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# Hierarchical multi-injection strategy and platoon manoeuvres at network junctions

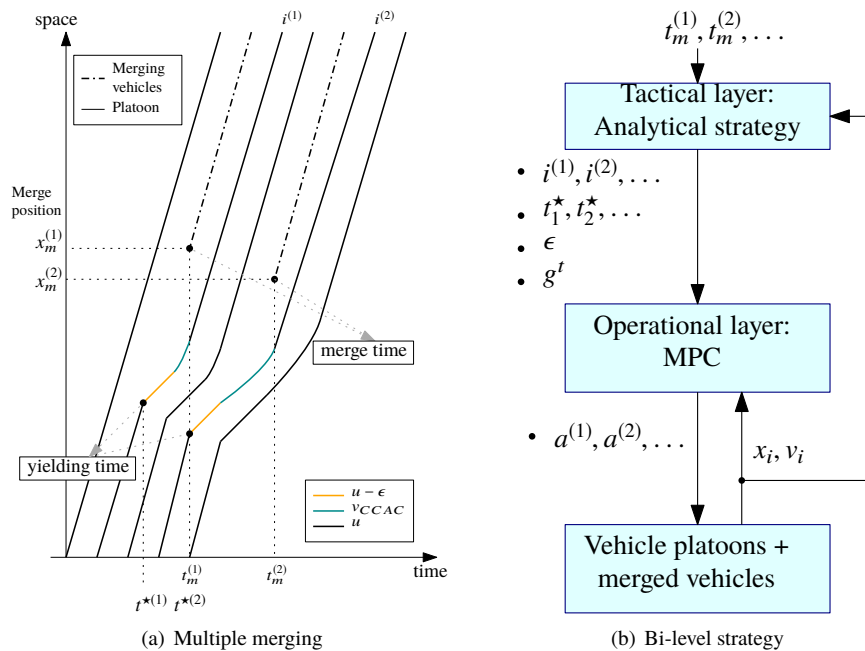
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During the recent years, connected automated vehicles (CAV) have shown to be a crucial technology for the upcoming developments towards the improvement of traffic conditions [2, 8, 9]. Considerable efforts have been concentrated in the development of automated strategies for longitudinal formation, a.k.a. cooperative adaptive cruise control (CACC), where inter-vehicle distance can be shortened, in order to maximize network flow and improve fuel efficiency [1, 10]. Nevertheless, one challenge prevailing in the design of such strategies is their robustness and flexibility to a variety of network configurations and traffic conditions, which implies CAV platoons should allow active platooning manoeuvres such as split, merge, join according to interactions with conventional vehicles in the network.

Despite all efforts on the subject, few concrete strategies have been proposed in order to tackle the interactions between vehicle platoons and traffic. Interaction protocols among CAVs for situations of merges and lane reductions were presented in [5]. 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 [7], 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. More recently, a truck platoon splitting strategy at network discontinuities was proposed in [4], specifically studying the merge of a single vehicle. This work is inspired in the relaxation phenomenon after lane changing described in [6] with the Car Following (CF) model and presents the formulation of the optimal anticipation time that allows the smooth merge of a conventional vehicle in the platoon.



For the design problem at hand, a hierarchical decision-making paradigm is often pursued [3]. One of the main issues when designing these type of strategies is the minimum information that should be transmitted from the tactical/supervisory level towards the operational/control level to perform efficient manoeuvres, particularly, in

situations where merges or lane reductions are present. Under full connectivity assumptions, the proposed solution in this research formulates the multi-merging problem at motorway entrances as a bi-level strategy (See Fig. 1(b)). Assuming anticipated merging times  $t_m^{(1)}, t_m^{(2)}, \dots$  of multiple 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 indices  $i^{(1)}, i^{(2)}, \dots$  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 gap  $g^t$ , and specifying the speed drop  $\epsilon$  it is possible to determine the yielding vehicle  $i^{(1)}$  and the optimal anticipation time  $t^{*(1)}$  to start the yielding manoeuvre. In particular, as shown in [4]:

$$t^{*(1)} = \frac{S^c - (g^t + L/u) \cdot u}{\epsilon} - \frac{\epsilon}{2 \cdot a_{\max}}, \quad (1)$$

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. In this contribution, we extend in an analytical way a procedure to perform multiple mergings. The Fig. 1(a) 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  $i^{(1)}, i^{(2)}, \dots$  in the formation and yielding start times  $t^{*(1)}, t^{*(2)}, \dots$ , 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  $t^{*(j)}$  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  $t^{*(j)} \approx f(t^{*(j-1)})$ .

The tactical decisions of the yielding vehicles index  $i^{(j)}$ , yielding start time  $t^{*(j)}$ , and design parameters of acceptable speed drop  $\epsilon$  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 vehicle 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 entails using 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.

Given the nature of the problem, this model is very likely to be perturbed by stochasticity in parameters such as the leader speed  $u$  and the variables communicated the tactical layer, in particular, the merging times  $t_m^{(j)}$  (and consequently  $t^{*(j)}$ ). Hence, they induce limitations on the full strategy performance. A study of the performance and the model limitations with respect to these conditions is also addressed in this research. The strategy is tested in different flow characterised scenarios as well as various connectivity scenarios an in-house microscopic traffic flow simulator developed by IFSTTAR, performances are assessed regarding safety, comfort and traffic impact.

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