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A Hierarchical Approach For Splitting Truck Platoons Near Network Discontinuities

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Abstract

Truck platooning has attracted substantial attention due to its pronounced benefits in saving energy and promising business model. However, one prominent challenge for the successful implementation of truck platooning is the safe and efficient interaction with surrounding traffic, especially at network discontinuities where mandatory lane changes may lead to decoupling of truck platoons. This contribution put forward an efficient method for splitting a platoon of vehicles near network merges. A model-based bi-level control strategy is proposed. A supervisory tactical strategy based on a first-order car-following model with bounded acceleration is designed to maximize the flow at merge discontinuities. The decisions taken at this level include optimal vehicle order after the merge, new equilibrium gaps of automated trucks at the merging point, and anticipation horizon that truck platoon start to act to track the new equilibrium gaps. The lower-level operational layer uses a second-order longitudinal dynamics model to compute the optimal truck accelerations so that new equilibrium gaps have been created when merging vehicles start to change lane and the transient maneuvers are efficient, safe and comfortable. The tactical decisions are derived analytically and the operational accelerations are controlled via model predictive control with guaranteed stability. Simulation experiments are provided in order to test the feasibility and demonstrate the performance of the proposed strategy.

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Keywords: truck platooning, merging, hierarchical control, traffic flow model, model predictive control, cooperative systems.

1. Introduction

Automated driving systems have attracted considerable attention in the recent years, because of the fundamental changes they bring to transportation systems and new services enabled by them. Literature has shown that the individual automation can hardly enhance traffic operations while it is commonly agreed that connected/cooperative automated vehicles (CAVs) possess great potential in increasing roadway capacity and traffic flow

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stability [13, 21, 23, 24, 28]. Vehicle platooning is one of multiple applications that stands out in the domain, characterized by a string of CAVs respecting a specified equilibrium spacing policy [3, 15, 22, 24]. Reduction of the equilibrium spacing breaks the capacity limits of today's network and enhances fuel economy.

Truck platooning is expected to be deployed earlier than passenger cars due to the pronounced benefits in terms of fuel saving [1] and promising business models [4, 17]. Several on-road pilots have identified problems that truck platooning brings to traffic at freeway entrances and exits [4, 17, 25], which is of paramount importance to traffic safety and maximization of throughput in the traffic network. Therefore, coordination and control at network discontinuities are important challenges for vehicle platooning in real world. This was well recognized early in the 1990s [9, 26, 27] under a hierarchical setting, where a platoon coordination layer is placed under the link control layer and on top of the vehicle control layer. The platoon coordination layer is primarily concerned with platoon-level maneuvers such as platoon formation, split, merge, and exit. Few active platooning strategies have been proposed in literature under within a full CAV environment. A set of protocols for platoon maneuvers in highways was proposed in [10], including merge, split, and lane change. The design of the protocol is based on a finite state description of platoon maneuvers under the command of an upper-level traffic control layer. Despite the pioneering role of this work, the design of the split protocol did not address operational decisions regarding where/when to split the platoon at highway entrance and optimal trajectories for vehicles.

In [7], entry and exit maneuvers of platoons on highway were discussed. Strategies proposed were applicable in cases where dedicated automated vehicle lanes and transitional lanes are disposed near highway entries and exits. The design was based on the assumption that the merging vehicle is a CAV and it required infrastructure changes, e.g. a parallel transition lane or dedicated ramps, raising concerns over the applicability in reality. In [9], two basic platoon maneuver strategies, merge and split, were proposed to facilitate another automated vehicle joining an existing platoon and a platoon member leaving the platoon respectively. The split strategy was further elaborated by sub-tasks of initiating split request, creating safe gap and changing lane. A similar design using finite state machine approach was also reported in [2] for platoon maneuver protocols. The protocols were combined with cooperative adaptive cruise control (CACC) logic was used to represent longitudinal behavior. However, when is optimal to start the gap creation process and how the transient maneuver looks like were not formulated, leaving the operational strategies and corresponding algorithms for platoon maneuvers unanswered.

Interaction protocols among CAVs for situations of merges and lane reductions have also been presented recently in [12]. The strategies herein detail two main scenarios: the first one establishes protocols mimicking human driver interaction within the V2V layer of communication in order to achieve a merge of a single vehicle. The second scenario studies the same type of protocols when lane reduction exists in the network. In [14], a decision algorithm that computes a target reference path for each vehicle and a fuzzy longitudinal controller that guarantees the merge for a vehicle approaching from the minor road tracks were proposed. A different vehicle string modeling approach was presented in [3], where a spring-mass-damper analogy was adopted to describe platooning dynamics. This modeling approach allows one to model platoon dynamics near highway entry and exit by controlling the spring constant and damping coefficient, where a CAV joins or leaves a platoon, but does not generate optimal merging decisions and trajectories.

Cooperative automated maneuvering protocols were designed for a highway lane drop scenario and an unsignalized T-intersection in [19]. Field tests by 9 teams with CAVs under a real network but restricting normal traffic show the performance of the maneuver protocols. These protocols determine largely the efficiency of the resulting traffic operations. However, this relation is not taken into account explicitly in the design and it does not handle mixed traffic conditions. [11] formulates a stochastic switched system model in which it is analyzed how platoon-induced congestion varies with the fraction of platooned vehicles at merge.

Notice that another body of literature focused on platoon formation strategies [8, 22]. We restrict the discussion on platoon formation since this paper concentrates on how to split a platoon rather than forming a platoon. Literature shows that quite some effort in defining platoon maneuver protocols at highway entry and exit. These studies focus on dynamics and interactions between platoons or between a platoon and an individual CAV, which implies communication between interacting platoons/vehicles. Some even require additional changes in the infrastructure, which may impede the near-term application of the strategies. In addition, there is a gap between finite state description of the platoon maneuvers and the detailed operational truck platooning strategies for the transition between states. In case of truck platooning, it is likely that the platoon has to be detached to facilitate merging vehicles from on-ramp sections. A

decision-making strategy to support when and where to split the truck platoon before the merge section was proposed in [5]. However, it assumes a single merging vehicle and the question of how to control the continuous trajectories of interacting vehicles remains unanswered.

This contribution proposes a hierarchical decision and control framework for automated truck platoons to facilitate lane-changing maneuvers of surrounding vehicles near on-ramps and off-ramps. The tactical layer uses a first-order traffic flow model to generate decisions about when and where to yield a safe and comfortable gap that maximizes throughput and the operational layer uses a second-order longitudinal dynamics model to control truck accelerations such that the gap has been created when the merging vehicle starts the lane change and the transient maneuvers are efficient, safe and comfortable.

The remainder of the paper is organized as follows. Section 2 presents the general hierarchical decision and control framework. Section 3 and 4 present the mathematical formulations of tactical and operational levels, respectively. Section 5 illustrates the performance of the proposed control framework under various connectivity assumptions and network configurations. Finally, Section 6 concludes the paper.

2. Merging problem and model-based hierarchical decision framework

Let us consider an existing platoon of CAVs in an equilibrium condition approaching the merging section (See Fig. 1a). At some specific point a lane reduction situation forces vehicles to merge into the formation. The following issues and questions appear as part of the problem formulation:

- How to design a full deployable strategy such that it considers the safe and efficient interaction between the CAV platoon and the merging traffic?
- How to perform the maneuver considering interaction between the CAV acceleration controller and the global strategy?

The control strategy here proposed, is composed by two levels (See. Figure 1b(b)). At the tactical level, the layer takes information from V2I communication regarding positions and speeds of vehicles in the platoon, and positions and speeds of merging vehicles if it is equipped with V2I communication or when they pass a fixed road-based sensor. A model-based strategy is used to determine the optimal vehicle indexes in the platoon to yield gaps for merging vehicles and time instants they should start the yielding process, given a speed drop that they accept compared to the equilibrium speed. It also outputs the desired state parameters for the interacting vehicles after merge, notably the desired time gap of the yielding trucks. The tactical decisions are then sent to the operational layer, where a model predictive controller determines the command accelerations that regulate the speeds and positions of CAVs in the platoon. Before the merging vehicles reach the end of the merging section, the CAVs open sufficient gap and they will change lane to the main carriage way (See. Figure 1b(a)). The tactical layer updates its decisions at low frequencies, e.g. every 5-10 seconds, while the operational layer updates vehicle accelerations at high frequencies, e.g. $dt \leq 1s$. When the operational layer fails to find feasible solutions that respect system constraints, it requests re-evaluation of the tactical decisions at irregular times and may even overrule the tactical decisions to find safe and comfortable trajectories.

The hierarchical design follows the architecture proposed earlier in [27] for automated highway systems. The tactical layer pertains to the coordination layer while the operational layer corresponds to the vehicle layer in [27]. In the ensuing, we formulate the two layers respectively.

3. Tactical level: analytical CF model with merging process

When one or several vehicles have to merge into a platoon of CAVs with short spacings, the platoon should anticipate and split to open sufficient gaps. Two problems arise : (1) How to find optimal ordering in the final formation, which determines the CAVs in the platoon that should decelerate and yield a gap for the merging vehicles; (2) How to find the anticipation times, which determines the time instants that the gap creation process should start for each yielding vehicle. The tactical layer proposes a solution for both, based on the analytical Newell car-following (CF) model with bounded acceleration.

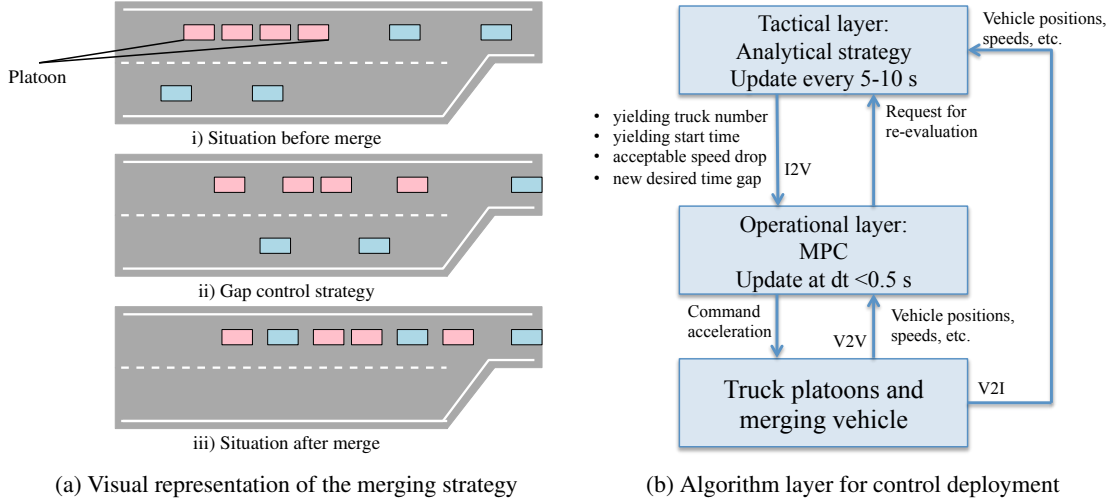


Fig. 1: Multiple merging problem and our approach to solution

Newell has proposed a simplified theory to describe the follow-the-leader behavior of vehicles. It describes equilibrium (safe and comfortable) states that maximize the flux, which can be summarized as follows: when the leading vehicle is very distant the following vehicle has a free-flow speed u . Under car-following situations, the following vehicle n replicates its leader $n - 1$ trajectory with a shift in time τ and space d . Under stationary conditions with vehicles traveling at the same speed v , vehicle spacing s becomes:

$$s = d + v\tau \quad (1)$$

Original formulation of the model allows for infinite acceleration. For a more realistic description, we consider that acceleration rate is comprised in a bounded interval denoted a^- and a^+ respectively. These bounds ensure feasible dynamics, in particular for trucks whose acceleration and braking capacities are limited. They may vary from one vehicle to another to replicate heterogeneous behavior.

Assumption 1. Car-following parameters. *For the sake of simplicity in the remainder of the paper, it is assumed that merging vehicles can be divided into 2 categories: connected automated vehicle and human driver vehicle (HDV). Both follow the Newell theory, CAVs have parameters $[d^p, \tau^p]$, designed with respect to the constant (time or space) gap policy under platooning operation, and HDVs d and τ . It is also assumed that the maximum wave speed is the same for both CAVs and HDVs: $w = d/\tau = d^p/\tau^p$. It should be noted that this assumption can be easily relaxed by considering individual parameters.*

3.1. Vehicle ordering process

The merging procedure can be modeled as an arrival process of vehicles from two different lanes $\ell-$, $\ell+$ to a particular point in the space X_m . The situation could involve the arrival of multiple types of vehicles in both lanes, CAVs or HDVs. The strategy follows by CAVs adapting their dynamics to reach new equilibrium situations to maximize the flow at the merging position.

Let us consider the situation of multiple vehicles driving in the lane $\ell-$ and willing to merge into the lane $\ell+$, where platoon CAVs are located. The initial conditions of the problem can be formulated as follow : $\mathcal{I}_{\ell+} = \{i_0, i_1, \dots, i_n\}$ and $\mathcal{J}_{\ell-} = \{j_1, \dots, j_m\}$ denote the maps of discrete values containing ordered indexes of vehicles traveling in the target and the original lanes respectively, and $g_k^\ell = [x_k^\ell \ t_k^\ell]$ is the position-time of the vehicle k in the lane ℓ .

Assumption 2. Boundary conditions. All vehicles belonging to the sets $\mathcal{J}_{\ell-}, \mathcal{I}_{\ell+}$ maintain their (free-flow) speed u between their initial positions and the merging position X_m . The leader trajectory establishes the boundary condition of the ordering problem. Also, HDVs that need to merge cannot be controlled and hence their trajectories are considered as (internal) boundary conditions of the problem.

Assumption 3. Final states. It is assumed that the platoon settles down to equilibrium at the position X_m with all vehicles following Newell equilibrium conditions, with parameters $[d_p, \tau_p]$ for CAVs following CAVs, and with parameters $[d, \tau]$ otherwise. The ordering of the final formation is given by an ordered sequence $\mathcal{O} = \{\sigma_0, \sigma_1, \dots, \sigma_{n+m}\}$ where the leader of the final formation is the leader of the initial formation: $\sigma_0 = i_0$.

We consider two main scenarios: the first one where vehicles willing to merge are all CAVs (see Figure 2); and the second one where mixed vehicles are arriving (see Figure 3). The new equilibrium conditions imply an ordering strategy which leads to a np -hard problem with combinatorial characteristics.

3.1.1. If vehicles willing to merge are all CAVs

The set of problem is illustrated in Figure 2a: where the green solid line is the leader’s trajectory (boundary condition); blue dashed lines denote CAVs following a specific platoon formation in lane $\ell+$ at some initial position X_b ; and brown dashed lines depict the detection of CAVs (via e.g. loop detectors, camera, GPS) moving along the lane $\ell-$ and willing to merge into $\ell+$ at X_m .

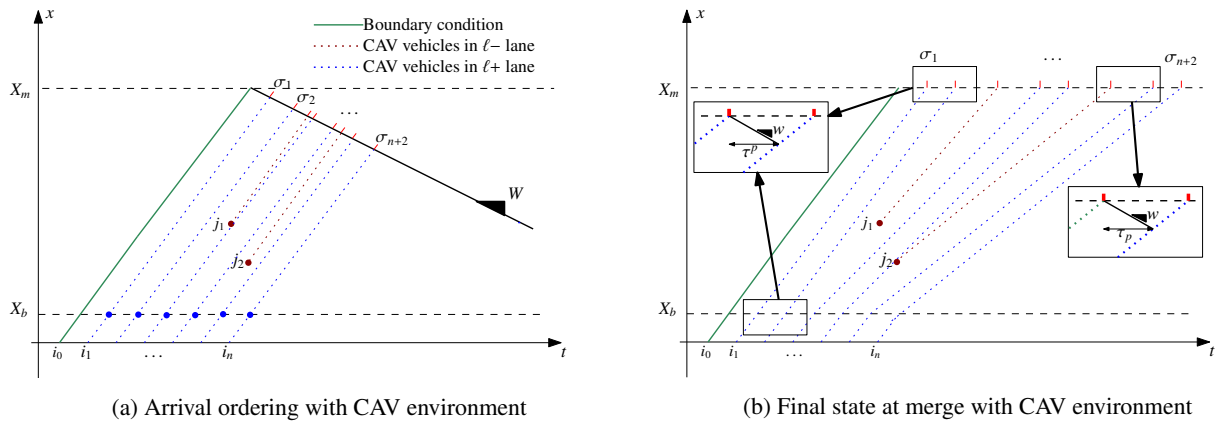


Fig. 2: Ordering and final state with CAV environment

With assumptions 2 and 3, the natural ordered sequence can be achieved by projecting initial conditions g_k^ℓ with the maximum speed u along a shock wave w , as illustrated in Figure 2a. Let $p(g_k^\ell)$ be the projection of a particular point $g_k^\ell = [x_k^\ell \ t_k^\ell]^T$ into the shock wave starting from the leader’s position $[X_m \ T_m^0]$ and propagating backward with a constant speed $-w$. The projection is the intersection of two planes, which can be formulated as a linear system:

$$\begin{aligned} P_1 : \quad x &= -wt + X_m + wT_m^0, \\ P_2 : \quad x &= ut + x_k^\ell - ut_k^\ell. \end{aligned} \tag{2}$$

The solution is given by:

$$\begin{bmatrix} p_x(g_k^\ell) \\ p_t(g_k^\ell) \end{bmatrix} = \frac{1}{u+w} \begin{bmatrix} 1 & u \\ -1 & w \end{bmatrix} \cdot \begin{bmatrix} X_m \\ x_k^\ell \end{bmatrix} + \begin{bmatrix} w & 0 \\ 0 & -u \end{bmatrix} \begin{bmatrix} T_m^0 \\ t_k^\ell \end{bmatrix} \tag{3}$$

The *a-priori* order O^* is given by the sequence organizing the full set of projections $\mathcal{P} = \{p(g_1^{\ell+}), \dots, p(g_{n+m}^{\ell+})\}$ in a time ordered set (see Figure 2a) such that:

$$p_t(g_k^{\ell+}) < p_t(g_{k+1}^{\ell+}), \forall k \in [1 : m + n] \quad (4)$$

At this stage, the optimal ordering sequence O^* is established. Let consider the vehicle with indexes $[i_x, \sigma_x]$ in the initial and final platoon respectively. Far upstream the merge position, it replicates the trajectory of the leader of the platoon with a time shift $T_{i_x}^0$. As it approaches the merging position, a transient period occurs and the vehicle opens a gap by increasing its time shift until it reaches the final value $T_{\sigma_x}^f$.

$$\begin{cases} T_{\sigma_x}^0 = \sum_{k=i_1:i_x} \tau_k & \text{initial shift in time (baseline = leader of the platoon)} \\ T_{\sigma_x}^f = \sum_{k=\sigma_1:\sigma_x} \tau_k & \text{final shift in time (baseline = leader of the platoon)} \end{cases} \quad (5)$$

3.1.2. If vehicles willing to merge are mixed HDVs/CAVs

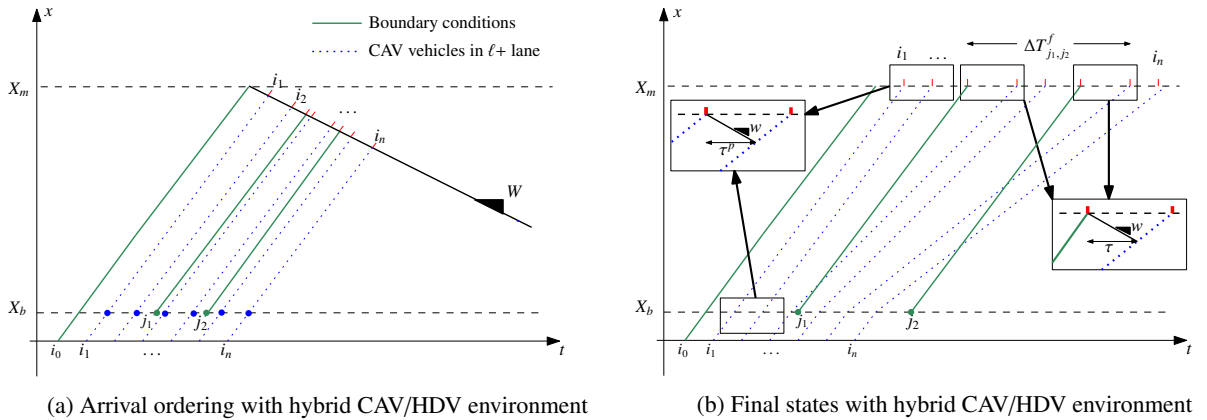


Fig. 3: Ordering and final state with hybrid CAV/HDV environment

An hybrid situation of merge can be found when HDVs traveling along lane $\ell-$ are willing to merge into $\ell+$. In this particular case the ordering process is not flexible anymore as Equation 4 due to internal boundary conditions imposed by (uncontrolled) HDVs' trajectories. This particular scenario is detailed in Figure 3a, where green solid lines denote internal boundary conditions of the problem. In this case, the *ordering problem* can be cast as a *resource allocation* problem where the objective of the controller is to allocate the maximum amount of CAVs between two consecutive internal conditions, i.e. HDVs' trajectory).

By considering the *a-priori* order as the default order of arrival, the number of CAVs η that can be allocated between two consecutive internal boundaries j_k, j_{k+1} is bounded as:

$$\eta \leq \left\lfloor \frac{\Delta\tau_{j_k, j_{k+1}}^f - 2\tau}{\tau_p} \right\rfloor + 1 \quad (6)$$

Where $\Delta\tau_{j_k, j_{k+1}}^f$ corresponds to the shift in time, along a shockwave w , between HDVs trajectories indexed j_k and j_{k+1} . In this case, let us split the ordering between all vehicles willing to merge represented as ordered sub-

sequences between two consecutive HDVs $\tilde{O} = \{O_{i_0, j_1}, O_{j_1, j_2}, \dots, O_{j_{m-1}, j_m}\}$ where $O_{j_k, j_{k+1}} = \{j_k, i_l, i_{l+1}, \dots, j_{k+1}\} = \{\sigma_0, \sigma_l, \dots, \sigma_{l+1}, \dots, \sigma_{\eta+1}\}$. Each of the sub ordered sequence becomes a local problem where the ordering process can be formulated by considering internal boundary conditions imposed by HDVs j_k, j_{k+1} . Instead, for the sake of simplicity in the presentation of the problem we introduce the desired equilibrium states for a sub sequence, given by :

$$\begin{cases} T_{\sigma_x}^0 = \tau_p & \text{baseline = CAV leader} \\ T_{\sigma_x}^f = \tau + \sum_{k=1:\sigma_x} \tau_p & \text{baseline = HDV leader,} \end{cases} \quad (7)$$

, where $T_{\sigma_x}^0$ denotes the initial shift in time, $T_{\sigma_x}^f$ the final shift in time, in this case the final equilibrium condition can be also bounded as $T_x^f \leq \tau + (\eta - 1)\tau_p$.

3.2. Yielding dynamic

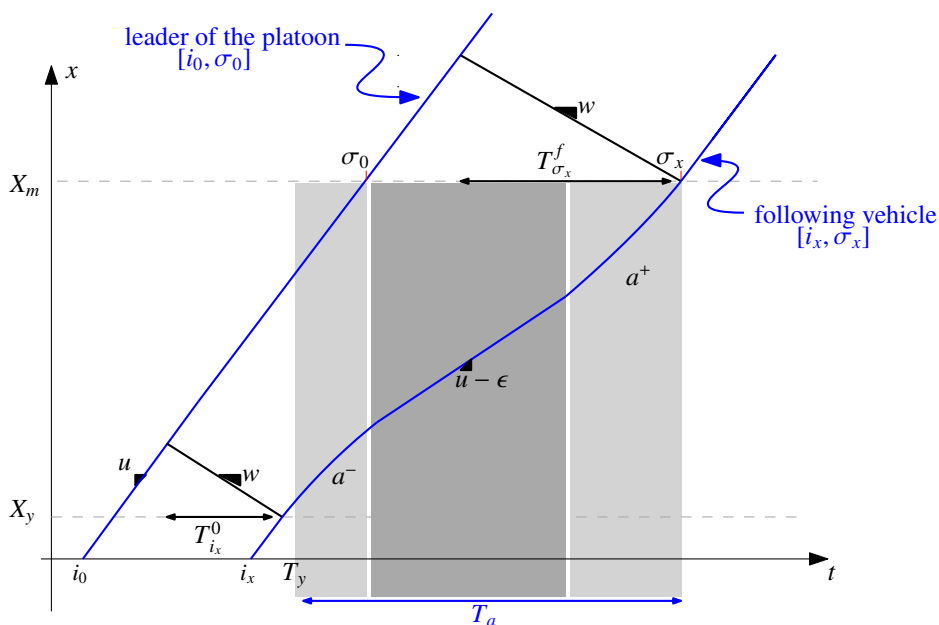


Fig. 4: Split dynamic merge: Vehicle separation process from its reference leader.

The duration of the transient period T_a for the vehicle $[i_x, \sigma_x]$, denoted T_a in the remainder of the paper, is a key decision variable to estimate. The problem is presented in Figure 4 with the following assumptions.

Assumption 4. Transient dynamic. *During the transient period, the yielding vehicle follows a dynamic in three successive phases:*

- deceleration period with a (negative) acceleration rate a^-
- speed drop period, with a constant speed $v = u - \epsilon$
- acceleration period with a acceleration rate a^+

The problem can be formulated as a linear problem where the anticipation time T_a is unknown, as illustrated graphically in Figure 4. The anticipation time involving three phases is formulated as follows:

$$T_a = \frac{\epsilon}{2} \cdot \left(\frac{1}{a^+} - \frac{1}{a^-} \right) + \frac{u+w}{\epsilon} \cdot (T_{\sigma_x}^f - T_{\sigma_x}^0) \quad (8)$$

Now consider the current position-time of CAV indexed i_x in the lane $\ell+$, denoted $g_{i_x}^{\ell+} = [x_{i_x}^{\ell+} \ t_{i_x}^{\ell+}]$, one can demonstrate that the time at which the vehicle should start the yielding maneuvers writes, after simplification:

$$T_y = \left(t_{i_x}^{\ell+} + \frac{X_m - x_{i_x}^{\ell+}}{u} \right) + (u+w) \left(\frac{1}{u} - \frac{1}{\epsilon} \right) (T_{\sigma_x}^f - T_{\sigma_x}^0) - \frac{\epsilon}{2} \cdot \left(\frac{1}{a^+} - \frac{1}{a^-} \right) \quad (9)$$

In Equation 8 and 9, the speed drop ϵ is assumed to be known a priori. However, if the yielding vehicle is too close to the merging position, ϵ may be too low for opening a sufficient gap. From Equation 8, the problem can be inverted and the speed difference ϵ becomes the new decision variable function of the anticipation time:

$$\epsilon = \frac{T_a}{2 \cdot (1/a^+ - 1/a^-)} \left(1 + \sqrt{1 - 2 \cdot \frac{(1/a^+ - 1/a^-) \cdot (u+w) \cdot (T_{\sigma_x}^f - T_{\sigma_x}^0)}{T_a^2}} \right) \quad (10)$$

4. Operational Layer: Model Predictive Control Approach

This section describes the model predictive controller at the operational layer and the control algorithm taking into account tactical decisions during the operation. The goal is to control the trajectories of the CAVs such that they follow the preceding vehicle with the constant time gap (CTG) policy [16, 18, 20], or equivalently a constant shift in time τ^p and space d^p

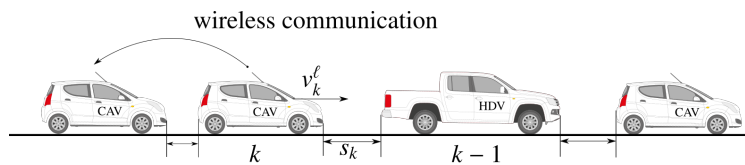


Fig. 5: Mixed fleet of CAV and HDV vehicles

4.1. System dynamics for CAV platoon

We consider the longitudinal dynamics described by the following linear kinematic model:

$$\begin{pmatrix} \dot{x}_k(t) \\ \dot{v}_k(t) \end{pmatrix} = \begin{pmatrix} v_k(t) \\ \alpha_k(t) \end{pmatrix} \quad (11)$$

where α_k denotes the controlled acceleration of vehicle k . Given that one of key objective is to regulate the spacing s_k (see Fig. 5) of two consecutive vehicles in the platoon, the system state from the perspective of the whole platoon with n CAVs (including the leader with index $k = 1$) can be described by the spacing errors $\mathbf{e}_s = (e_{s,1} \ e_{s,2} \ \dots \ e_{s,n})^T$ and speed errors $\mathbf{e}_v = (e_{v,1} \ e_{v,2} \ \dots \ e_{v,n})^T$ between consecutive vehicles, e.g.

$$e_{s,k}(t) = \begin{cases} s_1(t) & k = 1 \\ s_k(t) - s_k^r(t) & k = \{2, \dots, n\} \end{cases}, \quad e_{v,k}(t) = \begin{cases} u - v_1(t) & k = 1 \\ v_{k-1}(t) - v_k(t) & k = \{2, \dots, n\} \end{cases} \quad (12)$$

$s_k^r(t)$ denotes the reference/desired spacing, which is a linear function of vehicle speed (see Equation 1) with a time shift $T_{\sigma_x}^f$.

The full state vector represented by $\mathbf{x} = (e_{s,1}, e_{v,1}, e_{s,2}, e_{v,2}, \dots, e_{s,n}, e_{v,n})^T$. The control vector is the accelerations of all CAVs in the platoon: e.g. $\mathbf{u} = (u_1, u_2, \dots, u_n)^T$. The system dynamics model in state-space form is described by:

$$\frac{d}{dt}\mathbf{x} = \frac{d}{dt} (e_{s,1}, e_{v,1}, e_{s,2}, e_{v,2}, \dots, e_{s,n}, e_{v,n})^T = \mathbf{f}(\mathbf{x}, \mathbf{u}, \mathbf{d}) = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{C}\mathbf{d} \quad (13)$$

with

$$\mathbf{A}^{2n \times 2n} = \begin{pmatrix} A_1 & & & \\ & \ddots & & \\ & & A_1 & \\ & & & A_1 \end{pmatrix}, A_1 = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}; \mathbf{B}^{2n \times n} = \begin{pmatrix} B_1 & & & \\ B_2 & 0 & & \\ & \ddots & \ddots & \\ & & & B_n & 0 \end{pmatrix}, B_1 = \begin{pmatrix} -h_1^r & 0 \\ -1 & 0 \end{pmatrix}, B_k = \begin{pmatrix} 0 & -h_k^r \\ 1 & -1 \end{pmatrix}, k = \{2, \dots, n\};$$

$$\mathbf{C}^{2n \times 1} = (0, 1, \dots, 0)^T; \mathbf{d} = a_0$$

$\mathbf{d} = a_0$ denotes system disturbance, which is the acceleration of the uncontrolled vehicle preceding the first truck in the platoon.

4.2. Optimal platooning control problem

The platooning system seeks an optimal control trajectory $\mathbf{u}(\cdot)$ in the finite prediction horizon $[t_0, t_0 + T_p)$ that minimizes a cost function [29], which can be formulated as the following mathematical optimization programme:

$$J_{T_p} = \min_{\mathbf{u}_{[t_0, t_0+T_p)}} \int_{t_0}^{t_0+T_p} \mathcal{L}(\mathbf{x}(t), \mathbf{u}(t)) dt = \min_{\mathbf{u}_{[t_0, t_0+T_p)}} \int_{t_0}^{t_0+T_p} \mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t) + \mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t) dt$$

s.t.

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{C}\mathbf{d} = f(\mathbf{x}, \mathbf{u}) \\ \mathbf{x}(t_0) &= \mathbf{x}_0 \\ \mathbf{x}(t_0 + T_p) &= \mathbf{0} \\ \mathbf{x} &\in \mathcal{X} \\ \mathbf{u} &\in \mathcal{U} \end{aligned} \quad (14)$$

where \mathcal{L} denotes the so-called running cost or stage cost, and \mathbf{Q} and \mathbf{R} are positive definite weight matrices defined as:

$$\mathbf{Q} = \begin{pmatrix} \mathbf{Q}_s^{n \times n} & \mathbf{0}^{n \times n} \\ \mathbf{0}^{n \times n} & \mathbf{Q}_v^{n \times n} \end{pmatrix}, \mathbf{Q}_s^{n \times n} = \begin{pmatrix} c_1 & & \\ & \ddots & \\ & & c_1 \end{pmatrix}, \mathbf{Q}_v^{n \times n} = \begin{pmatrix} c_2 & & \\ & \ddots & \\ & & c_2 \end{pmatrix}, \mathbf{R}^{n \times n} = \begin{pmatrix} c_3 & & \\ & \ddots & \\ & & c_3 \end{pmatrix} \quad (15)$$

The optimal control problem in (14) shows the controller desire to minimize gap and speed errors, in addition to accelerations/decelerations. The optimization is subject to the system dynamics model of ??, initial condition of $\mathbf{x}(t_0) = \mathbf{x}_0$, terminal constraint $\mathbf{x}(t_0 + T_p) = \mathbf{0}$ and the admissible constraints on state and control variables: $\mathbf{x}(t) \in \mathcal{X}$, $\mathbf{u}(t) \in \mathcal{U}$.

The constraints on the state variable \mathcal{X} , \mathcal{U} are specified as:

$$\mathcal{X} := \{s_k(t) > s_0; v_k(t) \in [v_{\min}, v_{\max}]\}, \forall k \in \{1, \dots, n\} \quad (16)$$

$$\mathcal{U} := \{u_k(t) \in [a^-, a^+]\} \quad (17)$$

This implies that the spacing with respect to the preceding vehicle should be no less than the minimum distance $s_k^0 > 0$ and the controlled vehicles travel within a speed range of $[v_{\min}, v_{\max}]$. By default, $v_{\min} = 0$ and $v_{\max} = v_f$.

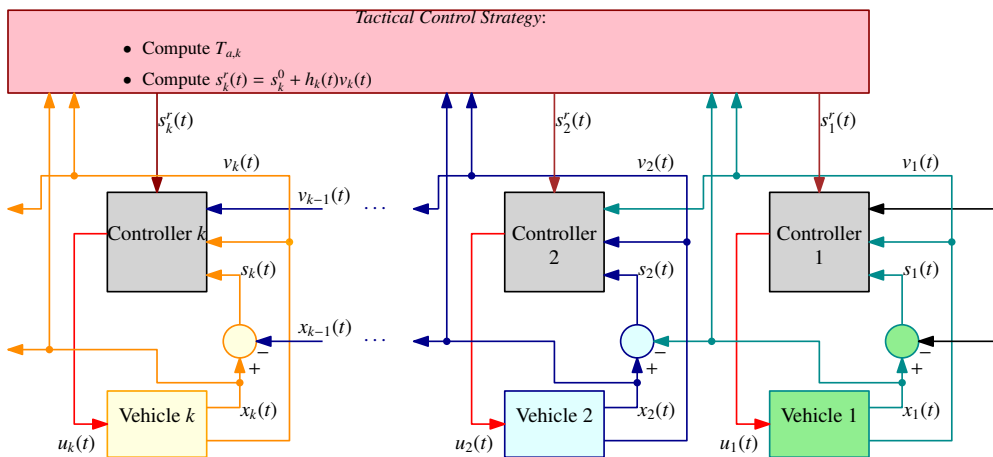


Fig. 6: Full control strategy deployment

4.3. Solution to the optimal control problem

At each time instant t_0 , the problem (14)-(17) is solved online with an efficient algorithm based on Pontryagin’s Principle, which entails defining the Hamiltonian \mathcal{H} as follows:

$$\mathcal{H}(\mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}) = \mathcal{L}(\mathbf{x}, \mathbf{u}) + \boldsymbol{\lambda}^T \cdot \mathbf{f}(\mathbf{x}, \mathbf{u}) \quad (18)$$

where $\boldsymbol{\lambda}$ denotes the so-called *co-state* or *marginal cost* of the state \mathbf{x} . Using the Hamiltonian, we can derive the *necessary condition* for optimality with: $\mathbf{u}^* = \arg \min_{\mathbf{u}} \mathcal{H}(\mathbf{x}, \mathbf{u}, \boldsymbol{\lambda})$. Furthermore, the co-state has to satisfy the following

dynamic equation:

$$-\frac{d}{dt}\lambda = \frac{\partial \mathcal{H}}{\partial \mathbf{x}} = \frac{\partial \mathcal{L}}{\partial \mathbf{x}} + \lambda^T \cdot \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \quad (19)$$

subject to the terminal conditions of $\lambda(t_0 + T_p)$ [29]. In particular, in this study the running cost in Equation 20 was implemented. This cost promotes smooth acceleration profiles for all vehicles while ensuring the desired performance.

$$\mathcal{L} = \sum_{k=1}^n \left(c_1 (s_k - s_k^r)^2 + c_2 (v_{k-1} - v_k)^2 + c_3 u_k^2 \right), \quad \forall k \in \mathcal{I}_{CAV} \quad (20)$$

where we omit the t dependence for the sake of readability. The optimal control problem is transcribed to a set of coupled ordinary differential equations of (13) and (19). An iterative algorithm is proposed to solve the problem efficiently. Algorithm ?? illustrates the full control strategy solved each time step t

4.4. Stability of operational layer

One of the important properties of closed loop systems is stability. Under model predictive control setting, this is not a trivial task. In the ensuing, we proof that the proposed operational layer controller guarantees stability of the closed loop system.

Proposition 1. *The closed loop longitudinal platooning control system is stable.*

Proof. The main idea is to use the value function J_{T_p} as the Lyapunov function and show that it is monotonically decreasing with time t [?], i.e. let $\delta t > 0$ denote the infinitesimal time duration, one wishes to show $J_{T_p}(\mathbf{x}(t_0)) > J_{T_p}(\mathbf{x}(t_0 + \delta t))$ for $\forall t_0$. Note that:

$$\begin{aligned} J_{T_p}(\mathbf{x}(t_0)) &= \min_{\mathbf{u}(\cdot)} \int_{t_0}^{t_0+T_p} \mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t) + \mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t) dt \\ &= \min_{\mathbf{u}(\cdot)} \int_{t_0+\delta t}^{t_0+T_p} \mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t) + \mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t) dt + \int_{t_0}^{t_0+\delta t} \mathbf{x}^{*T}(t) \mathbf{Q} \mathbf{x}^*(t) + \mathbf{u}^{*T}(t) \mathbf{R} \mathbf{u}^*(t) dt \\ &= J_{T_p-\delta t}(\mathbf{x}(t_0 + \delta t)) + \int_{t_0}^{t_0+\delta t} \mathbf{x}^{*T}(t) \mathbf{Q} \mathbf{x}^*(t) + \mathbf{u}^{*T}(t) \mathbf{R} \mathbf{u}^*(t) dt \end{aligned} \quad (21)$$

where \mathbf{u}^* and \mathbf{x}^* denote the optimal control and state trajectories respectively. Taking the limit of the right-hand-side of the above equation when $\lim \delta t \rightarrow 0$ yields:

$$J_{T_p}(\mathbf{x}(t_0)) = J_{T_p-\delta t}(\mathbf{x}(t_0 + \delta t)) + \underbrace{\left(\mathbf{x}^{*T}(t) \mathbf{Q} \mathbf{x}^*(t) + \mathbf{u}^{*T}(t) \mathbf{R} \mathbf{u}^*(t) \right)}_{\text{running cost}} \delta t \quad (22)$$

Hence

$$J_{T_p}(\mathbf{x}(t_0)) - J_{T_p}(\mathbf{x}(t_0 + \delta t)) = \left(J_{T_p-\delta t}(\mathbf{x}(t_0 + \delta t)) - J_{T_p}(\mathbf{x}(t_0 + \delta t)) \right) + \left(\mathbf{x}^{*T}(t) \mathbf{Q} \mathbf{x}^*(t) + \mathbf{u}^{*T}(t) \mathbf{R} \mathbf{u}^*(t) \right) \delta t \quad (23)$$

The positive definite nature of \mathbf{Q} and \mathbf{R} guarantees the positiveness of the second term on the right hand of Equation 23. For the second term, since we have the terminal constraint $\mathbf{x}(t_0 + T_p) = 0$, the non-increasing nature of the value function as a function of the prediction horizon T_p is guaranteed. Therefore, the first term in the right hand side is non-negative. This guarantees that $J_{T_p}(\mathbf{x}(t))$ is a monotonically decreasing function of time and thus is a *Lyapunov function*. This completes the proof. \square

4.5. Casting tactical decisions into the platooning problem

```

1 Data: Initial condition:  $[x_k^{\ell+}(0), v_k^{\ell+}(0)] \quad \forall k \in \mathcal{I}_{CAV}, \quad [x_k^{\ell-}(0), v_k^{\ell-}(0)] \quad \forall k \in \mathcal{I}_{HDV}$ 
2 Result: Control input:  $u_k^{\ell+}(t)$ , Gap:  $s_k^{\ell+}(t)$ 
3 begin
4   Tactical layer: at detection time  $t = t_k^{\ell}$ 
5   begin
6     Find projections:  $\mathcal{P} = \{p(g_1^{\ell+}), \dots, p(g_n^{\ell+}), p(g_1^{\ell-}), \dots, p(g_m^{\ell-})\}$  according to (3)
7     Determine ordering:  $\mathcal{O}^*$  as (4)
8     Determine equilibrium gap  $\mathbf{h} = \gamma(\mathcal{O}^*)$  via (24)
9     Compute anticipation times  $T_{a,k}$  using (5), (7), (8)
10  end
11  Operational layer: each time step  $t_i$ 
12  for each  $t_i$  do
13    for  $k \in \mathcal{I}_{CAV}$  do
14      Measure:  $s_k(t_i), v_k(t_i), v_{k-1}(t_i)$ 
15      Initialization:  $\Lambda_k^{(0)}(t) = (\Lambda_{s,k}^{(0)}(t) \quad \Lambda_{v,k}^{(0)}(t))^T = (0 \ 0)^T, t \in T_{\Delta} = [t_i, t_i + T_p]$ 
16      iteration number  $i = 1$ , initial convergence error  $e^{(1)} = e_0$ , and stopping error threshold  $e_{stop}$ 
17      while  $e^{(i)} \geq e_{stop}$  do
18         $u_k^{*(i)}(t) = \arg \min_u \mathcal{H}(v_k(t), v_{k-1}(t), u_k(t), \Lambda^{(i-1)}) = -\Lambda_{v,k}^{(i-1)}(t)/2c_3$ 
19        Project  $u_k^{*(i)}(t)$  into  $\mathcal{U}$ 
20        Solve forward dynamics with initial condition  $\mathbf{x}_k(t_i) = (e_{s,k}(t_i), e_{v,k}(t_i))^T$ 
21         $\dot{\mathbf{x}}_k(t) = f_k(\mathbf{x}_k(t), u_k^{*(i)}(t)) \Rightarrow \mathbf{x}_k^{(i)}(t), \quad t \in T_{\Delta}$ 
22        Solve backward co state dynamics with final condition  $\lambda_k(t_i + T_p) = 0$ 
23         $-\dot{\lambda}_k(t) = \frac{\partial \mathcal{H}(\mathbf{x}_k(t), \mathbf{x}_{k-1}(t), u_k^{*(i)}, \lambda(t))}{\partial \mathbf{x}} \Rightarrow \lambda_k^{(i)}(t), \quad t \in T_{\Delta}$ 
24        Update the costate:  $\Lambda_k^{(i)}(t) = (1 - \alpha)\Lambda_k^{(i-1)}(t) + \alpha\lambda_k^{(i)}(t)$ 
25        Compute error:  $e^{(i)} = \|\Lambda_k^{(i)}(t) - \lambda^{(i)}(t)\|_2$ 
26        Augment iteration:  $i = i + 1$ 
27      end
28      Output: Select first sample from  $u_k^{*(i)}(t) \Rightarrow \mathbf{u}^{*(i)}(t_i)$ 
29    end
30  end
31  Apply control  $\mathbf{u}^{*(i)}(t_i)$  to system (13)
32 end

```

Algorithm 1: Closed loop operation for the tactical and operational layer

In order to achieve the align the maneuvers and control, the decisions of vehicle order in the final formation and the time window for trucks that need to yield a larger gap for the merging vehicles. from the tactical layer (See section 3) need to be integrated into the lower level operations. The vehicle order determines the reference time gap h'_k for truck

k with respect to truck $k - 1$. The changed reference depends on the vehicle type of the merging vehicle. Consider the case in which m vehicles are willing to merge into the $\ell +$ lane. In this sense, the tactical strategy will find the final order of the combined vehicles according to the ordering process detailed in subsection 3.1. The final order corresponds to a mixture of CAV within the platoon \mathcal{I}_{CAV} and new vehicles. In general, let consider a headway function determining the equilibrium gap between consecutive vehicles given by a map $\mathbf{h} = \gamma(\mathcal{O})$, $\mathbf{h} = (h_1^r(t) \ h_2^r(t) \ \dots \ h_n^r(t))^T$ which can be detailed as

$$h_k^r(t) = \begin{cases} \tau_p & \text{if } \sigma_{k-1} \in \mathcal{I}_{\ell+} \\ \tau + \tau_p & \text{if } \sigma_{k-1} \in \mathcal{J}_{\ell-} \wedge \sigma_{k-1} \in \mathcal{I}_{\text{HDV}} \\ 2\tau_p & \text{if } \sigma_{k-1} \in \mathcal{J}_{\ell-} \wedge \sigma_{k-1} \in \mathcal{I}_{\text{CAV}} \end{cases} \quad \forall t \in [T_k - T_{a,k}, T_k] \quad (24)$$

In order to open sufficient gap at the moment of the merge the tactical layer decides the time should augment the gap between its predecessor and the current vehicle. This action maneuver should be coordinated in some specific time previous to the merging time T_k for a specific vehicle.

Given that at the moment of merge the desired gap $s_k^r(T_k) = s_k^0 + h_k^r(T_k)v_k(T_k)$ should be achieved, this task is achieved by modifying the value $h_k^r(t)$ such that Equation 24 is hold. The amount of time in order to perform the maneuver is $T_{a,k}$ given by Equation 8, so that $s_k^r(T_k - T_{a,k}) = s_k^0 + h_k^r(T_k)v_k(T_k - T_{a,k})$. This value is considered as an input within the solution of the optimal control problem (14).

In addition, a soft reference change is introduced given by a sigmoid function:

$$h_k^r(t) = \frac{\alpha}{1 + e^{-\beta(t - (T_y + T_a/2))}},$$

where the parameters α, β are calibrated such that the rise time of the sigmoid function is approximately T_a and the change corresponds to the amount of change from the equilibrium $T_{\sigma_x}^f - T_{\sigma_x}^0$. The control policy Equation 14 was applied over CAV vehicles only. The results lead to the dynamic time response for the time-shift reference as shown in Figure 7a. As it can be seen the controller at low level accomplishes its objective by taking the time-shift to the desired value. In this case the setting time for the controller is around 25.5s.

And finally, the maneuver considers the constraints in the new space of speeds $\mathcal{X}_c = \mathcal{X} \cup \{v_k(t) \leq v_{\max} - \epsilon\}$. This maneuver is detailed in the Figure 6 where the interaction between the tactical layer and the operational layer is depicted.

5. Simulation study case

To illustrate the performance of hierarchical control framework, the approach has been implemented and tested in an in-house microscopic traffic flow simulator, Symuvia. The scenario considers a platoon of 8 CAVs driving along a long single-lane freeway at the free-flow speed $v=25$ m/s and moving toward an on-ramp. In the same time, two conventional vehicles are coming from the on-ramp: they are detected over a loop sensor located far upstream the on-ramp section and their passage times and speeds are sent to the tactical layer. The merging times are predicted at $T_m = 42.5$ s and 46.5 s respectively, while the merging positions has been fixed at $X_m = 0$ m for the sake of readability.

The performance of the control strategy is presented at multiple stages. First, we analyze the behavior of the operational layer considering that merging vehicles are both CAVs. Second, we compare the traffic performance depending on whether merging vehicles are CAVs or HDVs.

5.1. Operational layer performance

The performance of the controller can be examined from the point of view of the control input. Here, acceleration boundaries have been fixed as [?] in between $(-1.5, 1.5)$ m/s². Figure 7 shows that acceleration rates do not reach

saturation meaning that the maneuver provides also comfort for the driver traveling in a CAV. For vehicles where the time-shift difference $T_{\sigma_x}^f - T_{\sigma_x}^0$ is larger it is expected to have stronger decelerations/accelerations as it is the case for the vehicle i_5 with a top deceleration of -0.958m/s^2 at 40.5s.

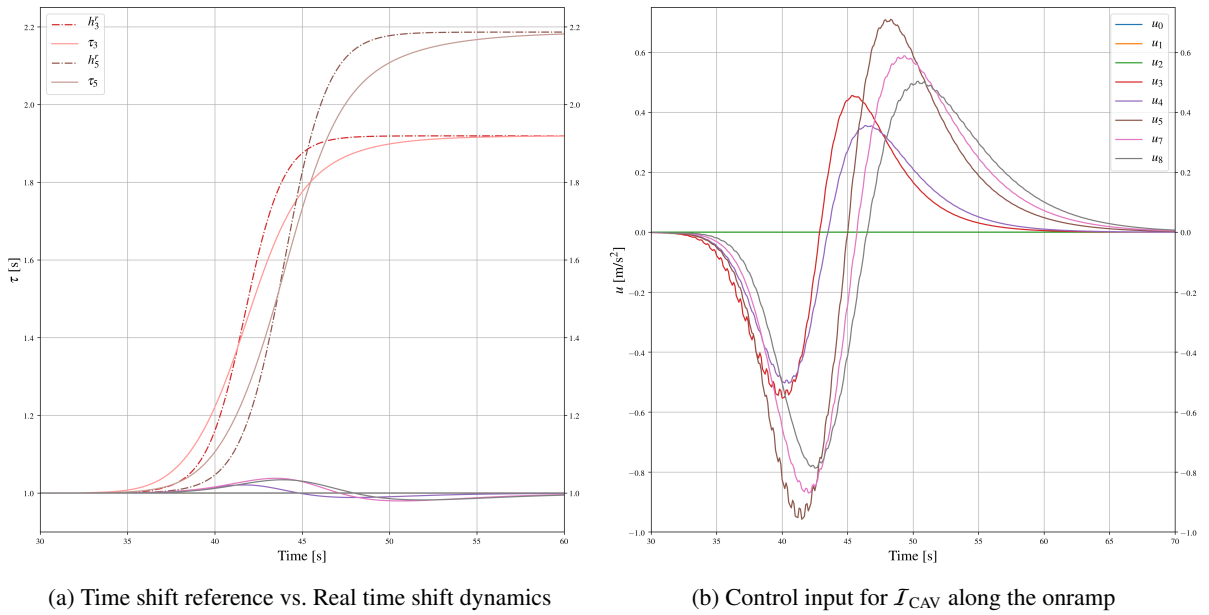


Fig. 7: Operational layer performance

5.2. Comparison between mixed traffic and full CAV merges

Now two types of vehicles are considered: CAVs which have a time-shift $\tau_p = 1.0\text{s}$; and HDVs which have a time-shift $\tau = 1.8\text{s}$. For both type of vehicles, the maximum wave speed is $w = 6.25\text{ m/s}$.

Tactical layer results. At the tactical layer, solution provide the yielding times T_y and corresponding time shift $T_{\sigma_x}^f - T_{\sigma_x}^0$ as presented in table Table 1. In this case two vehicles are inserted approximately at 7.9s and 11.9s.

In the first situation vehicles are considered to be HDVs, so in this case vehicles will work as constraints for the system, creating *internal boundary conditions*. Yielding times are computed according to Equation 7 according to the allocation rule established in Equation 6. In a second scenario vehicles are inserted at same point in time and space but they are CAVs, which are allowed to modify their equilibrium conditions as depicted in Figure 4.

The analytical strategy at the tactical layer yields the decisions as: vehicles of the platoon ($n^* = 3, 5, 8$) have to open a gap, with the maximum speed drop of $\epsilon = 3\text{ m/s}$; the anticipation time for each one is around $T_a = 30$ seconds, equivalent to the yielding start time of $T_y = T_m - T_a$ s for the operational layer.

Vehicle index i_k	Full CAV		Mixed scenario	
	T_a [s]	$T_{\sigma_x}^f - T_{\sigma_x}^0$ [s]	T_a [s]	$T_{\sigma_x}^f - T_{\sigma_x}^0$ [s]
3	12.44	2.18	12.44	2.18
5	16.60	1.91	16.60	1.91
6	37	1.91	NA	NA
9	37	1.91	NA	NA

Table 1: Vehicle index to be relaxed - Yielding times

In this case according to the policy allocation for the mixed scenario it can be seen that the conditions impose 3 internal boundary conditions where vehicles can be allocated upstream each internal boundary condition, in this case, 2 vehicles are allocated upstream the 2 first boundary conditions while the rest is allocated behind the 3rd internal boundary condition.

Performance indicators. In order to measure the performance of the strategy in both cases we consider two traffic indicators. The first, the *total delay* corresponding to the extra time vehicles spent in the network with respect to the equilibrium condition. The second is the *Outflow* at the merge point corresponding ratio between the total number of vehicles and the time interval between the first and the last vehicle crossing the merge. It should be noted that here, the outflow is a local measurement capacity which different and significantly higher that the road capacity. Results in both cases are illustrated in [Table 2](#)

Full CAV		Mixed scenario	
Total Delay [s]	Outflow [veh/s]	Total Delay [s]	Outflow [veh/s]
0.9	1.05	1.3	0.91

Table 2: Traffic indicators

Trajectories. A graphical illustration of the trajectories is presented in [Figure 8](#). First, in [Figure 8a](#) the mixed scenario is observed. It can be seen that only vehicles traveling in the on ramp modify their equilibrium in order to receive vehicles traveling in the on ramp. In [Figure 8b](#) a fully CAV scenario is deployed. Vehicles traveling along the on ramp in this case also perform a yielding maneuver in order to adapt to the optimal time-shift at the moment of merge.

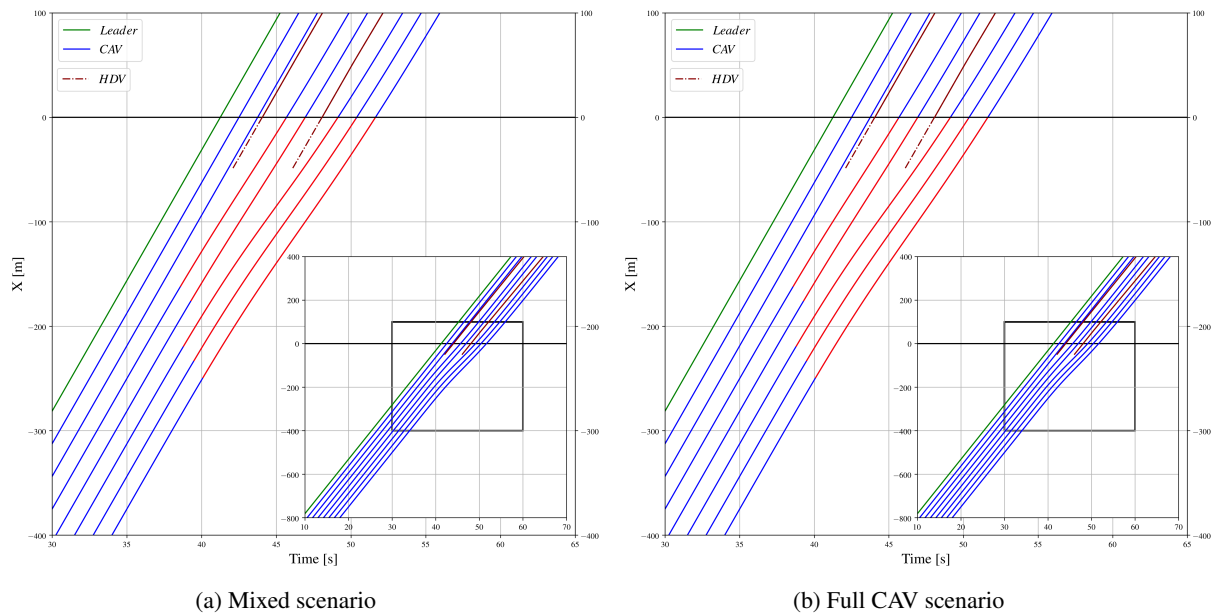


Fig. 8: Multiple merging problem and our approach to solution

6. Conclusion

Main findings. It is expected from platooning strategies to improve network capacities while minimizing fuel consumptions. The first item requires a careful management of conflicts situations between platoons and sur-

rounding conditions. The proposition of the paper contributes to minimize this drawback, by providing a rigorous and comprehensive framework for managing platoons near network discontinuities. It proposes a generic hierarchical approach to split platoons of trucks approaching an on-ramp. The hierarchical framework entails using an analytical car-following model to decide optimal tactical decisions and using a more detailed model to predict and control operational acceleration dynamics of trucks. The solution guarantees the possibility for the merging vehicles to join the platoon under safe and comfortable conditions, with limited impact on mainline traffic. In fact, the proposed framework is generic because: first, it can be extended to any types of connected and automated vehicles in presence of mixed surrounding vehicles and, second, it addresses any conflicting situations between mandatory lane-changing maneuvers and platooning systems. The framework can be deployed near on-/off-ramps, lane drops and weaving sections, where long platoon of trucks can become a problem for vehicles that must undertake mandatory lane-changing maneuvers. The solution can be adapted to any length of platoon, merging vehicle speed, number of vehicle(s) to merge, to passenger car platoons. It can also address the cooperative merging of CAVs by treating the merging CAVs as part of a virtual platoon.

The results of the paper can shed some light on the benefits on splitting strategies. It anticipates and control traffic surrounding merging maneuvers, which smooths traffic dynamics during the fuel consuming transient period, and which avoids unsafe over-reactive deceleration/acceleration maneuvers. Also, it optimizes outflows at network discontinuities, which determine the global network capacities.

Observations & future research. The proposed framework also paves the way for further research. We have presented a fully deployable hierarchical control strategy with the main objective to treat the problem of merges under the presence of connected and automated vehicles. The strategy accounts full observability of the system, and a centralized approach is used to solve a bi-level control strategy where a tactical strategy commands an operational layer designed in an optimal control framework. The full optimization problem is conceived to minimize a quadratic performance error in terms of the headway space and time. The reference level for the operational layer strategy considers information from the tactical level strategy where the communication channel is completely ideal and it is not affected by noise.

Future research in this line includes the analysis on perturbations in cases like assumption 3 which in general might be violated due presence of noise affecting the sensors in vehicles or the network infrastructure. In general, parameter uncertainty within the system can also introduce alterations in the performance of the strategy, computations such as T_m , X_m and performance of the controller is a subject of further analysis regarding impact of uncertainties. For instance, by exploring specifically the impact of HDV behaviors which are uncertain by nature, or, when leading vehicle of the platoon is disturbed by local perturbations (slow vehicle behind) or saturated situations.

Other research can extend the present work by considering the fuel consumption as part of the control strategy. The addition of fuel consumption and pollution models can be considered in the tactical layer and at the operational level where vehicle dynamic can be bounded to respect consumption constraints. Finally, the proposed control strategy is local while vehicle fleet managers approaches these problem from routing point of view at the network scale. Integration and coordination of local / global control will become a major challenge for upcoming years.

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