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Platoon-actuated variable area mainstream traffic control for bottleneck decongestion

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ABSTRACT

In this paper a platoon-actuated mainstream traffic control is proposed to decongest bottlenecks due to recurrent and nonrecurrent events. Indeed, differently from traditional mainstream control strategies, i.e., control strategies applied with fixed actuators, platoon-actuated control can be applied at any location on the freeway. In this work, the control actions to be communicated to the platoons, i.e., speed and configuration, are defined by means of a predictive control law based on traffic and platoon state detected in an area identified immediately upstream of the bottleneck. The main peculiarity of this scheme is that the size of the controlled area is dynamically adjusted based on the predicted congestion at the bottleneck. This approach keeps the control law computation burden low, while not sacrificing much control performance. Specifically, the number of platoons to be controlled and the time at which the platoons begin to be controlled depend on the size of the controlled area. Simulation results reported in the paper show the effectiveness of the proposed scheme, eliminating from 60% to 80% of the delay incurred from congestion compared with the uncontrolled case, depending on the level of traffic.

1. Introduction

The introduction of Connected and Automated Vehicles (CAVs) into the automotive sector represents one of the technological advances that will most revolutionize the future of road transportation. Although there are still technological challenges to be faced before CAVs can become commonplace in the vehicle market, several studies in the literature recognized that numerous advantages in terms of safety and efficiency will be achieved when these vehicles preponderate over traditional vehicles (see report [10] and the references therein). However, in the near future, traditional vehicles and CAVs will need to coexist in mixed traffic, for which new traffic management strategies need to be identified.

The conventional ways to control vehicular traffic are given by *road-based*, or *Eulerian* traffic control schemes. In these control schemes, the control actions to be implemented are defined according to traffic conditions, detected at specific locations, and actuated by means of dedicated equipment installed along the infrastructure. In the context of freeway traffic, the most popular road-based control strategies are ramp metering, mainstream control (usually via variable speed limits), or route guidance (the interested reader may refer to the survey in [13] for more details). However, the presence of CAVs in traffic opens up new scenarios in which *vehicle-based*, or *Lagrangian* control schemes, can be implemented, as done for instance in [15]. This means that the presence of CAVs can be exploited to regulate the traffic at the system level, pursuing some global objectives. The aim of this work goes in that direction by proposing a platoon-based mainstream traffic control in which the mainstream traffic flow is regulated through the use of truck platoons that act by restricting the traffic flow upstream of bottlenecks due to both recurring and non-recurring factors, allowing the congestion at bottlenecks to dissipate and improving the throughput of the road.

Truck platooning is a methodology that makes use of vehicle automation to create a string of virtually connected trucks that automatically brake, steer, and accelerate based on the actions of the leading vehicle [2]. Specifically, truck platooning originated with the idea of implementing fuel saving policies [1,6,14], but recently it has also seen its application for traffic flow control purposes such as the one proposed in this paper. For instance, in [8,9], truck platoons are modelled as moving bottlenecks and their speed is defined according to proportional-integral feedback regulators in order to mitigate congestion in the mainstream. In [11] the control

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law proposed in [8] has been embedded in two control schemes, one centralized and one decentralized, in which the control parameters are optimally defined according to the detected traffic conditions. In [4], instead, CAVs that are initially scattered on the road are first collected into platoons, and then used to dissipate stop-and-go waves, improving throughput and homogenizing traffic, while in [5], controlled platoons are exploited to avoid congestion and maximize throughput at stationary bottlenecks. Other works investigate the effects of the presence of platoons in the vehicular flow, as in [12] and [17].

The present work takes inspiration from the approach introduced in [5] in which the platoon speed and configuration (how many lanes the platoon takes) for each controlled platoon are defined based on a prediction of traffic and platoon state performed using the tandem queueing model with moving bottlenecks introduced in [5]. Differently from the work conducted therein, in this paper the control actions (i.e., platoon speed and configuration) are not computed for each truck platoon on the considered road but only for those traveling within a controlled area, which is identified upstream of a bottleneck. Indeed, the main peculiarity of this work is that the length of the controlled area is time-varying and defined according to the degree of total predicted congestion at the end of the prediction horizon.

This paper is organized as follows. Section 2 introduces the motivation and the main features of platoon-based mainstream control, while the control scheme based on the variable-length segment controller is presented in Section 3. Some simulation results are introduced in Section 4, in order to show the effectiveness of the proposed control scheme, whereas concluding remarks and future perspectives of platoon-actuated mainstream traffic control are drawn in Section 5.

2. Platoon-actuated mainstream traffic control

Freeway traffic control research has produced several strategies whose primary goal is to mitigate traffic congestion. These strategies differ in the control variables adopted (e.g., inflow from the on-ramps in ramp metering strategies, splitting rates in routing strategies, etc.) and in the actuators used to implement them, which, as mentioned in the Introduction, are typically placed at fixed locations along the infrastructure.

Among these methodologies, the one adopted to directly regulate the vehicular flows traveling on the road is denoted as mainstream control, and is typically designed to prevent the activation of bottlenecks, generally due to freeway layout (e.g., lane drops, merging zones with on/off-ramps, etc.), see for instance the works [7,16]. As mentioned in [3], this strategy can be implemented in various ways, such as by defining variable speed limits, displayed to users through variable message signs placed at significant locations on the freeway, by regulating the traffic stream through traffic lights at the roadway or through exploitation of intelligent vehicles. Regardless of the methodology adopted, the objective is to create controlled congestion (of significantly lower intensity and duration than the congestion that would be created in the absence of control) capable of sufficiently reducing the inflow into the bottleneck, thus avoiding its activation.

In this paper the concept of mainstream control is implemented using truck platoons as actuators. Therefore, the basic concept of this work is to exploit the presence of platoons in traffic that, properly controlled, i.e. by adjusting their speed and defining the number of lanes they should occupy, are able to regulate the inflow into the bottleneck area in order not to exceed its capacity (i.e. the maximum flow that the bottleneck can discharge), and thus prevent the formation of congestion. Compared with mainstream control with fixed actuators, mainstream control performed with platoons is more flexible allowing the management of non-recurring

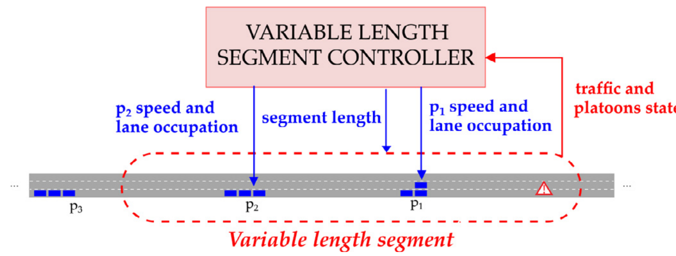


Fig. 1. Sketch of the proposed control scheme.

bottlenecks (such as those caused by accidents or roadworks) that may arise at any location within the freeway stretch. At the same time, it is worth noting that the effectiveness of platoon-based mainstream control depends on several aspects such as the number of platoons present in the freeway stretch, and their distance from the bottleneck.

To this end, a platoon-actuated mainstream traffic control scheme considering these two latter aspects is presented. In particular, the proposed control scheme is of the centralized type and exploits the complete knowledge of both traffic and platoons state in the whole freeway stretch. As shown in the sketch of the proposed control framework depicted in Fig. 1, in this scheme only the platoons that are within the controlled area identified immediately upstream of the bottleneck are controlled. Yet, the peculiarity of this approach is that the size of the controlled road segment, based on which the control actions are computed, is dynamically defined according to the severity of the predicted congestion.

It is worth noting that the size of the control area is a crucial issue for problems of this type, since its length determines some fundamental aspects of the control:

- the number of platoons that can be used as actuators of the mainstream control;
- the distance from which platoons start their control action.

Broadly, the longer the controlled road segment, the greater the likelihood that there will be a sufficient number of platoons to deal with the congestion. Additionally, since the platoons reference speed are lower-bounded by some value, the time each platoon can spend restricting the traffic flow is generally limited. Therefore, a long controlled road segment enables the platoons to delay the traffic flow for a longer time, allowing for a more effective action in preventing bottleneck activation. These observations suggest that severe congestion necessitates a long controlled road segment in order to be successfully dissipated. However, it should be noted that if the segment size increases, the problem size also increases and thus the computation time required to solve it. Moreover, large controlled segments require prediction horizons long enough to track the entire path of platoons, compromising the reliability of the prediction itself. Therefore, the idea of defining control actions over a zone of varying size allows us to adapt the control problem on the basis of current traffic conditions and platoon availability, thereby reducing the overall computational load of the problem and allowing its application for online control purposes.

3. The proposed control scheme

3.1. Description of the control scheme

As mentioned above, the aim of this work is to define a mainstream control strategy in which truck platoons are the actuators that operate by slowing down traffic in the mainstream so that the flow reaching the bottleneck does not exceed its capacity. Specifically, in this scheme we assume that the platoons arrive randomly, and that their speeds and the number of lanes they occupy are the

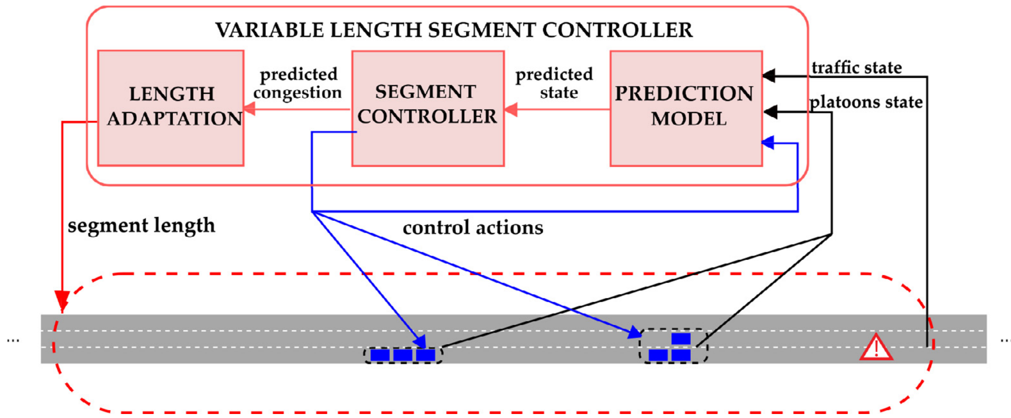


Fig. 2. The proposed control scheme.

control inputs, which are defined through a prediction-based control law.

As shown in the control scheme in Fig. 2, the controller receives the current traffic and platoons state measurements and uses them to predict the evolution of the numbers of vehicles accumulated in the queues at the moving and stationary bottlenecks, as a function of future control inputs. Then, using a control law derived from the prediction model, the controller computes and communicates to each controlled platoon the reference speed and the number of lanes that it should occupy to decongest the bottleneck downstream of it. Owing to the specific structure of the prediction model, the control action at each prediction time step is calculated directly from the predicted queue lengths at the previous prediction time step. At each control time step, only the first calculated control action is sent to the platoons for execution, acting in a receding horizon manner, and the prediction is repeated at the next control time step.

The number of platoons to be controlled and the instant at which the platoons begin to be controlled depend on the length of the segment on which the control actions are defined, which is dynamically adjusted according to the expected level of congestion at the bottleneck. Both the tandem queuing model used to perform the prediction, and the predictive control law included in the control scheme, are presented below. These two blocks form the inner control loop, whereas the controlled segment length adaptation forms the outer loop, enabling the inner loop to successfully achieve the control goals.

3.2. Prediction model

In this section the traffic model used to predict the traffic state and to compute the control actions is presented. This prediction model is based on the tandem queuing model with moving bottlenecks introduced in [5], and properly extended to represent the traffic behaviour in a road segment. Let s denote a generic freeway segment coinciding with the interval $\mathcal{X}_s(t_0) = [X_s^{\text{in}}(t_0), X_s^{\text{out}}(t_0)]$, where $X_s^{\text{in}}(t_0)$ and $X_s^{\text{out}}(t_0)$ are respectively the upstream and the downstream ends of the segment, and t_0 is the current time at which we are predicting the queue length evolution. The prediction is based on the current traffic state, i.e., the traffic density ρ, that can be either gathered from measurements of the real system or reproduced with a simulation model.

Assuming all the vehicles on the segment (at least approximately) share a common constant maximum free-flow speed V, as is the case when a triangular fundamental diagram is used, at time t_0 we may predict the outflow from the segment $q_s^{\text{out}}(t|t_0)$ for $t \le t_0 + \frac{\|\mathcal{X}_s(t_0)\|}{V}$, where $\|\mathcal{X}_s(t_0)\| = X_s^{\text{out}}(t_0) - X_s^{\text{in}}(t_0)$ is the segment length, using only the traffic state within it, i.e., without the need to know the future inflow to the segment. The segment traffic state consists of the traffic density $\rho(x, t_0)$, $x \in \mathcal{X}_s(t_0)$, and positions $\underline{x}_i(t_0)$ of all bottlenecks $i \in \mathcal{I}_s(t_0)$ that are within the segment at time t_0, $\underline{x}_i(t_0) \in \mathcal{X}_s(t_0)$. Finally, we also assume that the segment length is constant for the whole duration of the prediction. For conciseness, hereinafter we omit writing the time t_0, when the predictions are calculated, wherever it is obvious.

In this work we use the queuing model to represent three types of queues: *stationary bottlenecks*, that are the "physical" bottlenecks due to lane drops, traffic accidents, etc., *moving bottlenecks*, that are the controlled platoons which we use as traffic flow actuators, and *closed-loop controlled road segment*. This third type of queues encapsulates a portion of freeway that is controlled, allowing us to approximate a road segment as a single queueing server. Therefore, we introduce a general formulation of the queuing model in which the general element $i \in \mathcal{I}_s(t_0)$ (stationary bottleneck, moving bottleneck or closed-loop controlled road segment) can be modeled as a queuing server, with the number of queuing vehicles $n_i(t)$ evolving in time according to

$$\dot{n}_i(t) = q_i^{\text{in}}(t) - q_i^{\text{out}}(t), \quad t \ge t_i(t_0), \quad i \in \mathcal{I}_s(t_0) \tag{1}$$

where $q_i^{\text{in}}(t)$ is the traffic flow arriving at the queue, and $q_i^{\text{out}}(t)$ the flow discharging from it,

$$q_i^{\text{out}}(t) = \begin{cases} \min\left\{q_i^{\text{in}}(t), q_i^{\text{cap}}(t)\right\}, & n_i(t) = 0, \\ q_i^{\text{ctr}}(t), & 0 < n_i(t) \le n_i^{\text{ctr}}(t_0), \\ q_i^{\text{dis}}(t), & n_i(t) > n_i^{\text{ctr}}(t_0). \end{cases} \tag{2}$$

Here, $q_i^{\text{cap}}(t)$ is the maximum capacity of the queue, $q_i^{\text{ctr}}(t)$ and $q_i^{\text{dis}}(t)$ are the discharging flows from the partially and fully congested queue, respectively, $n_i^{\text{ctr}}(t_0)$ is defined as the queue length boundary between the partially and fully congested queue, and we have $q_i^{\text{cap}}(t) \ge q_i^{\text{ctr}}(t) \ge q_i^{\text{dis}}(t)$. We denote by $t_i(t_0)$ the first time when the queueing server begins affecting the rest of the road network.

Firstly, we model a stationary bottleneck $\beta \in \mathcal{I}_s(t_0)$, at position $\underline{x}_\beta(t) = X_\beta \in \mathcal{X}_s(t_0)$, by setting all queue parameters to constant values, $n_\beta^{\text{ctr}} = 0$, and $q_\beta^{\text{ctr}} = q_\beta^{\text{dis}} < q_\beta^{\text{cap}}$. Specifically, as soon as the stationary bottleneck becomes congested, $n_\beta(t) > 0$, the maximum outflow is reduced from q_β^{cap} to q_β^{dis} due to the capacity drop phenomenon.

Secondly, we model the platoons acting as moving bottlenecks $\xi \in \mathcal{I}_s(t)$, with trajectories $\underline{x}_\xi(t)$, $\underline{x}_\xi(t_0) \in \mathcal{X}_s(t_0)$, by assuming constant $n_\xi^{\text{ctr}} = 0$, and time-varying $q_\xi^{\text{dis}}(t) = q_\xi^{\text{ctr}}(t) = q_\xi^{\text{cap}}(t)$. These limits on the overtaking flow, enforced by controlling the formation of the platoons, are used as control inputs, $q_\xi^{\text{cap}}(t) \in \left\{q^{\text{lo}}, q^{\text{hi}}\right\}$, and set by the control law.

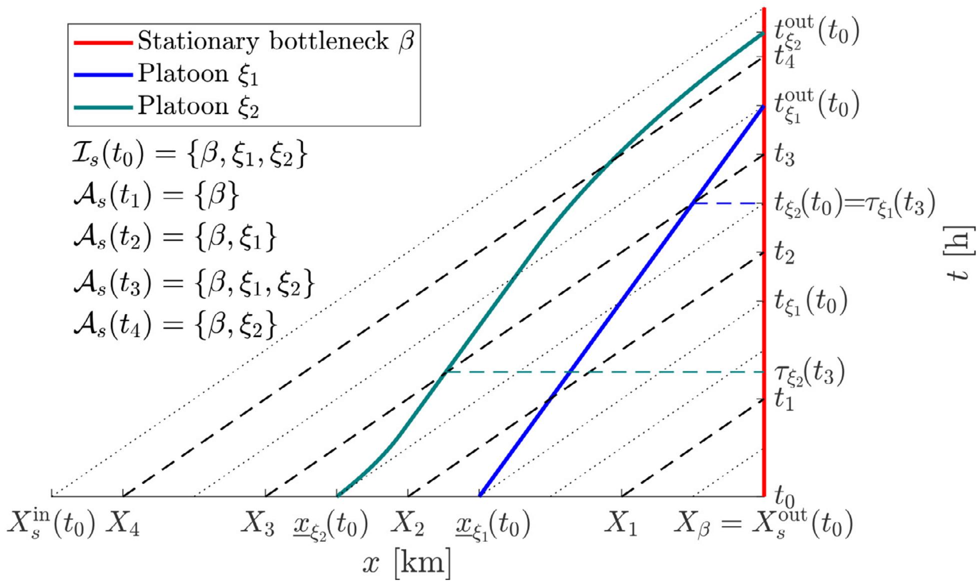


Fig. 3. Explanation of the model structure with one stationary bottleneck β at the downstream end of the segment, and two platoons, ξ_1 and ξ_2. Bottleneck trajectories are shown in coloured lines. Black dotted and dashed lines have slope $1/V$ and correspond to a single prediction time t. Contents of set $\mathcal{A}_s(t)$ for prediction times $t \in \{t_1, t_2, t_3, t_4\}$, indicated by dashed black lines, are displayed.

Finally, we can encapsulate the average behaviour of the closed-loop controlled road segment s as a queuing server with $n^{\text{ctr}}_s(t_0) = \|\mathcal{X}_s(t_0)\|\eta_{\text{ctr}} \geq 0$, and constant $q^{\text{cap}}_s \geq q^{\text{ctr}}_s \geq q^{\text{dis}}_s$. The choice of parameters and model structure will be elaborated in Section 3.4.

Due to the assumption that the free-flow speed V is constant everywhere on the considered road segment, the outflow from the segment $q^{\text{out}}_s(t)$ at times $t \in [t_0, t_0 + \frac{\|\mathcal{X}_s(t_0)\|}{V}]$ can be predicted at time t_0 based on the flow of the traffic originating from position $X^{\text{out}}_s(t_0) - V \cdot (t - t_0)$ at time t_0,

$$q^{\text{out}}_s(t) = V\rho\big(X^{\text{out}}_s(t_0) - V \cdot (t - t_0), t_0\big), \tag{3}$$

and the states and dynamics of those bottlenecks $i \in \mathcal{A}_s(t)$, for which there exists $\tau_i(t) \in [t_0, t]$ such that

$$\underline{x}_i(\tau_i(t)) = X^{\text{out}}_s(t_0) + V \cdot (\tau_i(t) - t), \tag{4}$$

$$\mathcal{A}_s(t) = \left\{ i \in \mathcal{I}_s(t_0) \middle| (\exists \tau_i(t) \in [t_0, t]) \right\}. \tag{5}$$

Essentially, bottlenecks $i \in \mathcal{A}_s(t) \subset \mathcal{I}_s(t_0)$ have trajectories that intersect the trajectory of a vehicle that would reach $X^{\text{out}}_s(t_0)$ at time t travelling at free-flow speed V. A graphical explanation of the discussed concepts is given in Fig 3, with $\tau_i(t)$ shown by horizontal dashed coloured lines. At every prediction time t, we order these bottlenecks by increasing $\tau_i(t)$, and denote the bottleneck immediately upstream of bottleneck i along the line $X^{\text{out}}_s(t_0) + V \cdot (\tau - t)$ (shown in dotted or dashed black for different t in Fig. 3) as $\overleftarrow{i}(t)$, $\tau_{\overleftarrow{i}}(t) < \tau_i(t)$, and $(\nexists j \in \mathcal{A}_s(t)), \tau_{\overleftarrow{i}}(t) < \tau_j(t) < \tau_i(t)$. If there are no bottlenecks upstream of bottleneck i at relative time t, we write $\overleftarrow{i}(t) = 0$. Therefore, it is much simpler to represent the dynamics of all queues $i \in \mathcal{I}_s(t_0)$ in “relative” time, i.e., time when a vehicle departing from the position of the bottleneck and travelling at free-flow speed would reach the downstream end of the segment. This is due to the fact that in this frame of reference, there are no delays between the queues and the inflow to each queue is

$$q^{\text{in}}_i(t) = q^{\text{out}}_{\overleftarrow{i}}(t), \quad i \in \mathcal{A}_s(t). \tag{6}$$

If $\overleftarrow{i}(t) = 0$, the inflow to queue i at relative time t is given by (6), and for this upstream-most queue i, we write $i = \vec{0}(t)$. Otherwise, the input is given as an output of the queue $\overleftarrow{i}(t)$ defined by (2). If there are on- and off-ramps between queues i and $\overleftarrow{i}(t)$, their net inflow to the road would also be added to $q^{\text{in}}_i(t)$.

Note that the structure of the chain of queueing servers $\mathcal{A}_s(t)$ representing the bottlenecks varies in time, as demonstrated in Fig. 3. We assume that there is a stationary queue at the downstream end of the segment, representing either a physical stationary bottleneck, or an encapsulation of the road downstream of the segment. This bottleneck is the downstream-most in the chain for all t, and we formally denote it by $\overleftarrow{0}$. Therefore, at time $t = t_0$, we have $\mathcal{A}_s(t_0) = \{\overleftarrow{0}\}$. As the prediction time is advanced, more bottlenecks will start affecting the outflow from the road segment, and will therefore be added to $\mathcal{A}_s(t)$ and to the queueing servers chain. Queues $i \in \mathcal{I}_s(t_0)$ are connected to the chain at its upstream end at time $t = t_i(t_0)$,

$$t_i(t_0) = t_0 + \frac{X^{\text{out}}_s(t_0) - \underline{x}_i(t_0)}{V}, \tag{7}$$

by changing $\vec{i}(t_i(t_0)+) = \vec{0}(t_i(t_0)-)$ and $\overleftarrow{i}(t_i(t_0)+) = 0$. We assume that the moving bottlenecks do not overtake each other until they reach the downstream end of the segment at time $t^{\text{out}}_\xi(t_0)$ for which $x_\xi(t^{\text{out}}_\xi(t_0)) = X^{\text{out}}_s(t_0)$. At this time, moving bottleneck ξ is removed from the chain by setting $\overleftrightarrow{\xi}(t^{\text{out}}_\xi(t_0)+) = 0$, and its queue is added to the queue at the downstream end of the segment,

$$n_{\overleftarrow{0}}(t^{\text{out}}_\xi(t_0)+) = n_{\overleftarrow{0}}(t^{\text{out}}_\xi(t_0)-) + n_\xi(t^{\text{out}}_\xi(t_0)-) + n^\pi_\xi, \tag{8}$$

where n^π_ξ is the passenger-car-equivalent number of vehicles in the platoon itself. This yields a hybrid structure of the prediction model, with the continuous dynamics described by a tandem queueing system, and discontinuous dynamics corresponding to changing the network structure.

3.3. Segment controller

In order to predict the future outflow from the segment, we need to know the future control inputs, i.e., $q^{\text{cap}}_\xi(t)$, as well as the times when the moving bottlenecks leave the road segment $t^{\text{out}}_\xi(t_0)$. Both of these information sets can be calculated during the prediction process, with $q_{\xi}^{\mathrm{cap}}(t)$ depending on the predicted evolution of the queues downstream of platoon ξ up to time t, according to the control law described here.

Firstly, the traffic flow overtaking the moving bottleneck ξ only affects the outflow from the segment $q_s^{\mathrm{out}}(t)$ for $t \in [t_\xi(t_0), t_\xi^{\mathrm{out}}(t_0)]$, i.e., while moving bottleneck ξ is in the queue chain, so it is enough to define $q_{\xi}^{\mathrm{cap}}(t)$ for that time interval. The reference speed of all platoons $\underline{u}_\xi(t_0)$ is constrained to be higher than some minimum speed $\underline{u}_\xi(t_0) \le U_\xi^{\min}$, so we know that the platoon should leave the segment at the latest at time $t_\xi^{\max}(t_0)$,

$$t_\xi^{\max}(t_0) = t_0 + \frac{X_s^{\mathrm{out}}(t_0) - \underline{x}_\xi(t_0)}{U_\xi^{\min}} \ge t_\xi^{\mathrm{out}}(t_0) \tag{9}$$

We denote the sum of the lengths of all queues downstream of bottleneck i as $\mu_i(t)$, and define it recursively,

$$\mu_i(t) = \begin{cases} n_{\bar{i}}(t) + \mu_{\bar{i}}(t), & i \in \mathcal{I}_s(t_0) \setminus \{\overleftarrow{0}\}, \\ 0, & i = \overleftarrow{0}. \end{cases} \tag{10}$$

The control law governing $q_{\xi}^{\mathrm{cap}}(t)$ is given by

$$q_\xi^{\mathrm{cap}}(t) = \begin{cases} q^{\mathrm{lo}}, & \mu_\xi(t) > 0, \\ q^{\mathrm{hi}}, & \mu_\xi(t) = 0, \end{cases} \tag{11}$$

i.e. the platoon allows the lowest possible overtaking flow q^{lo} in case there is predicted congestion downstream of it along the line $X_s^{\mathrm{out}}(t_0) + V \cdot (\tau - t)$, and allows the highest overtaking flow that does not exceed any of the downstream queueing servers' capacity, q^{hi}. In the considered case, q^{lo} corresponds to the traffic flow overtaking a platoon that is taking two lanes out of three, and q^{hi} to that overtaking a platoon that is taking a single lane. The speed of moving bottleneck ξ is controlled so that, if feasible, it reaches $X_s^{\mathrm{out}}(t_0)$ at time $t_\xi^{\mathrm{out}}(t_0) = t_\xi^{\mathrm{d}}(t_0)$, where $t_\xi^{\mathrm{d}}(t_0)$ is defined as the minimum time for which $\mu_\xi(t_\xi^{\mathrm{d}}(t_0)) = 0$ and $n_\xi(t_\xi^{\mathrm{d}}(t_0)) = 0$, or otherwise, so that it moves at minimum speed $U_\xi^{\min}$, in which case $t_\xi^{\mathrm{out}}(t_0) = t_\xi^{\max}(t_0)$.

Finally, once the predicted queue lengths and control inputs are calculated until time $t = t_0 + \frac{\|\mathcal{X}_s(t_0)\|}{V}$, we can use them to determine the control inputs for the real process. The overtaking flow limit applied by platoon ξ at time t_0 is thus

$$\underline{q}_\xi^{\mathrm{cap}}(t_0) = q_\xi^{\mathrm{cap}}(t_\xi(t_0)|t_0), \tag{12}$$

which will be enforced by having platoon ξ occupy an appropriate number of lanes. The platoon reference speed is given by

$$\underline{u}_\xi(t_0) = \begin{cases} \frac{X_s^{\mathrm{out}}(t_0) - \underline{x}_\xi(t_0)}{t_\xi^{\mathrm{d}}(t_0)}, & \exists t_\xi^{\mathrm{d}}(t_0) \le t_\xi^{\max}(t_0), \\ U_\xi^{\min}, & \nexists t_\xi^{\mathrm{d}}(t_0) \le t_\xi^{\max}(t_0). \end{cases} \tag{13}$$

3.4. Closed-loop segment model and length adaptation

The control law given in the previous section was analysed in [5], concluding that the platoons can be used to improve the throughput of the road segment with a single stationary bottleneck at its downstream end. This improvement is contingent on having enough platoons available for control, the initial level of congestion not being too high, and the length of the control segment being long enough. The control is able to return the stationary bottleneck to free-flow and improve the outflow $q_s^{\mathrm{out}}(t) > q_s^{\mathrm{dis}}$, by restricting the traffic flow, as long as the total level of congestion n_s does not exceed some value n_s^{ctr}. We may determine the total level of congestion of a road segment s as the sum of all the queue lengths at the end of the prediction,

$$n_s(t) = \mu_{\overleftarrow{s}}\left(t + \frac{\|\mathcal{X}_s(t)\|}{V}\middle|t\right). \tag{14}$$

Once $n_s(t)$ exceeds n_s^{ctr}, the control is unable to dissipate the congestion without extending the controlled segment.

Based on the conclusions of the analysis, and performed simulation experiments, it is apparent that the congestion level limit n_s^{ctr} depends on the length of the controlled segment $\|\mathcal{X}_s(t)\|$ approximately linearly for a reasonable range of $\|\mathcal{X}_s(t)\|$,

$$n_s^{\mathrm{ctr}} \approx \eta_{\mathrm{ctr}} \|\mathcal{X}_s(t)\|. \tag{15}$$

Parameter η_{ctr} can be identified from simulation experiments, together with identifying the average outflow from the segment $q_s^{\mathrm{ctr}}(t)$ for $n_s(t) < n_s^{\mathrm{ctr}}(t)$.

While it is beneficial to have the length of the controlled segment always be as large as possible, this leads to increased computational burden, due to the need for a longer prediction horizon. Therefore, we propose a scheme that dynamically adjusts the controlled segment length in order to keep $n_s(t)$ close to $n_s^{\mathrm{ctr}}(t)$. To prevent random perturbations pushing the segment into the fully congested regime, we adopt separate thresholds for extending and shrinking the control segment, respectively η_+ and η_-, $\eta_- < \eta_+ < \eta_{\mathrm{ctr}}$. After every control iteration, the segment length is adjusted by updating X_s^{in} as

$$X_s^{\mathrm{in}}(t+T) = \begin{cases} \max\left\{X_s^{\mathrm{in,min}}, \frac{n_s(t)}{\eta_+}\right\}, & \frac{n_s(t)}{\|\mathcal{X}_s(t)\|} > \eta_+, \\ \min\left\{X_s^{\mathrm{in,max}}, X_s^{\mathrm{in}}(t) - U_{\mathcal{X}} T\right\}, & \frac{n_s(t)}{\|\mathcal{X}_s(t)\|} < \eta_-, \\ X_s^{\mathrm{in}}(t), & \text{otherwise.} \end{cases} \tag{16}$$

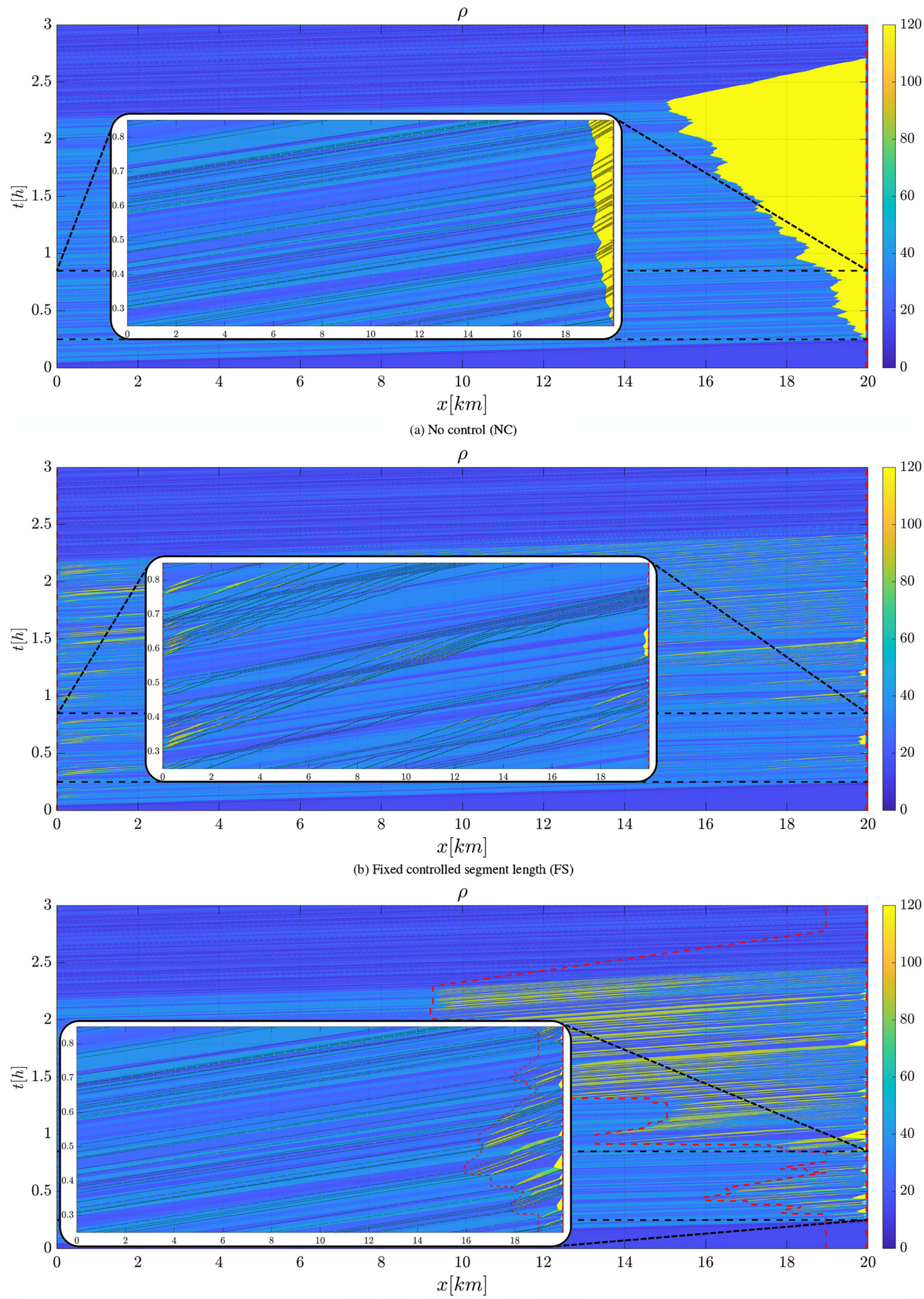
This way, the controlled segment will grow quickly in case there is excess predicted congestion, and slowly shrink in case the platoons in it are predicted to be able to successfully dissipate the congestion. The speed of control segment shrinking $U_{\mathcal{X}}$ is a control parameter, and is selected to be lower than the minimum platoon reference speed, $U_{\mathcal{X}} < U_\xi^{\min}$, in order to ensure that there is no congestion left outside of the controlled segment after it shrinks.

4. Simulation results

We tested the effectiveness of the proposed control law in 3 h long macroscopic simulations, on a 20 km long stretch of three-lane highway with a stationary bottleneck at $X_\beta = 19.95$ km. An example simulation run is shown in Fig. 4, depicting colour-coded traffic density profiles of one detail of the simulation. The platoon trajectories are traced by black dots, and the stationary bottleneck and and the upstream limit of the controlled segment are denoted by dashed red lines. As in [5], the simulation model used is multi-class CTM with platoons. Two cases of control law (12), (13) were compared against the uncontrolled case (NC):

- FS: With fixed controlled segment length, from the beginning of the road, $X_s^{\mathrm{in}} = 0$, to the stationary bottleneck location $X_s^{\mathrm{out}} = X_\beta$, and
- VS: With varying, dynamically adjusted controlled segment length, and $X_s^{\mathrm{in}}(t)$ given by (16).

The road is assumed to have a free-flow speed of $V = 100$ km/h, and the controllers used $U_\xi^{\min} = 40$ km/h and $U_{\mathcal{X}} = 20$ km/h. The capacity of the stationary bottleneck is $q_\beta^{\mathrm{cap}} = 4000$ veh/h, whereas the capacity of the rest of the road is $q^{\max} = 6000$ veh/h. Due to capacity drop, once the bottleneck gets congested, its discharging flow drops to $q_\beta^{\mathrm{dis}} = 3000$ veh/h. A platoon taking one and two lanes allows an overtaking flow of $q^{\mathrm{hi}} = 3600$ veh/h and $q^{\mathrm{lo}} = 2000$ veh/h respectively. The arrival of platoons at the start of the road is modelled as a Poisson process with an average gap of 0.0152 h between them. Under these conditions, a preliminary simulation study showed that the controlled road segment can be modelled by adopting a length-dependent $n_s^{\mathrm{ctr}}(t_0)$ with



(a) No control (NC)

(b) Fixed controlled segment length (FS)

(c) Variable controlled segment length (VS)

Fig. 4. An example simulation run, with a zoomed-in display of the period when congestion starts accumulating at the stationary bottleneck. In the zoomed-in view, platoon trajectories are shown by dotted black lines.

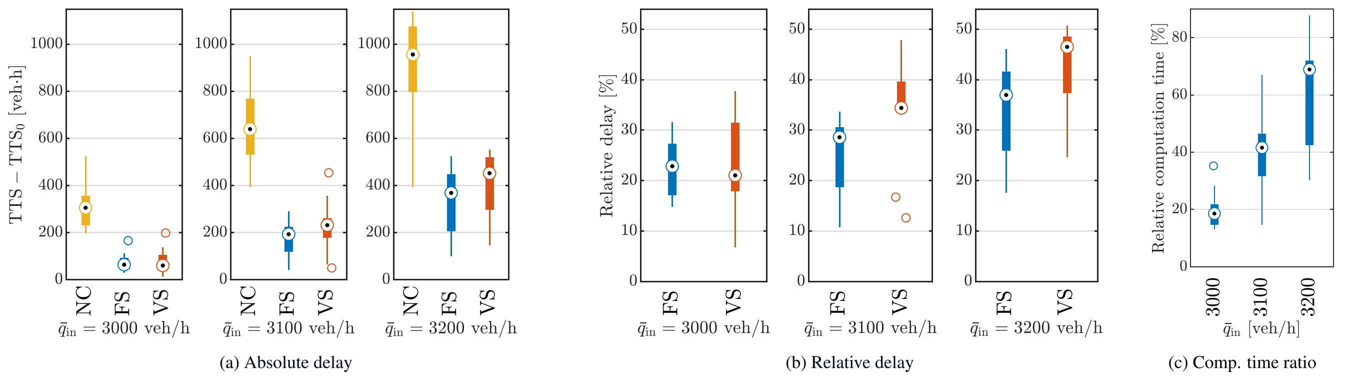


Fig. 5. Simulation results comparing (a) Absolute delay (difference in Total Time Spent compared to TTS_0), (b) Relative delay given by (17), and (c) Computation time ratio, for the uncontrolled case (NC) and the two controlled cases, with fixed controlled segment length (FS) and variable segment length (VS), under three different levels of nonplatooned traffic inflow. Filled circles indicate the medians, and boxes stretch from the 25th to the 75th percentile. Data points more than 1.5 times the box length away from the box edges are considered to be outliers, and indicated by empty circles. Whiskers stretch to extreme non-outlier data points.

Table 1
Average and median performance indices of the simulation results.

$\bar{q}_{in}$[veh/h]	Total Time Spent [veh h] (TTS_0 = 1656 veh h)						Relative delay [%]				Computation time ratio [%]	
	NC		FS		VS		$\frac{TTS_{FS}-TTS_0}{TTS_{NC}-TTS_0}$		$\frac{TTS_{VS}-TTS_0}{TTS_{NC}-TTS_0}$			
	mean	median	mean	median	mean	median	mean	median	mean	median	mean	median
3000	1918.8	1909.6	1678.8	1668.0	1685.2	1664.5	22.47	22.84	23.50	21.02	20.31	18.58
3100	2306.2	2295.0	1827.1	1849.0	1884.6	1887.4	24.66	28.57	32.82	34.40	39.60	4159
3200	2618.7	2663.4	2039.3	2075.7	2109.8	2159.2	34.66	36.96	42.85	46.50	62.01	68.89

η_{ctr} = 15 veh/km, achieving an outflow of q_s^{ctr} = 3200 veh/h in partially congested conditions. Based on these results, the controlled segment length adaptation was parametrized with η_+ = 10 veh/km and η_- = 4 veh/km, ensuring that the controlled segment does not become fully congested unless the limit on segment length is reached. The platoons are assumed to be 80 m long, consisting of 1.6 passenger-car-equivalents, due to shorter inter-vehicular distances within them. The inflow of the rest of the traffic takes uniformly distributed values $q_{in}(t) \in [q_{in}^{min}, q_{in}^{max}]$, changing every 0.012 h, with q_{in}^{min} = 2000 veh/h and $q_{in}^{max} \in \{4000, 4200, 4400\}$ varying over sets of simulations, yielding average non-platooned traffic inflow of $\bar{q}_{in} \in \{3000, 3100, 3200\}$. In order to ensure a fair comparison, the inflow is halved during the first 0.05 h and final 0.8 h of the simulation, providing warm-up and cool-down times.

The simulation run example shown in Fig. 4 is executed with $\bar{q}_{in}$ = 3000 veh/h. As can be seen in Fig. 4 a), in case we have no control, the arrival of a platoon at the stationary bottleneck causes capacity drop and congestion starts accumulating at the stationary bottleneck. Both FS and VS control successfully decongest the bottleneck, by creating controlled congestion at an upstream position, starting from the upstream end of the controlled area. The largest difference between the two control schemes is that, in case of FS control, most of the congestion is accumulated very far from the stationary bottleneck, at the start of the road, whereas in case of VS control, the controlled segment is much shorter, and the congestion is accumulated close to the stationary bottleneck. Furthermore, once the congestion is dissipated, the controlled segment length of VS control is decreased. The shorter controlled segment length reflects in shorter computation time for VS control compared to that of FS control.

We conducted three sets of 10 simulation runs each, varying the average non-platooned traffic inflow, comparing the performance of the two control laws with Total Time Spent (TTS) used as the performance metric. We compared the achieved relative delay incurred due to the stationary bottleneck,

$$\frac{TTS_{XS} - TTS_0}{TTS_{NC} - TTS_0}, \quad (17)$$

where TTS_{XS} is the TTS achieved using control scheme $XS \in \{FS, VS\}$, TTS_{NC} is the TTS of the uncontrolled case, and TTS_0 is the theoretical minimum TTS in case the stationary bottleneck was absent from the road. We also measured the computation time for the two control laws, under the same circumstances, and compared it between them, with the computation time ratio signifying the ratio between the computation time of VS control divided by the computation time of FS control.

The comparison results are shown in Fig. 5 as box plots, and given in Table 1 as mean and median performance indices. We can see that both control laws achieve a significant reduction of the TTS compared to the NC case, negating from close to 78% of the delay in the lighter traffic case $\bar{q}_{in}$ = 3000 veh/h, to close to 60% of the delay in the heavier traffic case $\bar{q}_{in}$ = 3200 veh/h, with FS control performing slightly better than VS control.

However, as shown in Fig. 5 c, the computation time FS control is much higher than that of VS control, from around 5 times higher in case of lighter traffic, to around 1.5 times higher in case of heavier traffic. This outcome was expected, since the VS control only has to calculate the prediction for a shorter time horizon proportional to the controlled segment length, whereas FS control always calculates the prediction for the full time horizon. In the heavier traffic case, this difference is less notable, since VS control will also tend to control the full road segment as congestion builds up.

5. Concluding remarks and future perspectives

In this paper a platoon-actuated mainstream traffic control scheme is proposed for dissipating the congestion created at a stationary bottleneck. The control is executed by appropriately controlling the platoons present on the road, by controlling their speed and commanding them to occupy a specified number of lanes. Thus, controlled platoons act as moving bottlenecks, reducing the inflow to the stationary bottleneck, returning it to free-flow conditions and keeping it from becoming congested again.

The main peculiarity of this approach lies in the fact that the controlled platoons are those travelling in an area identified upstream of the stationary bottleneck. Specifically, the length of this area is time-varying and defined based on the prediction of congestion at the stationary bottleneck. This aspect allow us to adapt the control law on the basis of the expected congestion and hence to reduce the computational time required. Furthermore, in this paper the results obtained by applying the variable length controller are compared with those obtained considering a segment with fixed length. The results show that both approaches are effective in decongesting the bottleneck, with a slightly better performance experienced when the control scheme with fixed segment length is applied. However, a substantial improvement of computational time is observed by using the variable length segment controller, while achieving very similar performance.

The findings provided by the simulations are rather encouraging, as they show that even a low presence of connected and automated vehicles, if properly controlled, can positively influence traffic behavior. These results, combined with the fact that the CAVs are likely to continue being a sparse minority compared to human-driven vehicles in the near future, further motivate the need to pursue research in the direction of the strategy proposed in this paper. The overall goal of future work is to define more sophisticated control schemes, that bring even greater benefits than the proposed approach, or conversely, are easier to implement. Furthermore, validation of the proposed control scheme using microscopic simulations should be performed.

One direction is to extend the control law to road networks consisting of multiple individually considered segments. In such case, a decentralized control law can be applied, with each segment considered according to the control law presented herein. Another potential extension would be to consider the possibility of creating and controlling platoons of CAVs only where and when useful for control purposes, and then dissolving them when they are no longer needed. Additionally, "classical" traffic control methods, e.g., ramp metering should be considered together with the presented platoon-actuated control. The used modelling framework also lends itself to this purpose, since the ramp flows could easily be included as additional inflows to the segment. In this configuration, platoon-actuated control and ramp metering would act together to avoid bottleneck activation, as well as to eliminate excess congestion. Indeed, similarly to mainstream control strategies with fixed actuators, platoon-actuated mainstream control regulates traffic flow by creating a moderate controlled congestion but does not completely eliminate congestion in the mainstream, therefore better performances can be obtained by the joint application of ramp metering and the mainstream control via platoons.

It is worth noting that these control schemes have a computational burden that may increase in scenarios where a large number of vehicles are present. To overcome this issue, development of further decentralized control schemes can be considered, in which the controller acts on a limited group of platoons or even at the individual platoon level. In these schemes, the control actions would be defined on the state measurements observed around the controlled platoons, with minimum communication among them. Implementation of this case would be simpler, albeit at the expense of control performance, since prediction would be based on estimates using incomplete knowledge of the system state.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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