Calibration and impact of control strategies for splitting truck platoons at on-ramps

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Calibration and impact of control strategies for splitting truck platoons at on-ramps:
A simulation study on fuel consumption

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Abstract

Heavy-duty vehicles or trucks contribute in a significant share with global green house emissions and energy consumption in transportation systems. Truck platoon coordination strategies have introduced new technologies for better coordination and management of those intelligent transportation systems (ITS) to account for environmental efficiency. Current control strategies focus their attention on specific factors such as fuel efficiency or safety while neglecting the intrinsic combined effect when interactions exist with conventional vehicles. In this work, a study considering fuel consumption and environmental effects is presented when platooning strategies are operated near merging areas (on-ramps), a consumption model that considers dynamic conditions on each one of the vehicles is calibrated from real data, and a suitable adaptation is provided to the platooning case to taking into drag effect. Different scenarios at the control level are studied to analyze the impact of splitting maneuvers.

INTRODUCTION

Freight transport systems constitute a key element in the movement of goods between multiple layers of the supply chain, ensuring the development of new economies and industries. The introduction of information technologies within these systems has increased the amount of available information in real-time, therefore enabling the possibility of new services [2, 12]. In particular, in the domain of connected and automated vehicles (CAV) s, heavy-duty vehicle truck platooning has emerged as one outstanding application that introduces vehicle control empowered by vehicle-to-vehicle (V2V) communication in order to coordinate a fleet of heavy-duty vehicles. In this framework, heavy-duty vehicles behave as controlled trucks that adapt their driving maneuvers and conditions to specific traffic situations defined by control strategies [6]. Two main issues can be identified within the platooning problem, the first related to the fleet formation where systems are designed to coordinate a fleet vehicle in order to promote and optimize the platoon creation process. Once the coordination problem is solved, the maneuver is achieved by means of local truck controllers and the analysis and control of those formations is of vital importance to tackle variations on traffic conditions [30].

The coordination problem of heavy-duty vehicle platooning in highways is characterized by the control of short spacing between consecutive vehicles, the leading vehicle is manually driven while follower vehicles modify steering and acceleration conditions based on actions of the leader. These maneuvers promote benefits in terms of road capacity while saving costs and enhancing the fuel efficiency of the system. Furthermore, these strategies have shown to work in experimental deployments [1, 7] where results show fuel efficiency improvements around 5%, that can be still be improved due to modifications in vehicles aerodynamics particularly designed for platoon maneuvers [18].

Vehicle platooning is a concept that has been studied since the early 90s [31], the U.S., PATH research on heavy-duty vehicle platooning started more than two decades ago. All major truck manufacturers have developed in an independent way technologies that enable platooning, and several field tests have been deployed or are currently taking place in Europe [3], Sweden [1], the U.S. [7, 22], Canada [18], Japan [27] and Australia [29]. Some projects now seek for technology standardization and first road-legal trucks equipped with platooning technology are expected soon.

Given the success of platoon strategies, multiple efforts have been put in the development of centralized and distributed control algorithms that optimize several performance indexes such as fuel efficiency [16] or coordination principles [5, 14]. Some algorithms have been also created to deal with splitting and overtaking situations and moreover, protocol specifications have emerged describing ways to deploy interaction among CAVs [9, 13]. The aforementioned strategies consider the control of the speed and spacing on each heavy-duty vehicle within the platoon, in some cases, they involve dynamic splitting maneuvers in order to adapt to predefined traffic conditions.

Adaptability to specific traffic conditions is an important feature of platoon control strategies applied on CAVs, in particular, when platoons are embedded into real traffic. Optimal strategies can be formulated to promote and maximize network's throughput at cost of modification of the equilibrium condition within the convoy traveling at some desired speed/spacing. Although, variables such as (speed/spacing/acceleration) are regulated and sometimes taken into account as part of the control design [8], the dynamic transitions may propagate spacing perturbations in the formation with respect to a settled equilibrium condition, the upstream effect also impacts the primary objective of the platoon regulation (e.g. the fuel-efficiency). The objective of this paper is therefore to analyze the impact of dynamic transient perturbations on heavy-duty platoon formations from the point of view of the fuel-efficiency, considering platoon formations at network discontinuities.

Literature review

Platoon strategies have been proposed as a solution for coordination problems in traffic more than 30 years ago, nevertheless, its environmental impact has been highlighted during the past 10 years [7, 11, 21, 35]. Multiple studies have proposed coordinating control strategies at different levels of abstraction [1, 20, 30]. These studies design control laws that can be implemented in a *coordination control* layer placed between the *traffic control* and the *vehicle control* layer. Among those strategies, different criteria such as comfort and fuel-efficiency are included as part of the design, regularly expressed as an optimization problem. Finally, the vehicle control layer deals with trajectory planning and coordination among platoons [28]. Some experiments [3, 24, 25] have demonstrated via test beds, the benefit in terms of fuel savings and coordination of the fleet when enabling platoon strategies, however, the impact on traffic conditions has not been formally tested.

Considerable efforts have been devoted to partially automate driving maneuvers for vehicles traveling in highways in order to improve their safety and efficiency, while at same time reduce traffic congestion. Immersion of platoons within traffic is of relevant interest nowadays. In [16] an optimal control strategy has been formulated in order to account for fuel-efficiency of small formations. A supervisory control strategy is designed to optimize vehicles' speed according to a cost function that estimates the fuel-consumption based on a dynamical model. A coordination algorithm to create new platoons in terms of the fuel-efficient costs is introduced, finally, an optimal algorithm decides whether the platoon should be created in case it is beneficial for the particular truck.

More recently in [9] a splitting strategy has been proposed to manage the platoon adaptability at network discontinuities, in particular the case of merges (on-ramps) is studied. Inspired by a transient process that describes a relaxation procedure occurring in real data trajectories [15], the strategy proposes a bi-level controller. Within the traffic control layer, a tactical strategy monitors traffic conditions and commands the gap dynamical opening conditions to an operational strategy by indicating opening gap times and the amount of space headway to be opened. At the vehicle control layer, a centralized predictive control strategy executes the tracking maneuver, by considering truck acceleration as the control input for each truck. Safety and comfort are the two key elements considered within the cost function to be optimized by the controller. The maneuver has been tested in a more general framework where CAV vehicles join the main lane and then incorporated into the platoon in [8].

The present paper focuses on the study of control of formation strategies and its impact from a fuel-efficiency perspective, in particular, a fuel consumption model is calibrated from real truck data trajectories. This model is then extended to a platoon case by considering a the relationship between aerodynamic drag and the space headway affecting platoon model, then the strategy implemented in [8, 9] is deployed in order to split the platoon and integrate vehicle insertions within the opened gap. Effects of splitting a platoon are important in relative long platoons given that perturbations appearing in the middle of a platoon propagate upstream by means of accelerations, hence promoting fuel-consumption.

In the remainder of this paper, we first present the vehicle-following model for platoons, then we introduce the existing loses within the platoon. The discussion continues with the formulation of the decision and control strategy. After that, we apply the strategy to derive and analyze multiple scenarios where several splitting maneuvers are presented. The performance of the strategy and the consequences at fuel-efficiency/consumption level are summarized in the results sections. We finally present the main findings and considerations for future research in the conclusion section.

FUEL CONSUMPTION MODELS FOR TRUCK PLATOONING

This section contains the dynamical model and the fuel-consumption extrapolation model that will serve as a basis for analysis and formulation of the optimal control problem. Fuel consumption remains as one of the main motivations to foster platoon strategies [6]. The close dependency between CO_2 emissions and fuel consumption is also as a key factor to design platoon strategies that reduce pollution generated by freight transport (see [26]). In particular CO_2 emissions / fuel consumption models are tied and can be devised from vehicle dynamics. Furthermore, model parameters can be estimated by using the current probe vehicle systems [33].

In order to account for the fuel consumption as part of the platoon strategy, three possible alternatives are available. In the first situation the strategy can be modeled as part of the tactical control strategy (a.k.a traffic control layer) where vehicle to infrastructure (V2I) and vehicle to vehicle (V2V) communication layers can transmit useful information such as headway space that should be augmented or speed regulation that should be regulated. Such variables can define indicators to maintain the fuel efficiency at maximum before the platoon is split to satisfy constraints in the traffic.

A second possibility is to include the effects of the platoon strategy as part of the operational control (a.k.a local control layer), in this case the controller estimates fuel consumption according sensor data capturing current dynamic situations. At this level the controller decides for specific real time maneuvers that aim to minimize fuel consumption. This approach benefits from higher accuracy but introduces computational complexity, however, model simplifications can be introduce to address non linearities while preserving the accuracy.

For better understanding of the aforementioned alternatives an assessment and study of the effect these models needs to be addressed. For this situation we first propose a simple model based on vehicle dynamics where model parameters can be reconstructed from probe vehicles as in [32, 36]. We describe first the fuel consumption model actuating on a single truck and how a simple principles can be considered to account for fuel efficiency, we then present the adaptation of this model to a platoon formation where aerodynamic effects play in important role. The succeeding sections will setup a control strategy for splitting maneuvers and dynamic regulation.

Single truck fuel consumption model

In general it is possible to formulate the model of longitudinal dynamics of a heavy-duty vehicle (See Figure 1) based on Newton's second law:

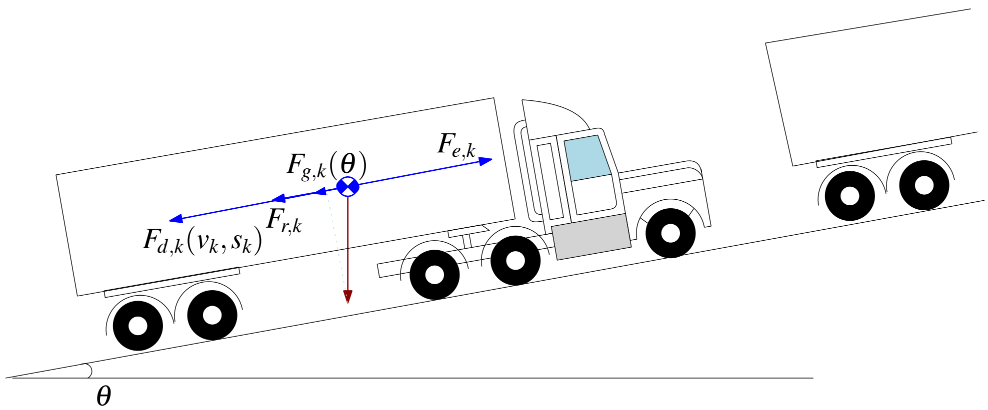


Figure 1: Longitudinal force diagram for a heavy-duty vehicle

$$m_k\dot{v}_k = F_{e,k} + F_{g,k}(\theta) + F_{r,k} + F_{d,k}(v_k,s_k), \tag{1}$$

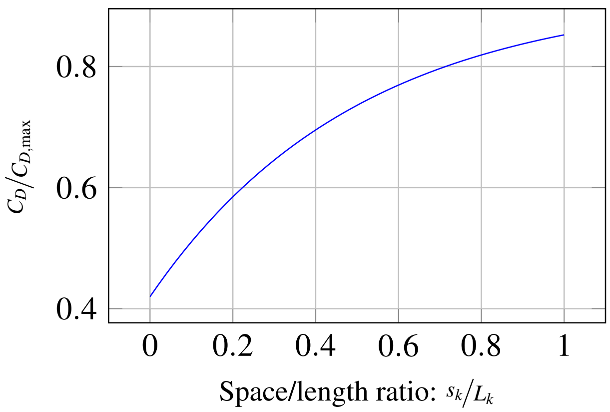
where v_k, s_k represent the speed and space headway correspondingly for a single vehicle indexed k. The expression contains the *inertial* force $m_k\dot{v}_k$, the external force $F_{e,k}$ coming from the power exerted by the motor to promote movement in the vehicle, the *up/downhill-slope* force which conditions the nature of the terrain, the *static friction* force $F_{r,k}$ determined by the road parameters as well as the surface contact between the vehicle and the road. Finally, $F_{d,k}(v_k,s_k)$ the *aerodynamic drag* is responsible of wind effects upon the vehicles. In case of platoons, it has been shown experimentally the dependence of this force in terms of the speed and the space headway [21]. The majority of aerodynamic drag of a ground-vehicle consists of "form" or "pressure" drag generated by the pressure differential between the front (high pressure field) and the rear (low pressure field) surfaces of the vehicle [21]. The aerodynamic benefit of platooning is primarily the result of the change in the aerodynamic pressure fields over the front and rear surfaces of vehicles present in a platoon configuration.

The relationship eq. (1) expresses the general forces actuating over a vehicle in movement. For small values of road grade ($\theta \approx \sin(\theta)$), eq. (1) can be alternatively detailed as:

$$\dot{v}_k = g_k(u_k,s_k,v_k) = \underbrace{\frac{F_{e,k}}{m_k}}_{u_k} - g(\mu+\theta_k) - \frac{1}{2}\frac{\rho A}{m_k}C_D(s_k)v_k^2, \tag{2}$$

where, m_k corresponds to the vehicle's mass, A the effective frontal cross section of the vehicle, ρ the density of air, μ the static friction coefficient between the truck and the road, and C_D the aerodynamic drag coefficient. θ_k represents the road grade. Although several studies have been conducted to analyze and understand the vehicle aerodynamics [4, 35], few studies have correlated its dependence with the headway space [11] when there exists a platoon situation. For this case, we consider the model presented in [28], illustrated in Figure 2 whose parameters α_1, α_2 could be fit from data captured by radar and gps sensors installed in heavy-duty vehicles eq. (3).

The dynamic model eq. (2) establishes the basis to devise the fuel consumption model. The power required to overcome the driving resistance is composed by the *idle* power P_0 and the power executed by the motor. This term can be adapted from [26] as:



$$\frac{C_D(s_k)}{C_{\max}} = 1 - \frac{\alpha_1}{\alpha_2 + s_k/L_k} \tag{3}$$

Figure 2: Normalized drag coefficient as a function of the normalized spacing

$$P(v_k, \dot{v}_k, s_k, \theta_k) = P_0 + \max\left(v_k F_{e,k}(v_k, \dot{v}_k, s_k, \theta_k), 0\right). \tag{4}$$

The term $F_{e,k}$ can be obtained from eq. (2) and replaced into eq. (4) as it considers acceleration phases as the ones generating the big proportion of the fuel consumption. The *energy density* describes the relationship between the energy stored in a specific volume of fuel with respect to the energy that can be transformed into mechanical power (see. [Sect-20.4 26]). The power P and the energy density as a fuel consumption indicator by:

$$\dot{FC}_k = \frac{P(v_k, \dot{v}_k, s_k, \theta_k)}{\gamma \omega_{\text{cal}}} \left[\frac{\text{g}}{\text{s}}\right], \tag{5}$$

where ω_{cal} is the energy density for the specific motor fuel, and γ is the motor efficiency. By plugging eq. (2) into eq. (4) and consequently in eq. (5) the fuel consumption rate can be expressed in terms of the dynamic variables of the model. We provide a simplified a generic equation in this case as a linear combination of parameters embedding vehicle and fuel parameters of the model as:

$$\dot{FC}_k = \beta_3 v_k^3 + \beta_2 v_k \theta_k + \beta_1 v_k + \beta_0 \dot{v}_k v_k. \tag{6}$$

Dependency on s_k has been included within a fixed parameter β_3 for calibration purposes. Fuel consumption data collected in most of the experiments does not account for spacing information [6]. Our assumption considers that trucks collecting fuel consumption data are not in platoon mood due to the current development of these technologies. The effects of eq. (3) are included in the experimental evaluation where simulation data is used to analyze for the control maneuver.

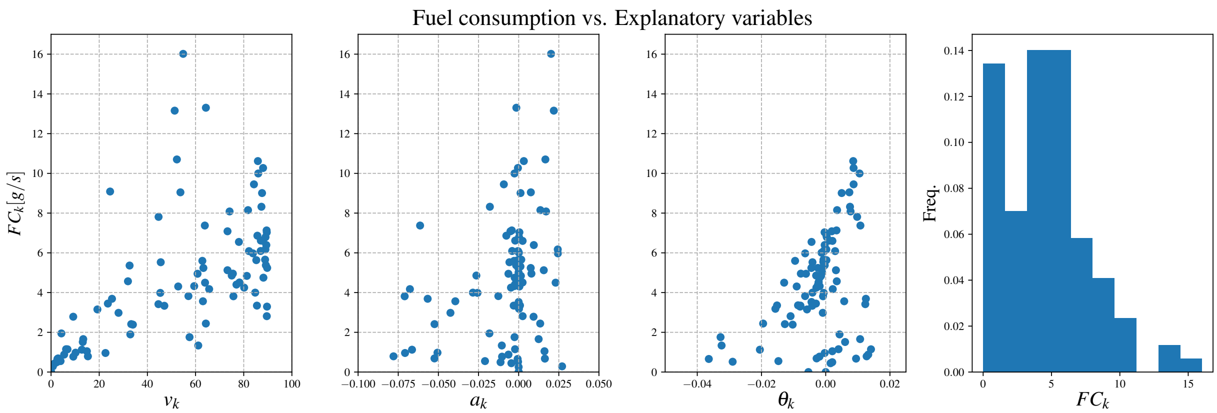
Platoon consumption function: eq. (6) accounts for the consumption of a single truck. In a more general sense, the model for the total fuel consumption of the platoon can be considered as the cumulated consumption of all the trucks within the platoon as:

$$\dot{FC}(t) = \sum_{k \in \mathscr{I}_{\text{CAV}}} \dot{FC}_k(t). \tag{7}$$

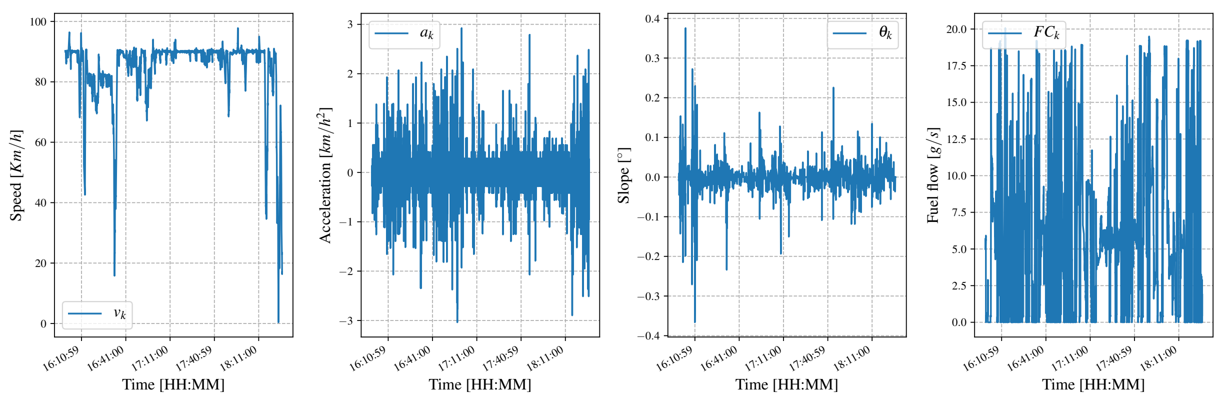
Calibration of fuel consumption model

The model presented in eq. (5) contains many parameters that are not frequently measured or require exhausting tests to be determined. Among them, the type of truck, fuel type, altitude and road grade, slope and truck load. Recent approaches like [32] have considered explanatory variables in terms of the power P measure in the motor in order to determine the coefficients that fit a good model. Inspired by [32] we follow a similar procedure, in eq. (6) a generic form of the fuel-consumption is expressed in terms of the explicit explanatory variables that can be monitored via on board devices installed in regular trucks. Let introduce the vector $\boldsymbol{\beta} = \begin{pmatrix}\beta_3 & \beta_2 & \beta_1 & \beta_0\end{pmatrix}^T$ containing the set of parameters and the set of fuel consumption measurements $\bar{\mathbf{z}} = \left(\bar{z}^{(1)} \quad \bar{z}^{(2)} \quad \cdots \quad \bar{z}^{(n)}\right)^T$ particularly taken at some specific moments in time . An ordinary least squares (OLS) estimator can be then formulated as a multiple linear regression problem with explanatory variables $\mathbf{h} = \left(v_k^3 \quad v_k\theta_k \quad v_k \quad \dot{v}_k v_k\right)^T$.

$$\hat{\beta} = \min_{\boldsymbol{\beta}} \sum_{j=1}^{n} \left(\bar{z}^{(j)} - \boldsymbol{\beta}^T \mathbf{h}\right)^2, \tag{8}$$



(a) Cross correlation among explanatory variables and fuel consumption



(b) Dynamical conditions for a truck trip

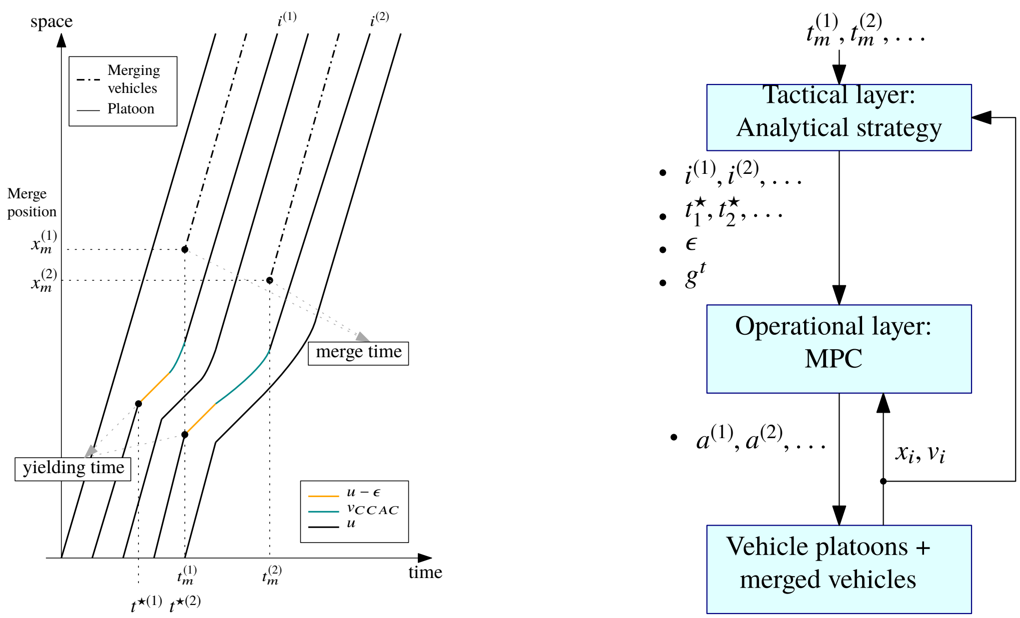
Figure 3: Correlation matrix for explanatory variables presented in the regressor eq. (8). The experiment collects data from the National project EQUILIBRE [17] where individual trucks collect fuel consumption trips along with dynamic state information

Figure 3 illustrates the experimental relationship existing for a particular trip between $v_k, \dot{v}_k, \theta$ with respect to fuel-efficiency $\dot{FC}_k$. The collection of the data here presented is a subset of the full trip information observed in Figure 5a. The information presented in between 16h00 and 18h00 reveals a truck traveling at maximum speed most of the time and experiencing some height increase at the beginning near 16h30. This information is useful enough to obtain a full range of possible values complete enough to calibrate the fuel consumption model. As it can be observed the relationships from experimental data demonstrate high correlation between the set of explanatory variables (speed, acceleration, slope) and the dependent variables (fuel consumption). In the case of the experimental data, headway spacing information is not available, hence, for the purpose of calibrating the coefficients $\boldsymbol{\beta}$ within the regressor, we consider spacing information on its maximum value since vehicles collecting data were in regular traffic and not necessary in a platoon formation. Then the relationship eq. (3) calibrated with data from [16] serves as a modeling for the case where vehicles enter into a platoon formation.

PLATOON CONTROL STRATEGY

Let us consider an existing platoon of CAV s in an equilibrium condition approaching the merging section. At some specific point a lane reduction situation forces vehicles to merge into the formation. In order to account for adaptability of the platoon, we consider the bi-level control strategy initially proposed in [9, 10] designed for unique splitting and adapted in [8] for multiple splitting scenarios.

Bi-level control strategy



(a) Space/time scenario in merging situations [8] **(b)** Bi-level strategy

Figure 4: Bi-level control strategy [9] and its operation

For the control design problem, a hierarchical decision-making paradigm is often pursued [9]. The control strategy there proposed, is composed by two levels (See. Figure 4). At the tactical level, the layer takes information from V2V communication regarding positions and speeds of vehicles in the platoon, and positions and speeds of merging vehicles (if they are equipped with V2V communication) or real time traffic information via V2I communication when they cross over fixed road-based sensor. A model-based strategy is used to determine the optimal vehicle indexes $y^{(i)}$ in the platoon to yield gaps for merging vehicles and time instants when they should start the yielding process; the speed drop ε that they should accept compared with respect to the equilibrium speed is also provided. The tactical layer also provides the desired state for the vehicles in the platoon once they reach the merging position, notably the desired time gap of the yielding trucks expressed as a headway space reference to be attained. The tactical decisions are then sent to the operational layer, where a model predictive controller determines the commanded accelerations (see 3.3) that regulate the speeds and positions of CAVs (heavy-duty trucks) in the platoon.

As an illustration example in Figure 4a, assuming anticipated merging times $t_m^{(1)}, t_m^{(2)}, \ldots$ of two vehicles from the on-ramp can be estimated by the infrastructure system or transmitted by the CAVs willing to be integrated into the platoon on the main carriageway, the tactical layer determines the yielding vehicle index $i^{(1)}, i^{(2)}, \ldots$ in the platoon that should adapt their actual vehicle-following behavior in order to allow the merge of new vehicles. Given a merging time $t_m^{(1)}$, a desired time gap g^t, and specifying the speed drop ε it is possible to determine the yielding vehicle $y^{(1)}$ and the optimal anticipation time $t^{\star(1)}$ to start the yielding maneuver. In particular, as shown in [9]:

$$t^{\star(1)} = \frac{S^c - (g^t + L/u) \cdot u}{\varepsilon} - \frac{\varepsilon}{2 \cdot a_{\max}}, \tag{9}$$

where S^c is the critical headway defined for safety at the merge, L the length of the truck, $a_{\max}$ the maximum allowed acceleration. Figure 4a illustrates this condition, in this case, two vehicles are required to merge at positions $x_m^{(1)}, x_m^{(2)}$. In order to guarantee the secured and comfortable merge with a minimal impact on traffic conditions, the tactical layer should identify the yielding vehicles within a set $\mathscr{I}_{\text{CAV}} = \{i^{(1)}, i^{(2)}, \dots, i^{(n)}\}$ in the formation and yielding start times $t^{\star(1)}, t^{\star(2)}, \dots$, transmit these decisions to the operational layer where a constant time gap control strategy can operate in a coordinated way (a.k.a) cooperative adaptive cruise control (CACC) to optimize performance indexes in the network such as flow or total travel distance. The order in which indexes $i^{(j)}$ and yielding times $t^{\star(j)}$ are determined is important within the formulation since potential decisions taken by leaders may impact the actions taken upstream drivers when seeking to achieve a successful merge, in general this condition can be expressed as $t^{\star(j)} \approx f(t^{\star(j-1)})$.

The tactical decisions of the yielding vehicles index $y^{(i)}$, yielding start time $t^{\star(i)}$, and design parameters of acceptable speed drop ε and desired time gap g^t are used to reformulate the optimal control problem within the operational layer. To this end, we distinguish whether the merging vehicle is a CAV or a conventional vehicle. If the merging vehicle is a CAV, the problem is transcribed into a cooperative merging problem, where the new platoon of length $N + j$ is formed virtually. If the merging vehicles is a conventional vehicle, the yielding vehicle tracks the speed of the conventional vehicle after merge as the leader. Given multiple merges are allowed we consider the condition of operation before the merging vehicles. The hierarchical framework uses a simple car following model to decide optimal tactical decisions and using a more detailed model to predict and control operational acceleration dynamics of vehicles to guarantee the possibility for the merging vehicle to join the platoon under safe and comfortable conditions, with limited impact on mainline traffic. This dynamical effect occurring during acceleration impact the aggregated fuel consumption described in eq. (7), therefore the index of yielding vehicles impacts the fuel-efficiency of the system.

Operational layer

Let us consider the situation of multiple vehicles driving a lane $\ell-$ and willing to merge into the lane $\ell+$, where platoon CAVs are located. Based on a dynamic model that considers the drag effects as eq. (2), the selection of a controller that optimizes a safety and traffic performance based on decisions from the top level layer is desirable. For the sake of simplicity, it is considered the CAV vehicle is permanently connected to the cruise control strategy. This means that even when vehicles insert from $\ell-$ within the platoon in $\ell+$ connectivity infrastructure for CAVs holds its properties along the time. Given that one of key aspect is to regulate the spacing policy s_k, the performance of the low level control strategy is formulated in terms of the error. The system state from the perspective of a vehicle platoon with n CAV (including the leader with index $k = 1$) can be described by the gap errors $\mathbf{e}_s = \begin{pmatrix} e_{s,1} & e_{s,2} & \cdots & e_{s,n} \end{pmatrix}^T$ and speed errors $\mathbf{e}_v = \begin{pmatrix} e_{v,1} & e_{v,2} & \cdots & e_{v,n} \end{pmatrix}^T$ between consecutive vehicles, e.g.

$$e_{s,k}(t) = \begin{cases} s_1(t) \\ s_k(t) - s_k^r(t) \end{cases}, \quad e_{v,k}(t) = \begin{cases} u - v_1(t) & k = 1 \\ v_{k-1}(t) - v_k(t) & k = \{2, \dots, n\} \end{cases} \tag{10}$$

CAV Model. As a basis for the control we consider a second order model describing the dynamic behavior of the spacing between consecutive vehicles and the input acceleration. In this case,

$$\underbrace{\begin{pmatrix} \dot{s}_k(t) \\ \dot{v}_k(t) \end{pmatrix}}_{\dot{\mathbf{x}}_k} = \underbrace{\begin{pmatrix} v_{k-1}(t) - v_k(t) \\ g_k(t) \end{pmatrix}}_{f(\mathbf{x}_k, \mathbf{x}_{k-1}, u_k)}, \ \forall i \in \mathscr{I}_{\text{CAV}} \tag{11}$$

where $s_k(t) = x_{k-1}(t) - x_k(t)$ represents the spacing between the i^{th} vehicle and its leader, $g_k(t)$ represents vehicle's acceleration to be determined by the control law and the aerodynamic drag effect. Note that when the fuel consumption is considered as in 3 non linear effects are introduced in the model. For the sake of simplicity in the analysis of this study the non-linearity introduced by $g_k(t)$ is estimated at each time step as if $s_k(t)$ remains constant during the prediction horizon. This strategy will account the fuel consumption eq. (5) as a perturbation at a given time t.

By considering the full state vector as $\mathbf{x} = \begin{pmatrix} \mathbf{s}^T & \mathbf{v}^T \end{pmatrix}^T$, $\mathbf{s} = \begin{pmatrix} s_1 & s_2 & \cdots & s_n \end{pmatrix}^T$, $\mathbf{v} = \begin{pmatrix} v_1 & v_2 & \cdots & v_n \end{pmatrix}^T$ the full system dynamics can be written as:

$$\begin{pmatrix} \dot{\mathbf{s}}(t) \\ \dot{\mathbf{v}}(t) \end{pmatrix} = \underbrace{\begin{bmatrix} \mathbb{0} & M \\ \mathbb{0} & \mathbb{0} \end{bmatrix}}_{\mathbf{A}} \begin{pmatrix} \mathbf{s}(t) \\ \mathbf{v}(t) \end{pmatrix} + \underbrace{\begin{bmatrix} \mathbb{0} \\ I \end{bmatrix}}_{\mathbf{B}} \mathbf{u}(t) + \begin{bmatrix} \mathbb{0} \\ E_1 \end{bmatrix} u_1(t), + \begin{bmatrix} \mathbb{0} \\ E_2 \end{bmatrix} \mathbf{d}, \tag{12}$$

where I corresponds to the identity matrix of size n, $E_1 = \begin{pmatrix} 1 & 0 & \cdots & 0 \end{pmatrix}^T$, is the first element canonical basis of $\mathbb{R}^n$, $M \in \mathbb{R}^{n \times n}$ the coupling matrix

$$M = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ -1 & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & -1 & 1 \end{pmatrix}.$$

In eq. (12) u_1 denotes a system disturbance, (e.g. perturbation in the traffic speed) which has a final effect on the acceleration of the leading vehicle v_1 in the platoon while $\mathbf{d}$ captures the dragging effects established for a certain space policy and a particular road grade, $E_2 = I \cdot \left(g\theta - \frac{1}{2}\frac{\rho A}{m_k} C_D(\mathbf{s}) \right)$ is the corresponding weight for this perturbation. The objective in order to regulate the space is to command the individual acceleration of each vehicle according to a control policy. Multiple strategies have been proposed in the literature [19, 23]. In this case we study a predictive control strategy due to its flexibility to deal with constraints in the control signal and the space of state space of the system. This strategy allow the integration of multiple criteria for qualifying the performance of the control, and they can be implemented in a centralized or a distributed way.

Predictive control strategy

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 [34], which can be formulated as the following mathematical optimization problem:

$$\begin{aligned} \min_{\mathbf{u}_{[t_0, t_0+T_p]}} \quad & \int_{t_0}^{t_0+T_P} \mathscr{L}(\mathbf{x}(t), \mathbf{u}(t)) dt \\ \text{s.t.} \quad & \mathbf{x} \in \mathscr{X} \\ & \mathbf{u} \in \mathscr{U} \\ & \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \end{aligned} \tag{13}$$

where $\mathscr{L}$ denotes the so-called running cost with $c_j, j = 1,2,3$ weight factors defined as

$$\mathscr{L}(\mathbf{x}(t), \mathbf{u}(t)) = \mathbf{e}_s^T \mathbf{e}_s + \mathbf{e}_v^T \mathbf{e}_v + \mathbf{u}^T \mathbf{u} = \sum_{k=1}^{n} c_1 e_{s,k}^2(t) + c_2 e_{v,k}^2(t) + c_3 u_k^2(t) \tag{14}$$

At each time instant t_0, the problem eq. (13) is solved online with an efficient algorithm based on Pontryagin's Principle [34], which entails the Hamiltonian $\mathscr{H}$ as follows:

$$\mathscr{H}(\mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}) = \mathscr{L}(\mathbf{x}, \mathbf{u}) + \boldsymbol{\lambda}^T \cdot \mathbf{f}(\mathbf{x}, \mathbf{u}) \tag{15}$$

where $\boldsymbol{\lambda} = (\lambda_{s,1}, \lambda_{v,1}, \dots, \lambda_{s,n}, \lambda_{v,n})^T$ 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: $\mathbf{u}^* = \arg\min_{\mathbf{u}} \mathscr{H}(\mathbf{x}, \mathbf{u}, \boldsymbol{\lambda})$.

Furthermore, the co-state has to satisfy the following dynamic equation:

$$-\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\lambda} = \frac{\partial \mathscr{H}}{\partial \mathbf{x}} = \frac{\partial \mathscr{L}}{\partial \mathbf{x}} + \boldsymbol{\lambda}^T \cdot \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \tag{16}$$

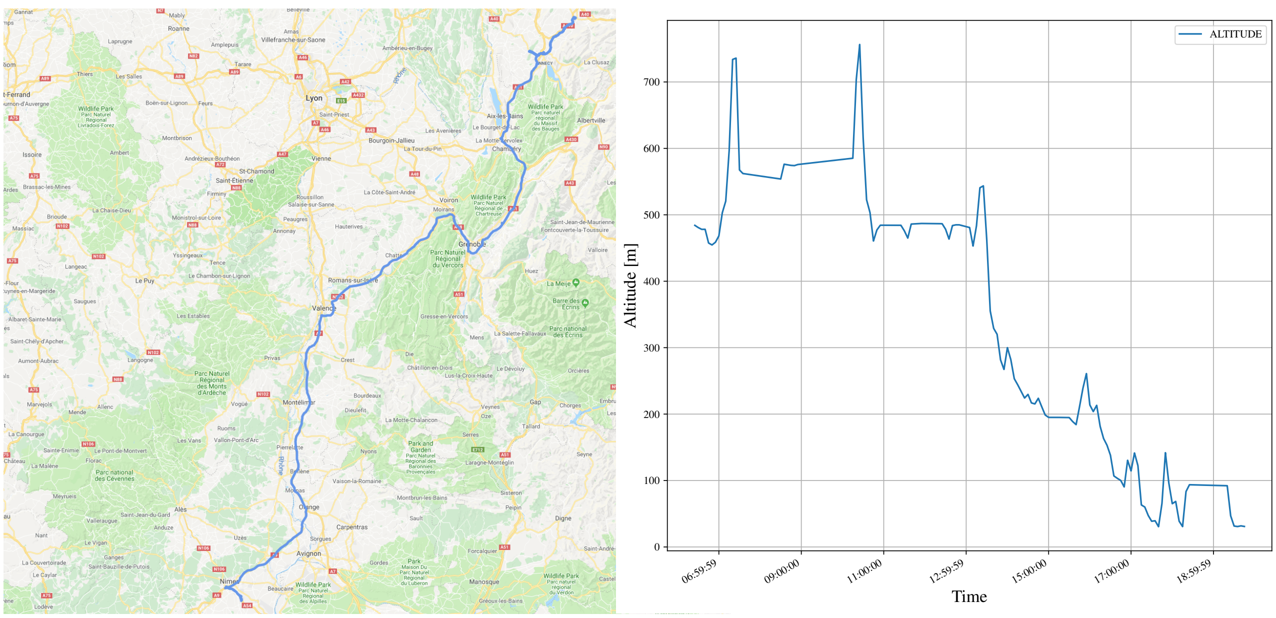
subject to the terminal conditions of $\boldsymbol{\lambda}(t_0 + T_p)$. The optimal control problem is transcribed to a set of coupled ordinary differential equations of (11) and (16). An iterative algorithm is proposed to solve the problem efficiently (see [8, 34]).

EXPERIMENTAL SETUP

The experimental setup consists in two main phases. During the first part, the evaluation of the dynamic model eq. (6) calibrated from real data is presented. Then based on this model, the corresponding extension to the platoon case is done by providing the effects via the function eq. (3). In a second part a simulated situation where platoons are split at different vehicle index (a.k.a. yielding index) is presented. The evaluation of the impact on fuel consumption is summarized by the end of the section where we provide some recommendations. [1].

Fuel consumption model calibration

For the calibration of the model eq. (3) via the OLS estimator eq. (8) a set of data from the European project EQUILIBRE (http://www.projetequilibre.fr) was used. In the experimental setup, a single truck following the trajectory indicated in Figure 5a was considered. The truck follows a long trip (400km) composed mainly by highway sections with variation in the road grade and altitude, as illustrated in Figure 5b. Gps position, vehicle dynamics (speed, acceleration), fuel-consumption and NOx emissions are monitored and collected during the full trip.



(a) Gps trajectory of the platoon

(b) Height profile

Figure 5: Scenario description for calibration of the fuel consumption model

The calibration of the individual fuel consumption model is based on real data collected at high sampling frequency 5 Hz. The original measurements where averaged at a coarser sampling time 1 min in order to fill missing values existing at some specific points. All units in the data where treated in the SI system. The results of the optimal problem eq. (8) are presented in the Table 1 where we also present the standard deviation for each one of the coefficients. To test the efficiency of the estimated model we analyze the behavior of the Figure 6. In the figure the experimental cumulative distribution is shown as well as the histogram of the distribution of the error. As it can be observed, the tends to observe errors around $2.0[g/s]$ with a probability of 80% indicating the good performance of the precomputed model.

Platoon scenario description

For the control scenario we consider a test in which 4 heavy duty vehicles follow a platoon formation at constant speed of 80 $\frac{\text{km}}{\text{h}}$. In each scenario the platoon is split at different vehicle index. The situation is better reflexed in Figure 7 where the positions illustrate each one of the yielding vehicles opening gaps for vehicles willing to merge. The strategy is controlled by the algorithm explained in the precedent sections. Each column in Figure 7 illustrates

[1]All results for visualization and reproduction of the results are available at https://github.com/research-licit/Energy-Impact-Platoon

Multiple Linear Regression	
Coefficient	Value
$\hat{\beta}_0$	4.6171
$\hat{\beta}_1$	0.4658
$\hat{\beta}_2$	12.5903
$\hat{\beta}_3$	-0.0004

Table 1: Multiple linear regression results

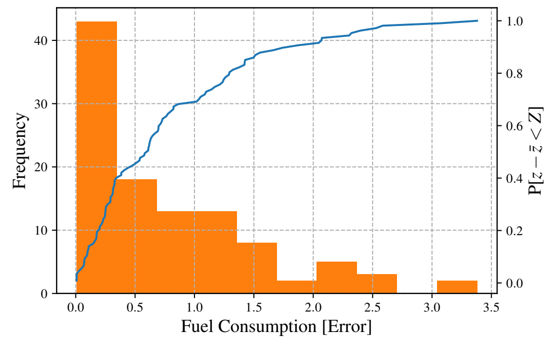


Figure 6: (ECDF) Experimental cumulative density function for the error

the dynamic evolution of state and control input of the system for each vehicle within the platoon.

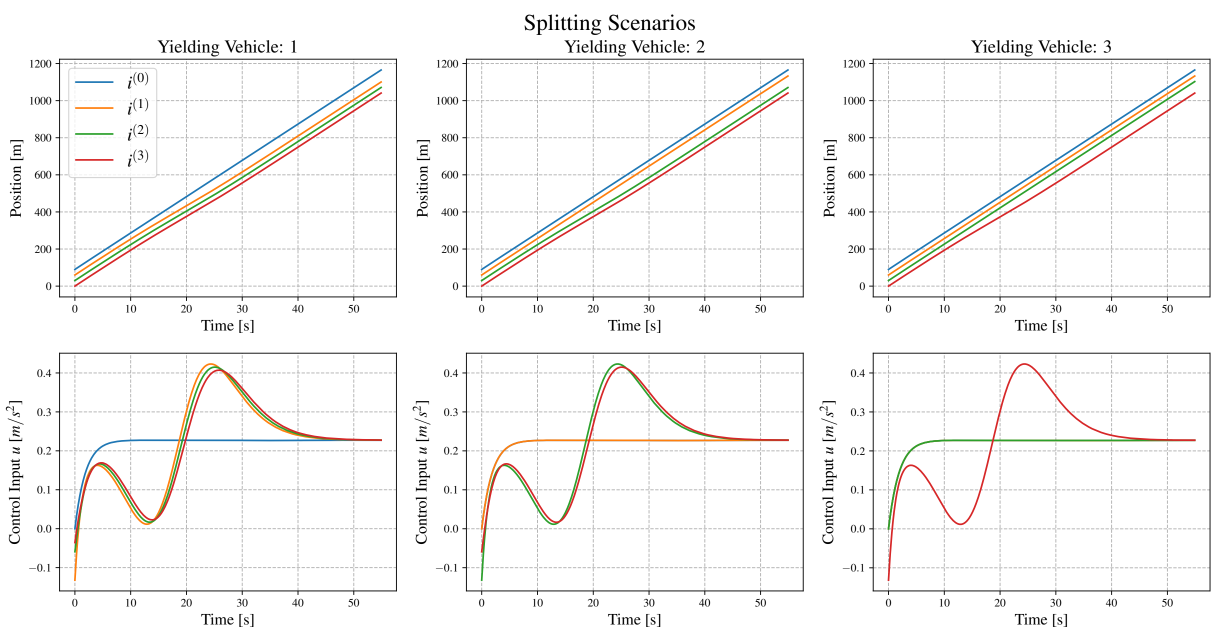


Figure 7: Control scenario

In order to address the assessment on the fuel consumption indicator the fuel consumption of each truck is computed according to eq. (6) based on the parameters $\hat{\boldsymbol{\beta}}$, and the total consumption is then aggregated (see eq. (7)). Since the dynamic conditions create large fluctuations within the fuel consumption index we examine the cumulated fuel consumption given by:

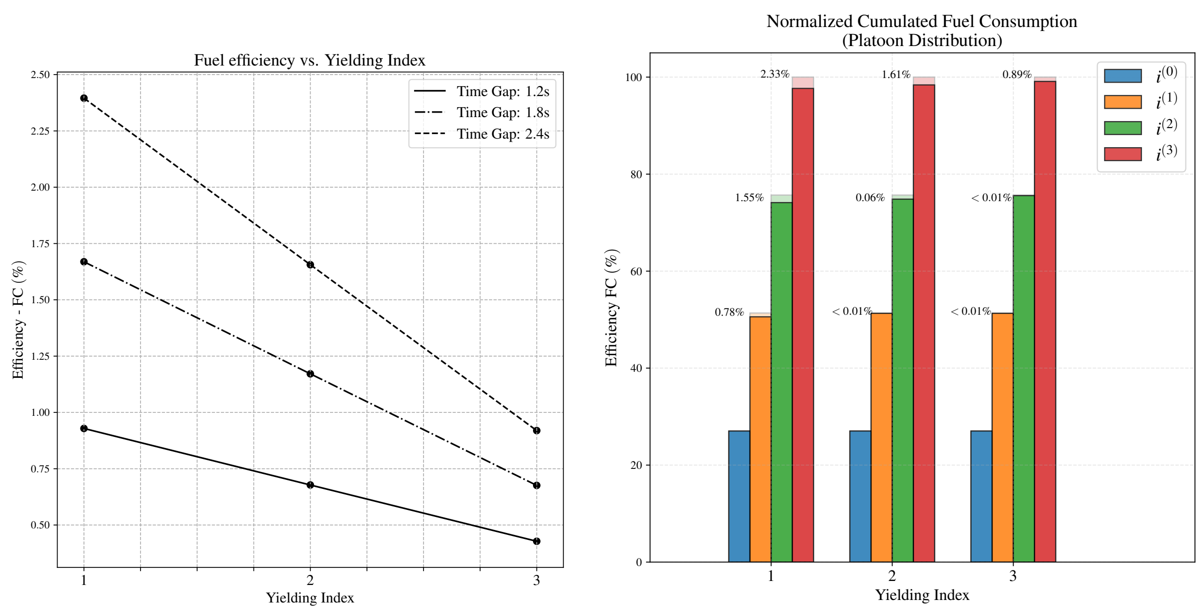
$$\int_0^T F\dot{C}(\tau)d\tau \tag{17}$$

where T corresponds to the simulation time. Let denote the vehicle index $i^{(k)}$ as the position occupied by each one of the trucks in a specific platoon formation, and $y^{(k)}$ yielding index denoting the vehicle which is ordered to decelerate in order to open a determined gap. The direct effect on the global consumption can be observed in Figure 8. In particular, in Figure 8a the cumulated fuel consumption is normalized with respect to the situation where trucks are traveling individually and no platoon is created. In this case the fuel efficiency computed as $100 \cdot (1 - FC_{\text{platoon}}/FC_{\text{not-platoon}})$ represents the benefit gained by the effect of creating a platoon. It can be observed that the efficiency is higher when the vehicle that decelerates is close to the leading vehicle. The situation holds for different time gap policies which represents larger spacing between trucks. This situation can be explained due to the fact that the control is designed to create regulated decelerations that diminish the fuel consumption and more over they are cumulated upstream in space once the truck is ordered to decelerate.

A second aspect important when assessing the platoon is how fuel saving is distributed along a platoon, in particular when multiple providers offer this type or service. In Figure 8b the normalized cumulated fuel consumption distributed is presented along a specific platoon formation. The situation aims to explain how fuel savings are distributed once a platoon is created. Each group of columns represents a percentage of the total cumulated fuel consumption for the platoon. The value is normalized with respect to the situation where no platoon is created (light bars on the background). At first glance, it can be seen the total cumulated fuel consumption is diminished when platoons are created and it is reduced starting from the yielding vehicle which is the first to decelerate. In this case the split situation benefits from the deceleration to save fuel for the yielding truck and all the following ones. The results for multiple gaps are presented in Table 2 where the situation has been examined for different gap openings. As a main observation it can be concluded that the total distribution of the fuel consumption slightly changes with respect to the yielding index, and it presents slow variations $1 \sim 2\%$ for different gap policies.

(%)	**Gap policy:** $1.2s$			**Gap policy:** $1.8s$			**Gap policy:** $2.4s$		
Yielding vehicle i_k	$y^{(1)}$	$y^{(2)}$	$y^{(3)}$	$y^{(1)}$	$y^{(2)}$	$y^{(3)}$	$y^{(1)}$	$y^{(2)}$	$y^{(3)}$
$i^{(0)}$	27.03	27.03	27.03	27.03	27.03	27.03	27.03	27.03	27.03
$i^{(1)}$	51.05	51.29	51.29	50.80	51.29	51.29	50.57	51.29	51.29
$i^{(2)}$	75.07	75.31	75.56	74.59	75.07	75.56	74.11	74.83	75.56
$i^{(3)}$	99.09	99.33	99.58	98.37	98.95	99.34	97.66	98.38	99.10

Table 2: % of Cumulated FC distributed along the platoon normalized with respect to a non platoon situation



(a) Fuel efficency vs Yielding Index

(b) Cumulated FC in ($i^{(k)}$) vs Yielding index

Figure 8: Cumulated fuel consumption for platoon strategies (Aggregated results)

Discussion and perspectives

Benefits of platoon formations can be perceived at simulation level for splitting cases, meaning that splitting maneuvers allow the adaptability of the platoon formation to traffic conditions while preserving fuel consumption with certain degree of degradation.

The proposed framework also paves the way for further research. We have presented an analysis on the fuel consumption for truck-platoon formations based on a hierarchical control strategy where the main objective is to treat the problem of merges under the presence of connected and automated vehicles. Results show that splitting the platoon towards the leader could lead to preserve in great majority the fuel efficiency of the platoon.

Future research interests account for the design of controls strategies that include the fuel consumption as part of their control objective, this integration can be done at different levels. When performed at tactical level the design can be added as part of the decision criteria for the merging time and yielding index of the vehicle. At operational level the problem could can be integrated in the term $\mathscr{L}$ of the control problem which can be enriched with fuel consumption criteria to be minimized. Moreover, for regulated splitting maneuvers, accelerations can be bounded so that the fuel savings are preserved.

The length of the platoon is also a parameter of interest, while the effect of efficiency was here tested in specific length situations, the increment in terms of total vehicles joining a platoon conducts to more significant quantities in terms of fuel-efficiency. Variations of this parameter may lead to better design of coordinating strategies since long platoons may increase the small saving effects shown in Figure 8b.

CONCLUSION

The previous work has presented the evaluation of fuel consumption models upon platoon formations. We have introduced a fuel consumption model with parameters that can be calibrated from real data via a simple multiple regression analysis. The integration of the fuel consumption model to the platoon strategies is adapted considering small perturbations for a model predictive control strategy. The analysis of split maneuvers in order to account for traffic adaptability has been presented, it is expected from platoon strategies to maximize network capacity by modifying spacing policies, nevertheless, the impact on fuel-efficiency may be degraded.

The results of the paper can conduct to some 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. The main difficulty is found that in order to preserve significant savings within the platoon strategy the platoon formation should be maintained for long periods in time and space, more over a small gap policy is required in order to minimize the drag effect. In order to coordinate platoon formations that account for fuel savings we promote the research on supervisory strategies which can include the variable as part of the design.

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