Model predictive control for multi-lane motorways in presence of VACS*

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Abstract— **A widespread use of vehicle automation and communication systems (VACS) is expected in the next years. This may lead to improvements in traffic management because of the augmented possibilities of using VACS both as sensors and as actuators. To achieve this, appropriate studies, developing potential control strategies to exploit the VACS availability, are essential. This paper describes a model predictive control framework that can be used for the integrated and coordinated control of a motorway system, considering that vehicles are equipped with specific VACS. Microscopic simulation testing demonstrates the effectiveness and the computational feasibility of the proposed approach.**

I. INTRODUCTION

The problem of traffic congestion has a strong economical and social impact in and around densely inhabited areas. One possible solution is the construction of bigger road infrastructures, with an enormous economical cost and significant environmental consequences. On the other hand, it is a known fact that the currently existing motorways are actually underutilised, especially in the period of high demand. A possible way to overcome this situation is the development and implementation of proper traffic control measures with the aim of reducing traffic congestion and increasing the overall capacity of traffic networks.

In the last two decades, a significant and increasing interdisciplinary effort by the automotive industry, as well as by numerous research institutions around the world, has been devoted to the planning, developing, testing and deploying a variety of Vehicle Automation and Communication Systems (VACS) that are expected to revolutionise the features and capabilities of individual vehicles within the next decades. Among the wide range of proposed VACS, only few have a direct impact on traffic flow, since the majority aims at improving safety or driver convenience. Some VACS, thus, may be exploited to interfere with the driving behaviour recommending, supporting, or even executing traffic control actions. This gives the possibility of having access to control actions that are not available with conventionally driven cars (e.g., individual vehicle speed or lane-change advices). On the other hand, the uncertainty in the future development of VACS makes a necessary requisite to design control strategies that are robust with respect to the possible types of VACS, as well as to their penetration rate.

The use of intelligent devices for traffic management has been considered in the Automated Highway System (AHS) [1], where it was assumed that platoons of fully automated vehicles may travel in specifically designed motorways. This very complex system was suggested to be controlled via a multi-layer control structure, where the traffic flow control strategies are included in a decentralised link-layer; one of the first works addressing link-layer control strategies was [2]. More recently, in [3], a model predictive control (MPC) approach was proposed for the integrated control (addressing speed, lane assignment and ramp metering) of platoon-based AHS, that involves both real-valued and integer variables leading to a mixed non-convex optimisation problem that may be difficult to be solved in real-time. A number of other works addressed specifically the problem of deciding on efficient vehicle lane-paths for a motorway under fully automated (AHS) or semi-automated driving (e.g. [4], [5], and [6]); however, to tackle the problem complexity, a number of simplifying assumptions were typically made, such as known and constant prevailing speeds along the highway and absence of traffic congestion, thanks to the assumed (but not addressed) operation of ramp metering (RM) at the highway entrances; also, a number of structural assumptions were made to limit the (otherwise vast) space of potential path assignments.

On the other hand, the coordinated and integrated exploitation of conventional traffic control actuators, such as roadside traffic signals and variable message signs (VMS) for route guidance, variable speed limits (VSL), and RM, has been proposed in several papers. In [7], the authors defined an optimal control problem based on the non-linear second-order model METANET [8], presenting also a feasible-direction algorithm for computing its solution. This approach takes into account, as decision variables, the metered ramp inflow and the splitting rates at bifurcations. Extensions of this tool were proposed in [9], where a hierarchical MPC approach considering the use of RM is described, and in [10], where the exploited control actions are RM together with VSL. In [11], the authors took into account the optimal coordination of VSL and RM in a motorway traffic network, aiming at minimising the total time spent. Again, the utilised traffic model is METANET, and a predictive coordinated control approach is defined, showing the interplay and synergy between RM and mainstream metering under certain conditions. Nevertheless, the intrinsic complexity of all these approaches may be an impediment for real-time application

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while also considering additional options and features offered by emerging VACS. Additional difficulties may appear due to the non-convex nature of the related optimal control problem.

The purpose of this paper is the development of a control framework based on an MPC scheme for the coordinated and integrated motorway traffic management, taking into account the possibility of using VACS both as sensors and as actuators, with the advantages of having an increased degree of freedom with respect to the control possibilities, as well as a more precise estimation of the motorway state. The core of the methodology is the convex optimisation problem proposed in [12], that is based on the piecewise linear macroscopic traffic flow model [13], which already considers, as decision variables, actions that are enabled with the aid of VACS. Since the application of this methodology in a real motorway will not be possible for several years to come, because of the necessary amount of vehicles equipped with the necessary devices, the only opportunity to test the proposed control strategy is by use of an appropriate microscopic traffic simulator; this latter aspect is widely considered in this paper.

The paper is structured as follows: Section II describes the proposed control framework. In Section III, the microscopic simulation environment is described, while in Section IV the obtained simulation results are shown, comparing them with a reference no-control case. Section V concludes the paper, highlighting the main results and introducing some challenging research tasks for the future.

II. CONTROL FRAMEWORK

A. The control structure

Motorway traffic flow, like most other processes, is affected by several factors, and any related mathematical model has necessarily a limited accuracy. On the other hand, the employed models must be simple enough to allow for computational tractability of the related optimal control problem. For these reasons, the use of an open-loop control strategy (whereby the control trajectories are computed at the initial instant, without being updated during the process) may lead to increasingly diverging process behaviour, compared with the predicted one, due to inaccuracies in predicting the external disturbances (mainly the demands) or model mismatches. A mitigation of these issues is offered by the utilisation of a receding horizon (or MPC) scheme, that entails that the control actions are re-computed periodically, using updated measurements and predictions [14]. This permits to maintain the difference between the model predictions and the real process outcome at low levels, thus improving the overall control performance. The proposed control framework, composed by three layers, is schematised in Fig. 1. In the following sections, each layer is described in more detail.

B. The adaptation and prediction layer

The purpose of this layer is essentially to process the data retrieved from the motorway system in order to obtain necessary information to be used by the lower layers, mainly as estimation of the current traffic state and prediction of future demands.

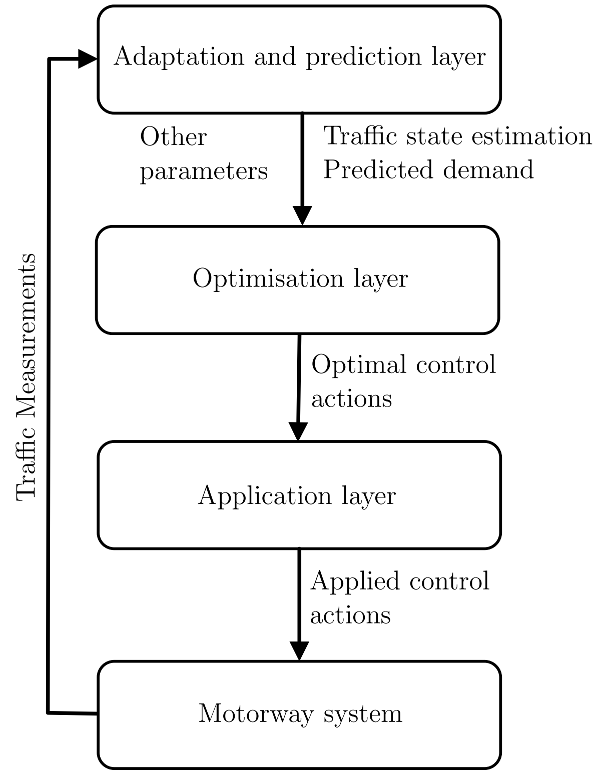

Fig. 1. The proposed control framework

With conventional vehicles, all the data available are retrieved from traffic sensors, that are placed at specific locations of the motorway (sometimes quite distant from each other). The use of VACS may give the opportunity to extend and enhance the measurement capabilities via available vehicle information from on-board sensors, such as vehicle speed, position (from GPS), and distance to the surrounding vehicles. These data may be shared with other vehicles (V2V communication) or with the infrastructure (V2I communication). These new possibilities lead to an unprecedent accuracy, richness, and granularity of available real-time information which opens new avenues for modelling and real-time control.

Traffic demand estimation is a complex task of crucial importance in an MPC framework, since the results of the optimisation problem are strongly influenced by a proper forecasting of the demand expected during the defined optimisation horizon. Classical forecasting models are based on measurements and historical data elaboration [14]. Again, a high penetration of VACS may give the possibility of improving the knowledge on the vehicles that are approaching a specific area, permitting to improve the demand prediction accuracy.

C. The optimisation layer

The optimisation layer contains the numerical solution of an optimisation problem, which is solved periodically at predefined control intervals. Since the numerical solution is computed in real-time, a crucial aspect is the time needed to obtain the optimal solution. In the present case, this was the motivation for the definition of a convex Quadratic Programming (QP) problem, which can be solved very efficiently with available algorithms. The traffic modelling aspects considered in this model have been widely described in [13] and [12]; hereafter a brief account of the modelling aspects is provided for self-completeness.

The given motorway stretch is subdivided into segments (indexed by $i = 1, \dots, I$) and lanes (indexed by $j = 1, \dots, J$); considering a discrete time step T and a given optimisation horizon K, the time index is $k = 1, \dots, K$, where $t = kT$. It is assumed to have the possibility of enabling the three following control actions, each one characterised by a specific (different) control time step:

- Ramp-metering (RM): These actions consist in regulating the inflow from the on-ramps to the motorway mainstream and they are currently applied on many motorways (see, e.g. [16]); they are represented by the control variable $r_{i,j}(k^R)$ [veh/h], where $k^R = \left\lceil \frac{kT}{T^R} \right\rceil$ and T^R is the control step for RM.
- Mainstream Traffic Flow Control (MTFC) via VSL: The use of VSL to regulate the mainstream traffic flow with the purpose of avoiding downstream traffic congestion was proposed in [18] and [19] and has been exploited in an increasing number of research works; the longitudinal flows are defined by the control variables $q_{i,j}(k^Q)$ [veh/h], where $k^Q = \left\lceil \frac{kT}{T^Q} \right\rceil$ and T^Q is the control step for MTFC.
- Lane Changing Control (LCC): The optimal lateral flows are computed for each segment-lane, thus enabling an optimal distribution of traffic flow among the different lanes; lateral flows are represented by variables $f_{i,j,\bar{j}}(k^F)$ [veh/h], where $\bar{j} = j \pm 1$, where $k^F = \left\lceil \frac{kT}{T^F} \right\rceil$ and T^F is the control step for LCC.

The dynamic equation for densities $\rho_{i,j}$ [veh/km] for each segment-lane, is described by the following conservation equation:

$$\begin{aligned}\rho_{i,j}(k+1) = \rho_{i,j}(k) + \frac{T}{L_i}\Big[& q_{i-1,j}(k^Q) + r_{i,j}(k^R) - q_{i,j}(k^Q) \\ & - \gamma_{i,j}(k)\sum_{j=1}^{J} q_{i,j}(k^Q) + f_{i,j+1,j}(k^F) + f_{i,j-1,j}(k^F) \\ & - f_{i,j,j-1}(k^F) - f_{i,j,j+1}(k^F)\Big] \end{aligned} \tag{1}$$

where the value $\gamma_{i,j}(k)$ is given as an estimation of the turning rates at off-ramps. The possibility of performing controlled RM actions may lead to the creation of queues $w_{i,j}$ [veh] at on-ramps, whose dynamics (coupled with the dynamics of extra-queues $W_{i,j}$ [veh], introduced to cope with potential mathematical infeasibility) are described by the following conservation equations:

$$w_{i,j}(k+1) = w_{i,j}(k) + T\big[d_{i,j}(k) - r_{i,j}(k^R)\big] \tag{2}$$
$$W_{i,j}(k+1) = W_{i,j}(k) + T\big[D_{i,j}(k) - d_{i,j}(k)\big] \tag{3}$$

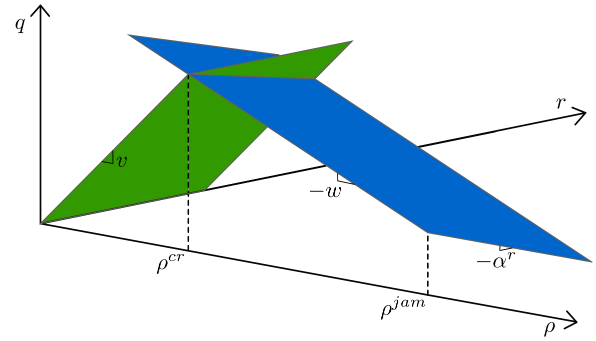

Fig. 2. The demand part of the used fundamental diagram: the flow q leaving a link is constrained; in uncongested state ($\rho < \rho^{cr}$), by an upper bound depending on the maximum speed v; in congested state ($\rho > \rho^{cr}$), q is decreased linearly with increasing density ρ (with a slope $-w$), as well as with increasing on-ramp flow r (with a slope $-\alpha^r$) and increasing lateral inflows (the latter not shown in the diagram for simplicity)

where $D_{i,j}(k)$ [veh/h] is the external (predicted) demand feeding the model, and $d_{i,j}$ [veh/h] is an auxiliary control variable used to connect the virtual with the real queues [12].

Longitudinal flow is constrained according to a first-order traffic flow model, characterised by a fundamental diagram (FD) that includes specific terms to account for the capacity drop phenomenon [13]. In the used formulation, the capacity drop is considered supposing that the outflow capacity of a segment-lane is linearly decreasing according to the increase of the current density (in case $\rho_{i,j}(k)$ exceeds the critical density $\rho^{cr}_{i,j}$); also the increase of the entering flow from the on-ramp (if any) and from the adjacent segments (lateral flows) are supposed to decrease capacity, since acceleration and braking of vehicles are considered as potential "disturbances" for the mainstream traffic. The demand part of the considered FD is illustrated in Fig. 2. Lateral flows are constrained only by the available flow and space [13], [12].

As mentioned earlier, the optimisation problem for coordinated and integrated motorway traffic control in presence of VACS has a convex QP form. Specifically, the quadratic cost function includes (see [12] for a detailed explanation):

- Three linear terms: one term reflecting the Total Time Spent (TTS), which is the most crucial control objective and two linear terms penalising extra-queues and lateral (lane-changing) flows.
- Several quadratic penalty terms to reduce time variations of RM and LCC control variables, as well as to reduce time and space fluctuations of the speed values (approximated via appropriate linearised expressions). Appropriate weights are introduced to each term to reflect the respective control priorities; see [12] for details.

The problem dynamics (linear equality constraints) comprise the linear conservation equations (1), (2), and (3). Linear inequality constraints take into account the piecewise linear terms related to longitudinal and lateral flows in the form of upper-bounds for the respective control variables. Fixed upper bounds (capacities) are also considered for the on-ramp queues and flows and for the off-ramp flows. Finally, non-negativity constraints are specified for all the variables. A detailed description of the constraints may be found in the original papers [12] and [20].

D. The application layer

The application layer is needed in order to convert the outcome of the optimisation layer to actual control actions present in the motorway system. Specifically, it includes procedures for handling the three defined control actions.

The application of RM actions is performed using ordinary traffic signals at on-ramps, via the definition of appropriate green and red phases, which depend on the computed ramp outflows, as detailed in [21]. Alternatively, in presence of VACS, the same results can be obtained providing the commands directly through an in-car information system.

For the MTFC action, the application of speed limits can be improved by the use of VACS. In fact, in the conventional case of manually driven vehicles, the application of a speed limit is effectuated by the use of VMS located on gantries which display the same speed limit for all lanes. The granularity of these actions is also dependent on the distance between successive VMS and cannot be changed. The use of VACS may drastically upgrade the possibilities of applying VSL. In fact, supposing that a sufficiently high number of vehicles is equipped with V2I communication, each equipped vehicle can receive a specific speed limit (or a suggested cruise speed) that should be respected while driving in the current location. In this case, the spatial granularity of the action is completely customisable by the control system, permitting to arbitrarily modify the application areas and lanes without expensive modifications of the infrastructure. A possible further step in this direction could be the integration within Adaptive Cruise Control (ACC) or Cooperative ACC [22], setting the desired speed directly in the vehicle driving systems, without requiring any intervention by the driver. It should be noted that a sufficient penetration of equipped vehicles will be effective to impose the speed limit to non-equipped vehicles as well.

The implementation of LCC actions is more cumbersome, even if all vehicles are in communication with the control center. The control actions can be implemented by sending lane-changing advices to an appropriate number of selected vehicles; the selection may be based on the known destinations of the vehicles and further criteria. Since, for a foreseeable future, the lane change advice will not be mandatory, the assignment will have to account for the compliance rate, as well as with other, spontaneous lane-changings decided by the drivers; the latter may be reduced by involving additional "keep-lane" advices to all equipped vehicles that do not receive a lane-change advice. Cooperative lane-changing possibilities of vehicles equipped with V2V communication capabilities may further facilitate the LCC action. Clearly, any mismatch between the optimal lateral flows and the actually triggered lane changes may be partially compensated thanks to the feedback included in the optimisation layer.

While more complex cases are subject of ongoing work, the following experiments in this paper are based on the assumptions that vehicles in the flow can receive a lane-changing advice and that the concerned drivers promptly follow these instructions, subject only to physical constraints that may disallow a vehicle to actually change its lane.

III. EXPERIMENTAL SETUP

A. Microscopic simulator setup

The proposed control methodology has been implemented and tested within the microscopic traffic simulator AIMSUN [23]. The standard configuration of this tool is based on car-following and lane-changing behavioural models derived from the Gipps Model ([24] and [25]). However, these models are characterised by two considerable drawbacks: first, the Gipps car-following model is often not reproducing a realistic capacity drop [26]; second, the ability to accurately capture the merging behaviour in a critical flow regime has been criticised [27]. In order to overcome the first issue, the Gipps car-following model has been replaced with the Intelligent Driver Model (IDM) [28], as in [29], that is deemed to provide more realistic results while reproducing the capacity drop.

The second issue has been tackled with the introduction of some heuristic rules that override the AIMSUN lane-changing policies, specifically at merge areas so as to obtain realistic merging situations. Note that, in AIMSUN (as in most real infrastructures as well), an on-ramp leads to an acceleration lane which runs parallel to the mainstream lanes for some 200 m. Thus, vehicles exiting the on-ramp, enter the acceleration lane and need eventually to change lane in order to enter the mainstream before the acceleration lane drop. In the modified lane-changing model, a vehicle is allowed to enter the mainstream if a number of defined conditions are satisfied; they include the vehicle position on the acceleration lane, its current speed, the relative speed with respect to the mainstream vehicles, and the available gap in the mainstream (the gap is calculated as a function of the space, the speed of the merging vehicle, and the speeds of the upstream and downstream mainstream vehicles travelling within the target lane). Similar rules are also applied to all other lanes of the merge area, albeit using different parameters than for the shoulder lane. The modified model was visually observed to produce a realistic merging behaviour under many different scenarios and flow levels. Calibrating the modified merging model with real data is an interesting though non-trivial task, which requires a high amount of real microscopic data; and is certainly beyond the scope of the present work, which focuses on testing and evaluating a comprehensive motorway traffic control strategy.

B. Network description

A set of experiments is performed on a motorway stretch of 2 km in length, composed by three lanes ($j = 1, 2, 3$ from the shoulder lane to the median lane), with an on-ramp placed at 1.6 km from the motorway entrance. The on-ramp leads to an acceleration lane of 190 m in length. Traffic signals for RM are placed at 20 m upstream of the acceleration lane.

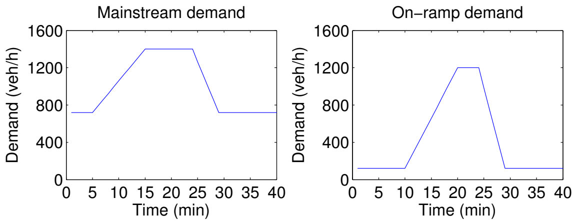

Fig. 3. The trapezoidal demand entering the network; for the three lanes of the mainstream, the same mean values are used

The entire simulation horizon is 40 minutes. The average traffic demand is set according to a trapezoidal shape (see Fig. 3), however, assuming that the vehicle arrivals follow a Poisson distribution, the time intervals between two consecutive arrivals (headway) are sampled according to an exponential distribution. This permits to have different actual demand profiles for different simulation replications, which may be deemed to emulate a recurring traffic pattern that may appear at the same location on different days.

The network is composed of 10 homogeneous sections of 200 m in length, whereby the on-ramp is placed in segment 9. The use of detectors is not necessary, since it is assumed that the traffic state can be obtained accurately via V2I communication systems.

The results presented in Sections IV-A and IV-B are related to a single replication, which is used also for the calibration of the macroscopic model. Section IV-C describes the application of the proposed methodology to a set of 100 replications, using the same macroscopic model parameters obtained from the first replication, in order to demonstrate and evaluate the robustness of the proposed approach.

IV. RESULTS

A. Scenario 1: no-control case

Scenario 1 represents the reference case, in which control actions are not applied; it will be used for performance evaluation of the proposed control strategy. A fixed speed limit is set as $v^{max} = 100$ km/h for all the motorway sections and lanes, whereas the lateral movements are delegated to the decisions of the microscopic lane-changing behaviour model, properly modified as described in Section III-A to reflect the specificity of the merging section.

As it can be seen from the contour plots in Fig. 4 (left), a congestion is created at the ramp location after about 16 minutes because of the high demand both from the mainstream and the on-ramp. The congestion quickly spreads over the three lanes and it spills back, covering up to section 6. At $t = 25$ min, the demand starts to decrease, leading to the gradual decrease of the congestion extent and its complete disappearance from all lanes at $t = 31$ min. In the no-control case, a $TTS = 70.2$ veh·h is finally obtained.

B. Scenario 2: application of optimal results

According to the topology of the motorway stretch, the macroscopic traffic flow model described in Section II-C, that is used in the optimisation layer, has been calibrated

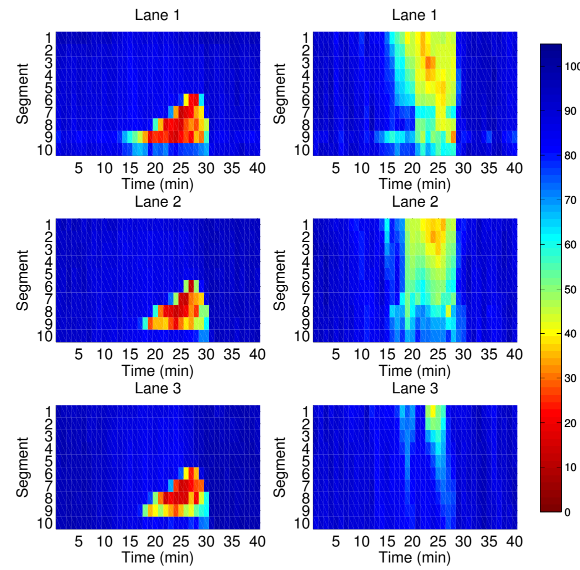

Fig. 4. Contour plots for the mean speed for the no-control case (left column) and in the controlled case (right column)

following the methodology discussed in [13], obtaining a reasonable match of the congestion pattern, that comprises also the capacity drop phenomenon.

An optimisation horizon of 6 minutes has been set for the optimisation layer, that corresponds to the time necessary to drive along the whole stretch at a speed of 20 km/h; this is a reasonable assumption according to [14]. The update period for the optimisation is 2 minutes. The demand during the optimisation horizon has been set using the average between historical data (in this case, the mean values shown in Fig. 3) and a constant value computed using an exponential smoothing of the currently measured demand. The control steps for RM and LCC are set to 2 min, whereas for MTFC a value of 5 s is used, that is also the simulation step (that dictates the update of state variables). This choice has been made since, within the optimisation problem, the longitudinal flows are constrained by linear functions in dependence of the current densities (which are updated according to the simulation step); thus, in case the control step includes more than one simulation steps, there is only one active constraint (the one considering the minimum density) that causes to unnecessarily bound the longitudinal flows also for simulation intervals when density is actually higher. It is also supposed that the maximum queue length for RM is 20 veh. All the cost weighting coefficients were tuned and kept constant during the entire simulation. This configuration allows to solve the optimisation problem in a computation time between 2 s and 3 s for all the instances of the problem (wall-clock time using an Intel® Core i5 personal computer), that is a suitable value for real-time applications.

The described methodology, applied to the designed scenario, generates an amelioration of the traffic conditions; specifically, a $TTS = 64.1$ veh·h is obtained, which is an 8.7% improvement with respect to the no-control case. The main reasons beneath this improvement lies in the mitigation

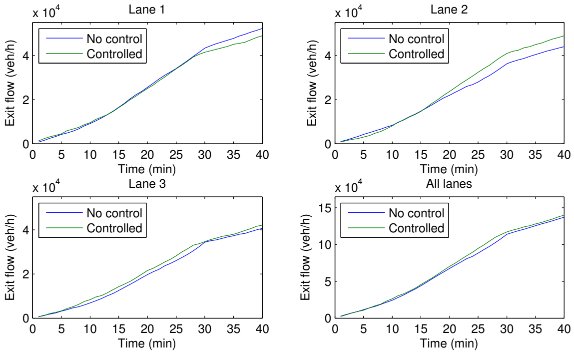

Fig. 5. The time-accumulated flows at the network exit are shown; in the controlled case, the flow exiting from lane 1 is decreased, while an increase is present for the other two lanes, which results in an overall increased throughput, generating the TTS improvement

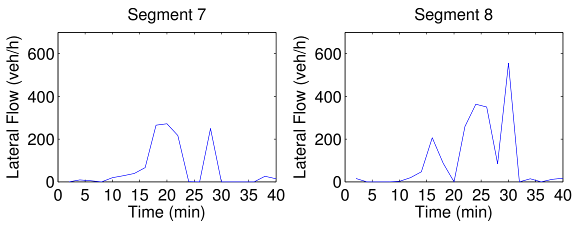

Fig. 6. Lateral flows from lane 1 to lane 2 applied in the segments upstream of the merge area

of the congestion-induced capacity drop and the better usage of the three lanes, thanks to the control actions; this leads earlier arrivals of vehicles at the network exit, as it can be seen by inspection of Fig. 5; in fact, the overall throughput is seen to be higher in the controlled case during the peak demand period.

These results are achieved via in an integrated use of all the three available control actions. Specifically:

- A strong RM action is performed during the demand peak period (between $t = 16$ min and $t = 28$ min). Because of the limited storage space on the ramp, after $t = 20$ min, the outflow of the ramp has to be increased, therefore the RM action is not sufficient to fully avoid the congestion.
- Appropriate LCC actions take place in segments 7 and 8 (that are characterised by a lower penalty cost) in order to facilitate the merging of vehicles entering from the ramp and avoid an excessive increase of vehicles in the merge area; these actions are shown in Fig. 6.
- Because of the full on-ramp, MTFC actions are performed in lanes 1 and 2 (and to a lesser extent also in lane 3) of segments 1-8 from $t = 20$ min to $t = 28$ min, limiting the flow arriving at the merge area. This creates, as it is shown in Fig. 4 (right), a controlled congestion which has a higher internal speed than the one present in the no-control case.

C. Statistical comparison

The results presented in the previous sections are related to a single replication. As previously mentioned, the macroscopic model used in the optimisation problem is calibrated with the data obtained from the same replication for which the control results were presented. At this point, it is interesting to check the effectiveness of the proposed control strategy in different cases, where different demand profiles are utilised. Thus, in order to evaluate the robustness of the proposed approach, a set of 100 random replications has been defined; they share the same mean values for the network demand, but they involve different demand profiles because of the different random seeds applied while determining the arrival times. Moreover, within AIMSUN, all the parameters related to vehicles are defined according to a normal distribution (also here, the mean values and the variances are common to all replications) and have therefore different realisations for different replications. As a matter of fact, the differences observed in various (no-control) replications are partially significant in terms of the space-time extent of the formed congestion.

The summarised comparative simulation results, related to 100 replications, are presented in Table I. It may be seen that the average TTS improvement (over the whole space-time window of the simulation) is 10.6%; of course, the improvement is higher within a tighter space-time window that includes the congestion. On the other hand, different replications produce different outcomes (particularly in the no-control case), and, in fact, higher improvements are produced for replications where more severe congestion is present without control; the maximum individual TTS improvement reaching 27%. Another significant improvement is related to the TTS variance across replications. While this variance is relatively high in the no-control case, it is strongly reduced, by 75.5%, when optimal control is applied. This implies that the variation of traffic conditions from replication to replication is relatively strong when no control is applied, but much less pronounced in the control case. Making the rough but reasonable assumption that each replication corresponds to a working day, this result implies a large potential enhancement in terms of travel time reliability, which is a significant objective of modern traffic control systems, as it entails improved predictability of the daily travel times for the road user. Finally, a statistical two-tailed t-test [30] has been performed in order to support the hypothesis that the mean TTS improvement is greater than a specific percentage, assuming the specified risk level α. The corresponding results, also included in Table I, prove that a TTS improvement greater than 7% is expected, even assuming a very low risk factor ($\alpha = 0.001$).

TABLE I

STATISTICAL TTS COMPARISON RELATED TO 100 REPLICATIONS

	No-control case	Controlled case	Improvement
Average TTS	67.9	60.7	10.6%
Best TTS improvement	91.8	67	27%
TTS variance	84	20.6	75.5%
T-test TTS improvement	-	-	7%

As a last remark, in the controlled case, a potential source of TTS degradation may be the application of (minor) control actions in uncongested conditions, due to imprecise measurements, model mismatch, or inaccurate numerical approximations. This may be overcome via the definition of an activation/deactivation logic (e.g., using appropriately defined density thresholds), which permits to apply control only when it is necessary, leaving the system uncontrolled when control actions are not needed.

V. CONCLUSIONS

The paper outlines a MPC approach for solving a coordinated and integrated motorway traffic control problem. The control structure is defined in order to deal with the different aspects of the problem, particularly focusing on the beneficial aspects that the use of VACS could bring to traffic conditions. The chosen convex QP problem facilitates a real-time feasible tool for optimising the proposed coordinated and integrated traffic problem, that can be applied also for large-scale systems. The method calls for very low computation times and guaranteed a global optimum, in contrast to other non-linear approaches. The results obtained via microscopic simulation demonstrate that this approach may generate significant improvements in terms of mitigation of traffic congestion, in an application setting where all vehicles were assumed to be equipped with specific devices and to be able to accomplish the given control tasks.

Because of the intrinsic uncertainty in the evolution of traffic conditions and the possible model mismatch (certainly amplified by the simplifications made in the proposed model), future work includes the definition of a hierarchical control structure composed of different layers featuring a feedback loop [15], [16].

Another aspect that has to be treated is the consideration of mixed traffic conditions, where vehicles equipped with VACS are travelling together with manually driven vehicles.

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