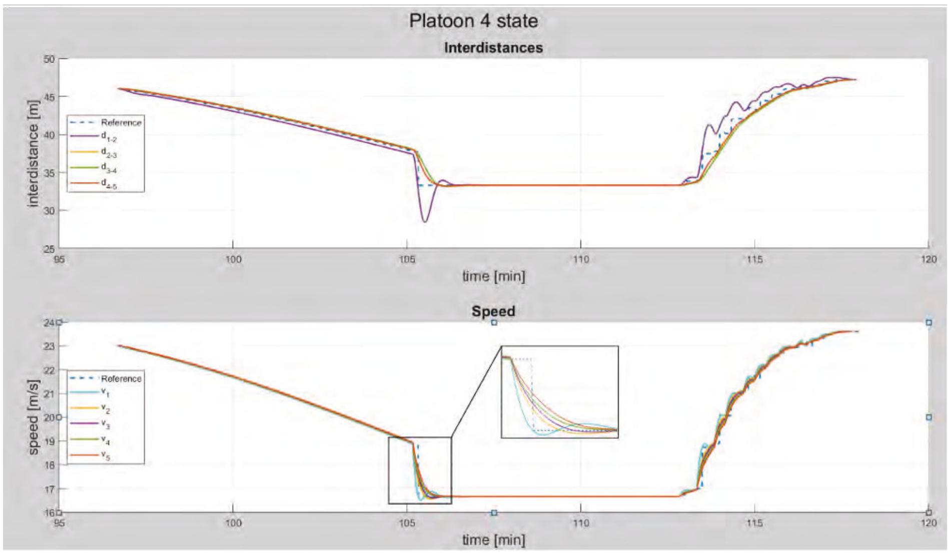


Figure 7: Evolution over time of platoon #4.

As the goal of this control architecture is to improve the operation of truck platoons, in terms of time spent in the congested area and in terms of speed variations, two suitable performance indices are introduced to quantify the performance of the controller. These indices are defined based on the Micro-Macro METANET model and described as follows:

- The time spent in the congested area by platoon z is denoted as τ^z and given by:

$$\tau^z = T \sum_{k=0}^{K} \eta^z(k), \tag{1}$$

  where η^z is equal to 1 if platoon z is, at time step k, in a section in which the traffic density exceeds the critical value, and K is the number of time steps of the considered horizon.

- The second performance index computes the smoothness of the speed profile of platoon z, that is strongly related with comfort levels. This index is denoted as σ^z and is given by:

$$\sigma^z = \sum_{k=1}^{K} \left(v^z(k) - v^z(k-1)\right)^2, \tag{2}$$

  where $v^z(k)$ is the speed of platoon z at time step k (expressed in kilometres per hour).

The effectiveness of the platoon speed controller can be computed considering the entity of the reduction of τ^z and σ^z compared with the uncontrolled case. Analysing the overall performance of the controller in improving these two indexes, and depending on the traffic conditions encountered by the platoons, we can see in Table 1 that the control acts by improving the performance indices, as is the case of platoons $z = 1, 3, 4$, or by keeping the conditions of the uncontrolled case unchanged, as is the case of $z = 2$ platoon.

Table 1: Performance parameters.

Platoon	τ^z **no-control**	τ^z **control**	**% of improvement**
$z = 1$	6.33	6	5.3
$z = 2$	1.83	1.83	0
$z = 3$	5.33	4.83	9.4
$z = 4$	5.83	5.5	5.7
Platoon	σ^z **no-control**	σ^z **control**	**% of improvement**
$z = 1$	17584	16892	3.9
$z = 2$	15548	15530	0.1
$z = 3$	17659	16741	5.2
$z = 4$	16702	16158	3.3

4 Conclusions

In this paper, a hierarchical control system is proposed to control the speed of platoons on highways. The objective of the control system is to improve the driving performance of each platoon by reducing the time it spends in congestion, and to improve driving safety by limiting the abrupt change of speed due to congestion. The main feature of this system is the combination of a high level of control, based on the traffic conditions detected in a defined environment around the instantaneous position of each controlled platoon, and a low level of control, based instead on the state of the individual vehicles in the platoon. The results obtained in a case study show the efficiency of the proposed control scheme and suggest the application of this approach also to more sophisticated control frameworks, where platoons can be used as actuators for control actions that benefit the overall traffic flow.

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