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Real-time planning of platoons coordination decisions based on traffic prediction

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Abstract— **This paper deals with the optimal speed control of two platoons that share part of their freeway routes and need to perform merging and diverging procedures. The proposed control scheme has a centralized nature and is applied periodically by the platoons coordinator which receives in real time the state of the platoons and the traffic measurements on the network, based on which a traffic prediction is made. Based on this information, the coordinator applies specific optimal control algorithms to decide whether the merger is convenient or not and to compute the optimal speed profiles of the two platoons before the merging, during the shared journey and after the diverging phase.**

I. INTRODUCTION

One of the most popular transport mode for freight is represented by road transport, which, thanks to its flexibility allows the realization of door-to-door services. At the same time, road haulage has several drawbacks that can be summarized in pollution, traffic congestion and road safety issues. A possible way to mitigate the negative effects of road freight transport is to incentivize the cooperation among haulers. Cooperation among carriers may take place in several ways. For instance, a possible form of cooperation is known as horizontal cooperation. In these policies, a coalition is formed among carriers who are willing to share their transport demand or a portion of it. In this form of cooperation, monetary compensation policies are defined for carriers who give up a trip in favor of a coalition partner. Hence, the final goal is to optimally plan the trips of the carriers so that unprofitable trips are minimized, and monetary profits are maximized, allowing all carriers to benefit from the cooperation [1].

Another effective way to implement cooperation among carriers is the formation of truck platoons (see [2]). In truck platooning, haulers share part of their route to form a convoy of trucks with the main objective of minimizing fuel consumption by taking advantage of the lower aerodynamic drag of trucks traveling within the platoon. From the methodological point of view, several issues have to be faced to implement truck platooning. Many works in the literature involve the development of automatic control strategies to actuate longitudinal and lateral control of vehicles [3], [4] and to follow the trajectory defined by the leader truck and maintain a predetermined intra-vehicle space [5]. Other papers are devoted to the optimal definition of platoon plans, i.e., the definition of compatible truck trips, platoon routing, meeting points, and so on (see for instance the work in [6]). In fact, coming from different origins, trucks can join together to form a platoon in several ways: during the route [7] or at a certain point in the network (a parking area, gas station, etc.) where one truck, or platoon, can wait for other trucks to join it [8]. The more the platoons are formed in a day, where trucks join each other on the common part of their trip, the higher the rewards and profits are. The idea is to maximize the profit from platooning (fuel savings, cost reduction, less congestion, etc.) while respecting the schedule of the deliveries and not increasing the overtime payments of the drivers. It is worth noting that although the traffic conditions actually encountered during the route strongly influence the possibilities of effectively implementing platooning plans, only a few works in the literature include traffic predictions in defining the planning and control schemes for truck platoons (see, for example, the works in [9], [10]). Other papers, such as [11], define the speed of the trucks that want to form a platoon taking into account that the maximum speed of trucks varies depending on legal restrictions that change along their route. The present work fits into this line of research by proposing a centralized control scheme executed off-board, named platoons coordinator, in which the optimal speeds of platoons that might share a portion of the trip, are defined online based on the expected traffic conditions along their route using the METANET model.

The paper is structured as follows. In Section II, a detailed description of the proposed control scheme is presented. In Section III the traffic-based optimal control problems and the control algorithms applied by the platoon coordinator are given. The application of the proposed control algorithms to a case study is discussed in Section IV. Finally, some concluding remarks are given in Section V.

II. THE CONTROL SCHEME OF THE PLATOONS COORDINATOR

The definition of planning and control schemes for truck platooning has been extensively studied and put into practice through various research projects (see for instance the most recent projects Sweden4Platooning [12] and ENSEMBLE [6]). As part of the latter projects, a scheme of the hierarchical decision-making structure for the formation and control of platoons has been developed. The scheme of this decision structure given in [6], consists of four levels: service, strategic, tactical and operational. The service and strategic levels are the two decision-making levels that produce high-level decisions, which are executed off-board and off-line to define the platoon plans and in particular to coordinate trucks

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that have compatible schedules and missions, defining times, rendezvous points, and speed profiles required to join in a platoon. The tactical and operational levels are performed on-board and on-line and consist of maintaining vehicles cohesion within each platoon and safely executing the maneuvers of trucks entering and exiting from the platoons (tactical level) and longitudinal control of each vehicle so as to meet the acceleration and speed profiles defined at the tactical level (operational level).

This work falls between the strategic and tactical levels by proposing a centralized control scheme executed off-board and on-line that aims to re-plan the coordination decisions taken at the strategic level, considering the influence of traffic conditions predicted in real time. This is a crucial aspect, since traffic conditions can significantly influence the choices defined at a higher planning level, making the off-line decisions no longer convenient or even not feasible. Differently from existing studies, in this work the speed profiles of the platoons are defined online by a *platoons coordinator* that, with a predictive control scheme, periodically makes a prediction of traffic conditions on the routes in which platoons are traveling and determines the convenience or not to meet and the optimal speed they should maintain to respect their schedule. This preliminary work focuses on the coordination of two platoons for which it has been decided, at the strategic level, that they will meet at a specific hub located on the shared part of their routes, while the case of multiple platoons and multiple hubs on the network will be addressed in future works. It is worth noting that considering the influence of traffic conditions in the coordination of platoons is even more important if the platoons that have to meet have different time requirements, thus, we consider the case in which one of the two platoons is constrained to arrive at its final destination within a predefined time window (e.g., the case of a platoon that need to reach in time a seaport gate equipped with truck appointment systems), while the second platoon has more flexibility in reaching its final destination. Therefore, from now on we will call *priority platoon* the platoon which has the main objective of reaching the final destination at a given time, while we will call *non-priority platoon* the one having more flexibility but for which the choice of merging depends on the time when the priority platoon is expected to arrive at the hub.

The proposed control scheme has a centralized nature since the online platoons coordinator knows the schedules and the missions of both platoons and receives in real time the state of platoons and the traffic measurements on the network used to initialize the traffic prediction. Based on this information, the coordinator solves some cascading problems. The first optimal control problem solved by the coordinator determines the optimal speed that allows the priority platoon to arrive at its final destination at the scheduled time. Based on the solution of this optimization problem, the expected arrival time of the priority platoon at the hub is determined and used to solve a second optimal control problem. This second optimal control problem aims to determine whether it is convenient to meet at the hub and, if so, to define the optimal speed the non-priority platoon must maintain to arrive at the hub at the expected arrival time of the priority platoon. If, conversely, the solution of this optimization problem shows that the meeting is not convenient or even impossible, the two platoons proceed disjointly. This means that the platoons coordinator periodically solves, for both the platoons, two optimization problems (as the one solved for the priority platoon) allowing them to reach the final destination at the scheduled time, as shown in Fig. 1. In case the meeting at the hub is convenient, the first optimal control problem is solved periodically (with the goal of minimizing the delay of the priority platoon) from the time in which the two platoons merge until when they diverge to reach their respective final destinations. Then, starting from the time in which the platoons diverge, the first optimal control problem is again solved periodically but disjointly for the two platoons with the objective of meeting their respective schedules.

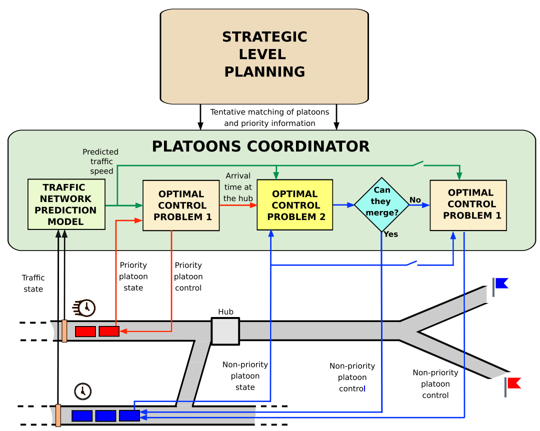


Fig. 1: The proposed control scheme for determining the convenience of the merging between platoons.

III. Traffic-based optimal control problems

This section introduces the traffic-based optimal control problems solved in cascade by the platoons coordinator to define the optimal speed profiles of the priority and non-priority platoons. In the following we will refer to the priority platoon using the superscript P, to the non-priority platoon using the superscript N, while we will use the superscript X to denote a generic platoon that can be either a priority platoon or a non-priority platoon.

A. Traffic prediction model

In order to apply the platoon speed control algorithms proposed in this work, it is necessary to predict traffic conditions on the freeway networks in which the platoons travel. These predictions can be done with dynamic models (see [14] for a detailed review) or data-driven models. As a prerequisite for this work, these models must be able to reproduce the time series of the average traffic speed along the platoon routes. In this work, the model used for predicting traffic conditions is the well-known METANET model, of which, for the sake of brevity, only the main features are given. For further details, the interested reader may refer to [13]. According to this model, a freeway network is represented by an oriented graph consisting of M freeway links, where m with $m = 1, \ldots, M$ represents a generic link, and O origin links, where o with $o = 1, \ldots, O$ represents a generic origin link, connected by nodes. In turn, each freeway link m is subdivided into N_m sections, each of length L_i, where i, with $i = 1, \ldots, N_m$, denotes a generic section of the freeway link m. Since the METANET model is also discrete in time, the dynamic equations of the model are updated at each time step $k \in \mathcal{K}$, where $\mathcal{K}$ is the set of time steps composing the time horizon. The optimal control problems presented below are based on the prediction of the average traffic speed $v_{m,i}^{\text{traffic}}(k)$ performed on the route of each platoon X by applying the METANET model to only the portion of the network that constitutes the path of platoon X, i.e.,: the links m that belong to the set of freeway links $\mathcal{M}^{\mathrm{X}}$, the sections i that belong to the set of sections $\mathcal{I}^{m,\mathrm{X}}$, and the origin links o that belong to the set $\mathcal{O}^{\mathrm{X}}$. Furthermore, each problem is solved on the time horizon $\mathcal{K}^{\mathrm{X}}$ associated with the platoon X.

B. Optimal control problem to reach the final destination

This optimal control problem allows to define the optimal speed of a platoon that aims to reach the final destination of its journey while limiting delays from its scheduled arrival time. Let us consider a generic platoon X whose final destination has a distance Π^{X} from its initial position, expressed in [km], and must be reached at time step $K^{\mathrm{fin,X}}$.

For platoon X the state variable is the position $p^{\mathrm{X}}(k)$, in [km], defined as the distance from the initial position of the platoon, while the control variable is the speed that is denoted with $v^{\mathrm{X}}(k)$ in [km/h]. Some auxiliary variables are needed in order to compute the position of the platoon in the network used for the traffic prediction and to have linear constraints. To this end we denote with $p_{m,i}$ the position in [km] of the beginning of section $i \in \mathcal{I}^{m,\mathrm{X}}$ of link $m \in \mathcal{M}^{\mathrm{X}}$, then the auxiliary variables are defined as follows: $y_{m,i}^{\mathrm{X}}(k) \in \{0,1\}$ is equal to 1 if $p^{\mathrm{X}}(k) \geq p_{m,i}$, i.e. if platoon X is after the beginning of section i of link m at time step k, 0 otherwise; $w_{m,i}^{\mathrm{X}}(k) \in \{0,1\}$ is equal to 1 if $p^{\mathrm{X}}(k) \leq p_{m,i+1}$, i.e. if platoon X is before the beginning of section $i+1$ of link m at time step k, 0 otherwise; $\lambda_{m,i}^{\mathrm{X}}(k) \in \{0,1\}$ is introduced to represent the product $y_{m,i}^{\mathrm{X}}(k) \cdot w_{m,i}^{\mathrm{X}}(k)$, therefore $\lambda_{m,i}^{\mathrm{X}}(k)$ is equal to 1 if platoon X is in section i of link m at time step k (i.e. if $y_{m,i}^{\mathrm{X}}(k) = w_{m,i}^{\mathrm{X}}(k) = 1$), 0 otherwise.

The optimal control problem to reach the final destination of a platoon X, which can be a priority platoon, with $\mathrm{X} = \mathrm{P}$, or a non-priority platoon, with $\mathrm{X} = \mathrm{N}$, can be stated with the following mixed-integer linear quadratic formulation.

Problem 1:

$$\min \quad \alpha_1 \Big(\Pi^{\mathrm{X}} - p^{\mathrm{X}}(K^{\mathrm{fin,X}}) \Big)^2 + \alpha_2 \sum_{k \in \mathcal{K}^{\mathrm{X}}} \Big(v^{\mathrm{X}}(k+1) - v^{\mathrm{X}}(k) \Big)^2 \tag{1}$$

subject to:

$$p^{\mathrm{X}}(k+1) = p^{\mathrm{X}}(k) + v^{\mathrm{X}}(k) T \qquad k \in \mathcal{K}^{\mathrm{X}} \tag{2}$$

$$p^{\mathrm{X}}(k) - p_{m,i} + M\big(1 - y_{m,i}^{\mathrm{X}}(k)\big) \geq \epsilon \qquad i \in \mathcal{I}^{m,\mathrm{X}},\, m \in \mathcal{M}^{\mathrm{X}},\, k \in \mathcal{K}^{\mathrm{X}} \tag{3}$$

$$p_{m,i} - p^{\mathrm{X}}(k) + M y_{m,i}^{\mathrm{X}}(k) \geq 0 \qquad i \in \mathcal{I}^{m,\mathrm{X}},\, m \in \mathcal{M}^{\mathrm{X}},\, k \in \mathcal{K}^{\mathrm{X}} \tag{4}$$

$$p_{m,i+1} - p^{\mathrm{X}}(k) + M\big(1 - w_{m,i}^{\mathrm{X}}(k)\big) \geq 0 \qquad i \in \mathcal{I}^{m,\mathrm{X}},\, m \in \mathcal{M}^{\mathrm{X}},\, k \in \mathcal{K}^{\mathrm{X}} \tag{5}$$

$$p^{\mathrm{X}}(k) - p_{m,i+1} + M w_{m,i}^{\mathrm{X}}(k) \geq \epsilon \qquad i \in \mathcal{I}^{m,\mathrm{X}},\, m \in \mathcal{M}^{\mathrm{X}},\, k \in \mathcal{K}^{\mathrm{X}} \tag{6}$$

$$\lambda_{m,i}^{\mathrm{X}}(k) \leq y_{m,i}^{\mathrm{X}}(k) \qquad i \in \mathcal{I}^{m,\mathrm{X}},\, m \in \mathcal{M}^{\mathrm{X}},\, k \in \mathcal{K}^{\mathrm{X}} \tag{7}$$

$$\lambda_{m,i}^{\mathrm{X}}(k) \leq w_{m,i}^{\mathrm{X}}(k) \qquad i \in \mathcal{I}^{m,\mathrm{X}},\, m \in \mathcal{M}^{\mathrm{X}},\, k \in \mathcal{K}^{\mathrm{X}} \tag{8}$$

$$\lambda_{m,i}^{\mathrm{X}}(k) \geq y_{m,i}^{\mathrm{X}}(k) + w_{m,i}^{\mathrm{X}}(k) - 1 \qquad i \in \mathcal{I}^{m,\mathrm{X}},\, m \in \mathcal{M}^{\mathrm{X}},\, k \in \mathcal{K}^{\mathrm{X}} \tag{9}$$

$$v^{\mathrm{X}}(k) \geq \sum_{m \in \mathcal{M}^{\mathrm{X}}} \sum_{i \in \mathcal{I}^{m,\mathrm{X}}} \lambda_{m,i}^{\mathrm{X}}(k) v_{m,i}^{\mathrm{min,X}}(k) \qquad k \in \mathcal{K}^{\mathrm{X}} \tag{10}$$

$$v^{\mathrm{X}}(k) \leq \sum_{m \in \mathcal{M}^{\mathrm{X}}} \sum_{i \in \mathcal{I}^{m,\mathrm{X}}} \lambda_{m,i}^{\mathrm{X}}(k) v_{m,i}^{\mathrm{max,X}}(k) \qquad k \in \mathcal{K}^{\mathrm{X}} \tag{11}$$

where ϵ is a small quantity arbitrarily chosen and M is a large quantity arbitrarily chosen.

In the objective function of Problem 1, the first term, weighted with α_1, penalizes the quadratic difference between the actual position of the platoon $p^{\mathrm{X}}(K^{\mathrm{fin,X}})$ at the final time step and its expected final position Π^{X}. The second cost term, weighted with α_2, allows to limit the oscillations of the speed between two consecutive time steps. Constraints (2) are the state equations for the platoon and compute the covered distance on the basis of its speed. Constraints (3)-(9) are introduced to correctly define the position of the platoon along the freeway network. Specifically, according with the state variable $p^{\mathrm{X}}(k)$, constraints (3)-(4) allow to define the binary variables $y_{m,i}^{\mathrm{X}}(k)$, (5)-(6) allow to define the binary variables $w_{m,i}^{\mathrm{X}}(k)$, while constraints (7)-(9) define $\lambda_{m,i}^{\mathrm{X}}(k)$ on the basis of $y_{m,i}^{\mathrm{X}}(k)$ and $w_{m,i}^{\mathrm{X}}(k)$. Constraints (10)-(11) impose lower and upper bounds for the speeds. More in detail, (10) impose that the speed of the platoon has to be greater than the platoon minimum speed $v_{m,i}^{\mathrm{min,X}}(k)$ defined as $v_{m,i}^{\mathrm{min,X}}(k) = \min\{v^{\mathrm{min,X}}, v_{m,i}^{\text{traffic}}(k)\}$. Constraints (11) impose that the speed of the platoon cannot exceed the maximum speed $v_{m,i}^{\mathrm{max,X}}(k)$ defined as $v_{m,i}^{\mathrm{max,X}}(k) = \min\{v^{\mathrm{max,X}}, v_{m,i}^{\text{traffic}}(k)\}$.

C. Optimal control problem to reach the hub

This optimal control problem allows to define the speed of a non-priority platoon that wants to join the priority platoon in a predefined hub position π^{hub} at the time step $\tilde{k}^{\text{P}}$ defined by taking into account the position of the priority platoon in the optimal solution of Problem 1. The hub position is defined with respect to the original position of the non-priority platoon N and is expressed in [km]. The decision of the non-priority platoon to join or not the priority platoon depends whether it can arrive at the meeting point on time or not. In particular, the decision of not merging can occur under two circumstances: first, the non-priority platoon arrives too late (e.g., the non-priority platoon finds congestion along its route); second, the non-priority platoon arrives too early and the waiting time at the meeting point is not compensated by the benefit obtainable from platooning (e.g., the priority platoon finds congestion on its route and the resulting expected arrival time at meeting point is not convenient for the non-priority platoon). Analogously to Problem 1, the state variable is represented by the position of the non-priority platoon $p^{\text{N}}(k)$ and the control variable is the speed of the platoon $v^{\text{N}}(k)$. In order to formalize the optimal control problem, an auxiliary binary variable must be added expressing whether or not the non-priority platoon joins the priority platoon: $z^{\text{N}} \in \{0, 1\}$ is equal to 1 if the merging occurs and equal to 0 if it does not occur. Furthermore, let us denote with B the profit [€] that the non-priority platoon can obtain by joining the priority platoon, and with W the unit waiting cost for the non-priority platoon if it arrives early at the meeting point [€/km]. Thus, the objective of this optimal control problem is to define the speed of the non-priority platoon so as to maximize the profit achievable by traveling with the priority platoon, taking into account the cost due to waiting at the meeting point, i.e.

$$\max \quad Bz^{\text{N}} - W\left(p^{\text{N}}(\tilde{k}^{\text{P}}) - \pi^{\text{hub}}\right) \cdot z^{\text{N}} \tag{12}$$

The objective function (12) has a nonlinear form, then the auxiliary variable Γ^{N} is introduced in order to formulate a mixed-integer linear problem. Specifically, this variable is included to express the product $p^{\text{N}}(\tilde{k}^{\text{P}}) \cdot z^{\text{N}}$ and is defined as follows

$$\Gamma^{\text{N}} = \begin{cases} p^{\text{N}}(\tilde{k}^{\text{P}}) & \text{if } z^{\text{N}} = 1 \\ 0 & \text{if } z^{\text{N}} = 0 \end{cases} \tag{13}$$

Hence, using the auxiliary variable Γ^{N}, the optimal control problem can be stated with the following mixed-integer linear formulation.

Problem 2:

$$\max \quad Bz^{\text{N}} - W\left(\Gamma^{\text{N}} - z^{\text{N}}\pi^{\text{hub}}\right) \tag{14}$$

subject to constraints (2)-(11), with $\text{X} = \text{N}$, and to:

$$p^{\text{N}}(\tilde{k}^{\text{P}}) - \pi^{\text{hub}} + \sigma \geq -L^{\max} + (L^{\max} + \delta)z^{\text{N}} \tag{15}$$

$$\Gamma^{\text{N}} \leq L^{\max} z^{\text{N}} \tag{16}$$

$$\Gamma^{\text{N}} \geq 0 \tag{17}$$

$$\Gamma^{\text{N}} \leq p^{\text{N}}(\tilde{k}^{\text{P}}) \tag{18}$$

$$\Gamma^{\text{N}} \geq p^{\text{N}}(\tilde{k}^{\text{P}}) - L^{\max}(1 - z^{\text{N}}) \tag{19}$$

$$-\overline{\Delta V} \leq v^{\text{N}}(k+1) - v^{\text{N}}(k) \leq \overline{\Delta V} \quad k \in \mathcal{K}^{\text{N}} \setminus \{K^{\text{N}} - 1\} \tag{20}$$

where σ and δ are small quantities.

The first term of the objective function of Problem 2 refers to the profit obtainable by traveling in platoon, while the second term determines the waiting cost at the hub. Constraints (15) allow the decision variable z^{N} to be appropriately defined. Specifically, the constraint is defined so that if $p^{\text{N}}(\tilde{k}^{\text{P}}) - \pi^{\text{hub}} \geq 0$ (the non-priority platoon is early or on time), the decision variable z^{N} can take either value 0 or value 1 in accordance with the goal of maximizing (14). If $p^{\text{N}}(\tilde{k}^{\text{P}}) - \pi^{\text{hub}} < 0$ (the non-priority platoon is late), then the decision variable can only be $z^{\text{N}} = 0$. In (15) σ is a tolerance on position and is defined such that $\sigma > \delta$, while $L^{\max}$, in [km], is the maximum path length that the non-priority platoon can travel. Constraints (16)-(19) are included to impose the relation defined in (13). Constraints (20) allow to avoid undesired fluctuations of speed imposing that the speed variation between one time step and the next one cannot exceed $\overline{\Delta V}$ [km/h]. Note that K^{N} is fixed as $K^{\text{N}} = \tilde{k}^{\text{P}} + \varpi$, with ϖ being a given tolerance.

D. Control algorithms of the platoons coordinator

The traffic prediction model and the optimal control problems described above are periodically run by the platoons coordinator. In particular, let us assume that they are run at each time step $\bar{k} = nS$, where $n = 0, 1, 2, \ldots$ and S is an integer representing the number of time steps between one run and the next one. The considered time horizon for Problem 1 starts from the actual time $\bar{k}$ and goes until the expected arrival time at destination, which is in general different for the two platoons since it depends on the time required to cover their routes, and is given by $K^{\text{fin,P}}$ and $K^{\text{fin,N}}$ respectively. Let $K = \max\{K^{\text{fin,P}}, K^{\text{fin,N}}\}$. As for Problem 2, instead, the time horizon starts in $\bar{k}$ and goes to $\tilde{k}^{\text{P}} + \varpi$. In particular, three different control schemes are applied according to the decision of merging or not. More precisely, Control Algorithm 1 is applied by the platoons coordinator at a generic time step $\bar{k}$ if the merging decision is still valid and up to $\tilde{k}^{\text{P}}$. If the merge is executed, i.e., $z^{\text{N}} = 1$, the Control Algorithm 2 is applied to find the optimal speed of the new platoon formed at the hub, which for simplicity of notation is still called priority platoon, that has the goal of reaching the final destination at $K^{\text{fin,P}}$. Control Algorithm 2 is applied periodically until the platoons diverge to reach their respective final destinations or until the end of the considered horizon if the two platoons have the same destination. Control Algorithm 3 is instead applied periodically, until the end of the time horizon, after the platoons diverge or if, by applying Control Algorithm 1, it results that the merging phase is not convenient or impossible, i.e., $z^{\text{N}} = 0$.

Control Algorithm 1: Control algorithm applied by the platoons coordinator before the platoon merging

1 Measure the traffic state $v_{m,i}^{\text{traffic}}(\bar{k})$ on each platoon X path, $m \in \mathcal{M}^{\text{X}}$, $i \in \mathcal{I}^{m,\text{X}}$, $o \in \mathcal{O}^{\text{X}}$ - Go to Step 2
2 Run the traffic prediction model with $\mathcal{K} = \{\bar{k}, \dots, K\}$ - Go to Step 3
3 Measure the priority platoon state $p^{\text{P}}(\bar{k})$ - Go to Step 4
4 Solve Problem 1 with $\text{X} = \text{P}$ and $\mathcal{K}^{\text{P}} = \{\bar{k}, \dots, K^{\text{fin,P}}\}$, and compute $\tilde{k}^{\text{P}}$ - Go to Step 5
5 Actuate the optimal speed profile of the priority platoon $v^{\text{P}}(k)$, $\bar{k} \le k \le \bar{k} + S - 1$ - Go to Step 6
6 Measure the non-priority platoon state $p^{\text{N}}(\bar{k})$ - Go to Step 7
7 Solve Problem 2 with $\text{X} = \text{N}$ and $\mathcal{K}^{\text{N}} = \{\bar{k}, \dots, \tilde{k}^{\text{P}} + \varpi\}$, with $\tilde{k}^{\text{P}}$ obtained in Step 4 - Go to Step 8
8 Check the value of z^{N}. If $z^{\text{N}} = 1$, go to Step 9, otherwise go to Step 10
9 Actuate the optimal speed profile of the non-priority platoon $v^{\text{N}}(k)$, $\bar{k} \le k \le \bar{k} + S - 1$
10 Communicate to the platoons the decision of not merging - Go to Step 11
11 Solve Problem 1 with $\text{X} = \text{N}$ and $\mathcal{K}^{\text{N}} = \{\bar{k}, \dots, K^{\text{fin,N}}\}$ - Go to step 12
12 Actuate the optimal speed profile of the non-priority platoon $v^{\text{N}}(k)$, $\bar{k} \le k \le \bar{k} + S - 1$ - Go to step 13
13 Apply Control Algorithm 1 from now on

IV. Case study and results

In order to test the proposed control scheme, two scenarios considering the possible pairing of two platoons have been taken into account. Specifically, we have applied the control algorithms to two couples of platoons traveling in a freeway network shown in Fig. 2 in which the hub where the meeting may occur is located at the beginning of the first section of link m7 (yellow square in Fig. 2). In this case study we have assumed that the discretization time interval is equal to 10 seconds, while the number of time steps between two executions of the optimal control problems S has been set to 6, implying a recalculation of the control actions every minute. Furthermore, for each platoon, we have assumed that the maximum speed is $v^{\text{max,X}}$=75 [km/h], while the minimum speed is $v^{\text{min,X}}$ = 50 [km/h]. Concerning *Scenario 1*, the priority platoon starts its journey at $k = 0$ from link o1 and must arrive at destination D at $K^{\text{fin,P}}$ = 95, covering the distance Π^{P} = 15.4 [km]. The non-priority platoon starts its journey at $k = 0$, but entering from link o2 and must reach destination D at $K^{\text{fin,N}}$ = 100, which makes its route length Π^{N} = 14 [km]. For this case, the platoons coordinator, based on the traffic prediction on the freeway (see for instance in Fig. 3 the traffic speed predicted in one run of the Control Algorithm 1), determines that the platoons

Control Algorithm 2: Control algorithm applied by the platoons coordinator after the merging and until the platoons diverge

1 Measure the traffic state $v_{m,i}^{\text{traffic}}(\bar{k})$ on platoon P path, $m \in \mathcal{M}^{\text{P}}$, $i \in \mathcal{I}^{m,\text{P}}$, $o \in \mathcal{O}^{\text{P}}$ - Go to Step 2
2 Run the traffic prediction model with $\mathcal{K}^{\text{P}} = \{\bar{k}, \dots, K^{\text{fin,P}}\}$ - Go to Step 3
3 Measure the priority platoon state $p^{\text{P}}(\bar{k})$ - Go to Step 4
4 Solve Problem 1 with $\text{X} = \text{P}$ and $\mathcal{K}^{\text{P}} = \{\bar{k}, \dots, K^{\text{fin,P}}\}$ - Go to Step 5
5 Actuate the optimal speed profile of the priority platoon $v^{\text{P}}(k)$, $\bar{k} \le k \le \bar{k} + S - 1$

Control Algorithm 3: Control algorithm applied by the platoons coordinator if the merging decision is not valid or after the platoons diverge

1 Measure the traffic state $v_{m,i}^{\text{traffic}}(\bar{k})$ on each platoon X path, $m \in \mathcal{M}^{\text{X}}$, $i \in \mathcal{I}^{m,\text{X}}$, $o \in \mathcal{O}^{\text{X}}$ - Go to Step 2
2 Run the traffic prediction model with $\mathcal{K}^{\text{X}} = \{\bar{k}, \dots, K^{\text{fin,X}}\}$ - Go to Step 3
3 Measure the priority platoon state $p^{\text{P}}(\bar{k})$ - Go to Step 4
4 Solve Problem 1 with $\text{X} = \text{P}$ and $\mathcal{K}^{\text{P}} = \{\bar{k}, \dots, K^{\text{fin,P}}\}$ - Go to Step 5
5 Actuate the optimal speed profile of the priority platoon $v^{\text{P}}(k)$, $\bar{k} \le k \le \bar{k} + S - 1$ - Go to Step 6
6 Measure the non-priority platoon state $p^{\text{N}}(\bar{k})$ - Go to Step 7
7 Solve Problem 1 with $\text{X} = \text{N}$ and $\mathcal{K}^{\text{N}} = \{\bar{k}, \dots, K^{\text{fin,N}}\}$ - Go to step 8
8 Actuate the optimal speed profile of the non-priority platoon $v^{\text{N}}(k)$, $\bar{k} \le k \le \bar{k} + S - 1$

merging is convenient. The meeting takes place at time step $\tilde{k}^{\text{P}}$ = 52, and the speed profiles to be implemented by the priority platoon and the non-priority platoon to perform the rendezvous at the hub are shown in Figs. 4a and 4b, respectively, while Fig. 4c depicts the speed profile of the new platoon created at the hub to reach the final destination by applying Control Algorithm 2.

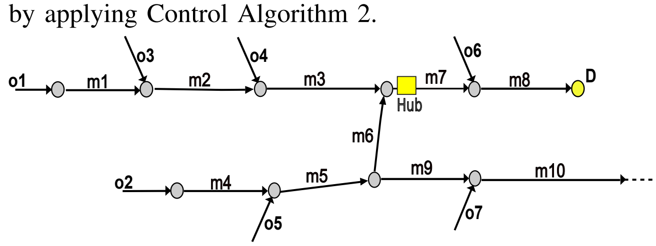


Fig. 2: The considered freeway network.

In *Scenario 2* the pair of platoons covers the same routes of the couple of platoons of *Scenario 1* but in different time frames. Specifically, the priority platoon begins its journey at k = 300 and must reach the destination D at $K^{\text{fin,P}}$ =

395, while the non-priority platoon starts its journey at k = 320 and should reach destination D at $K^{\text{fin,N}}$ = 420. The platoons coordinator predicts congestion on the path of the priority platoon, which makes the meeting with the non-priority platoon at the hub impossible. Therefore, the platoons coordinator optimizes the speed of each platoon disjointly according to Control Algorithm 3, and the resulting speed profiles for each platoon are displayed in Fig. 5.

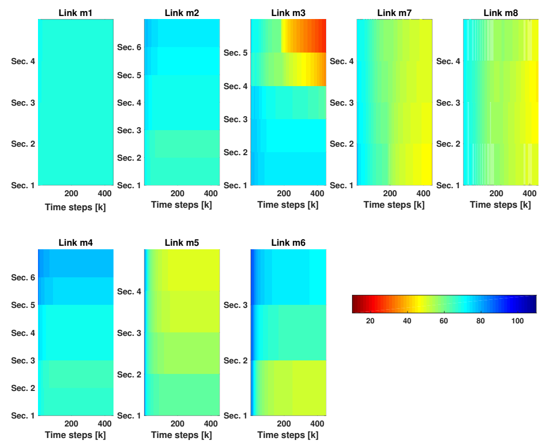
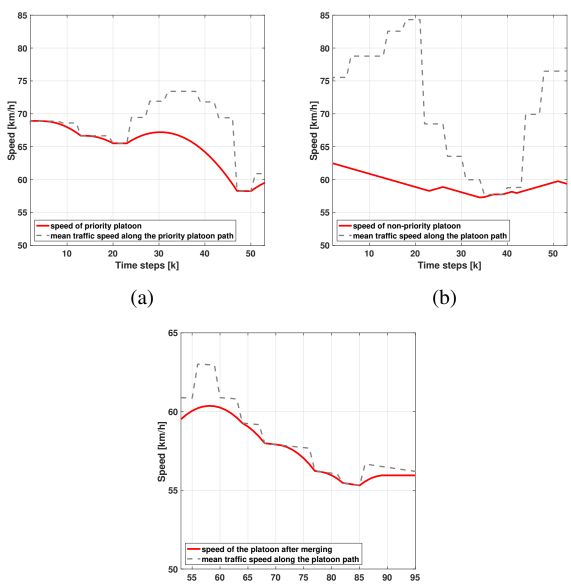


Fig. 3: Predicted traffic speed.



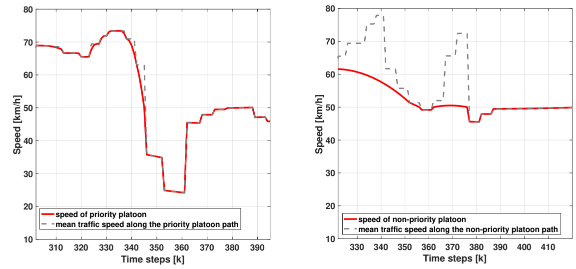
(a) (b)

(c)

Fig. 4: Speed of the priority platoon (4a) and the non-priority platoon (4b) before the merging , speed of the new platoon after the merging (4c) in *Scenario 1*.

V. Conclusion

In this paper, a traffic-based platoons coordinator has been proposed for real-time re-planning of platoons plans defined at a strategic level. The proposed control scheme consists of a centralized controller which optimizes the speeds of the platoons before the merging, during the shared journey and after the diverging phase, based on predictions of traffic conditions on the routes traveled by the platoons. In addition, the platoons coordinator also allows the determination of whether or not it is convenient for the platoons to merge into a single platoon and share part of their route.



(a) (b)

Fig. 5: Speed of the priority platoon (5a) and the non-priority platoon (5b) to reach their final destinations in *Scenario 2*.

References

[1] C. Caballini, S. Sacone, M. Saeednia. Cooperation among truck carriers in seaport containerized transportation. In *Transportation Research Part E*, 93, pp 38–56, 2016.
[2] A. K. Bhoopalam, N. Agatz, R. Zuidwijk. Planning of truck platoons: A literature review and directions for future research. In *Transportation research part B*, 107, pp. 212–228, 2018.
[3] A. Coppola, D. G. Lui, A. Petrillo, S. Santini, Eco-Driving Control Architecture for Platoons of Uncertain Heterogeneous Nonlinear Connected Autonomous Electric Vehicles. In *IEEE Transactions on Intelligent Transportation Systems*, 23:12, pp. 24220–24234, 2022.
[4] B. Caiazzo, D. G. Lui, A. Petrillo, S. Santini, Distributed Double-Layer Control for Coordination of Multiplatoons Approaching Road Restriction in the Presence of IoV Communication Delays. In *IEEE Internet of Things Journal*, 9:6, pp. 4090–4109, 2022.
[5] B. Besselink, K. H. Johansson. String Stability and a Delay-Based Spacing Policy for Vehicle Platoons Subject to Disturbances. In *IEEE Transactions on Automatic Control*, 62:9, pp. 4376–4391, 2017.
[6] A. Johansson, T. Bai, K. H. Johansson, J. Mårtensson. Platoon Cooperation Across Carriers: From System Architecture to Coordination. In *IEEE Intelligent Transportation Systems Magazine*, pp. 132–144, 2022.
[7] S. van de Hoef, K. H. Johansson, D. V. Dimarogonas. Fuel-efficient en route formation of truck platoons. In *IEEE Transactions on Intelligent Transportation Systems* 19, pp. 102–112, 2018.
[8] A. Johansson, E. Nekouei, K. H. Johansson, J. Mårtensson. Strategic hub-based platoon coordination under uncertain travel times. In *IEEE Transactions on Intelligent Transportation Systems*, 23:7, pp. 8277–8287, 2021.
[9] S. Sacone, C Pasquale, S. Siri, A. Ferrara. Centralized and Decentralized Schemes for Platoon Control in Freeway Traffic Systems. In *Proc. of the 60th IEEE Conference on Decision and Control*, pp. 2665–2670, 2021.
[10] M. Čičić, C. Pasquale, S. Siri, S. Sacone, K. H. Johansson. Platoon-actuated variable area mainstream traffic control for bottleneck decongestion. In *European Journal of Control*, 68, 100687, 2022.
[11] S. van de Hoef, J. Mårtensson, D. V. Dimarogonas K. H. Johansson. A predictive framework for dynamic heavy-duty vehicle platoon coordination. In *ACM Transactions on Cyber-Physical Systems*, 4:1, pp. 1–25, 2019.
[12] J. Axelsson, T. Bergh, A. Johansson, B. Mårdberg, P. Svenson, V. Åkesson. Truck platooning business case analysis. Sweden4Platooning, Public Report, 2020.
[13] A. Kotsialos, M. Papageorgiou, C. Diakaki, Y. Pavlis, F. Middelham. Traffic flow modeling of large-scale motorway networks using the macroscopic modeling tool METANET. In *IEEE Transactions on Intelligent Transportation Systems*, 3: 282–292, 2002.
[14] S. Siri, C. Pasquale, S. Sacone, A. Ferrara. Freeway traffic control: a survey. In *Automatica*, 130, 109655, 2021.