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Model predictive control for motorway traffic with mixed manual and VACS-equipped vehicles

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Abstract

Vehicle automation and communication systems (VACS) are expected to appear in an increasing amount of vehicles within the next years. Among the wide range of proposed VACS, the ones that include vehicle-to-infrastructure communication capabilities may be exploited both as sensors and as actuators. This enables traffic control centres to obtain more accurate information on the current traffic state and to assign to each vehicle appropriate control tasks, so as to achieve a global traffic flow target. The concept employs and exploits the synergistic (integrated) action of a number of old and new control measures, including ramp metering, vehicle speed control, and lane changing control, at a macroscopic level. The problem is tackled through a Quadratic Programming optimisation problem used as the core of a model predictive control framework. The optimal control actions may be sent directly to vehicles equipped with adaptive cruise control (ACC), affecting directly their cruise speed and, in addition, their lane-changing behaviour. The effectiveness and the computational feasibility of the proposed approach are demonstrated via microscopic simulation for a variety of ACC settings and penetration rates of equipped vehicles.

Keywords:
Motorway traffic control; Vehicle automation and communication systems; Model predictive control.

1. Introduction

The problem of traffic congestion in and around densely inhabited areas has a strong economical and social impact. Considering that the currently existing motorways are actually underutilised, especially in the periods of high demand, due to congestion (Papageorgiou et al., 2003), the utilisation of proper traffic control strategies may contribute to an improvement of traffic conditions, increasing the overall capacity of traffic networks.

In the last two decades, a significant and steadily increasing interdisciplinary effort by the automotive industry, as well as by numerous research institutions around the world, has been devoted to 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 (Bishop, 2005). Among the wide range of

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proposed VACS, only few have actually a direct impact on traffic flow, since the majority of VACS aims at primarily improving safety or driver convenience (Diakaki et al., 2015). Some VACS may thus be exploited to interfere with the driving behaviour via recommending, supporting, or even executing appropriately designed traffic control tasks. 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 advice). On the other hand, the uncertainty in the future development of VACS calls for the design of control strategies that are robust with respect to the possible types of VACS, as well as to their penetration rate.

The use of an intelligent and connected infrastructure for traffic management has been considered in the Automated Highway System (AHS) concept (Varaiya, 1993), where it was assumed that platoons of fully automated vehicles travel on specifically designed motorways; a multi-layer control structure was defined, assuming that the traffic-level control strategies are included in a decentralised link-layer (Rao and Varaiya, 1994). A number of other works addressed the problem of deciding on efficient vehicle lane-paths for a motorway under fully automated (AHS) or semi-automated driving (Hall and Lotspeich, 1996; Kim et al., 2008). 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.

Kesting et al. (2008) present an adaptive cruise control (ACC) strategy where the acceleration characteristics automatically adapt to different traffic situations; Hegyi et al. (2013) exploited the improved capabilities given by intelligent vehicles in sensing traffic perturbations; whereas Wang et al. (2015) analysed the possibility of affecting the behaviour of intelligent vehicles through specific speed commands sent by a link-level traffic controller.

Several studies have shown that different settings for the ACC vehicles may affect the overall traffic conditions (VanderWerf et al., 2002, van Arem et al., 2006, Ntousakis et al., 2014). For example, current ACC systems allow the drivers to choose from a range of possible inter-vehicle time gaps (e.g. from 0.5 s to 2 s), with 2 s being the recommended value (Dragutinovic et al., 2005); this corresponds to a capacity of less than 1800 veh/h/lane, which is lower than the flow capacity commonly observed with manually driven vehicles. A macroscopic traffic control strategy may allow to compensate this issue, contributing in a further amelioration of traffic conditions.

In this paper, that extends the one proposed by Roncoli et al. (2014), a control framework based on a MPC scheme for the coordinated and integrated motorway traffic management is described. It is taken into account that VACS-equipped vehicles can be exploited 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, compared to conventional systems. Specifically, VACS-equipped vehicles have the capability of bidirectional communication with the infrastructure (V2I); appropriate control actions are decided in a centralised manner by a Traffic Management Center (TMC) and dispatched to specific vehicles for their implementation. The core of the methodology is the convex optimisation problem proposed by Roncoli et al. (2015b), that is based on the piecewise linear macroscopic traffic flow model introduced by Roncoli et al. (2015a), which considers, as decision variables, actions that are enabled with the aid of VACS. Considering the lack of a necessary amount of vehicles equipped with appropriate devices, a microscopic traffic simulator is utilised to perform experiments applying the proposed control methodology. In the provided investigations, equipped vehicles are assumed to operate an ACC (adaptive cruise control) system which may be directly influenced via speed commands by the TMC; various penetration rates and various settings for equipped vehicles are considered.

The paper is structured as follows: Section 2 describes the proposed control strategy. In Section 3, the microscopic simulation environment is described; Section 4 illustrates the used motorway network and the uncontrolled case; while in Section 5 the obtained simulation results are presented and compared with a reference no-control case; Section 6 concludes the paper, highlighting the main results.

2. Control strategy

Motorway traffic flow, like many other complex processes, is affected by several factors, and any related mathematical model has necessarily a limited accuracy. On the other hand, the employed model must be simple enough to allow for computational tractability of the related optimal control problem. In addition, the use of an open-loop control strategy (whereby the control trajectories are computed at the initial instant, without being updated during the

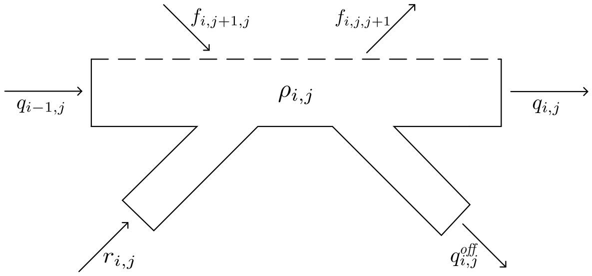

Fig. 1. The segment-lane variables used in the model formulation.

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 limited model accuracy. 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 (Camacho and Bordons, 1995). This permits to reject past inaccuracies and to maintain the difference between the model predictions and the real process outcome at low levels, thus improving the overall control performance.

The related optimal control problem is solved periodically, at predefined control intervals in the order of minutes. Since the numerical solution is computed in real-time, a crucial aspect is the time needed to obtain it. In the present approach, 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 described in detail by Roncoli et al. (2015a) and Roncoli et al. (2015b); 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 discrete time index of the employed model is $k = 1, \dots, K$, where $t = kT$. The following three control actions, each one characterised by a specific control time step, may be activated:

- Ramp-metering (RM): It consist regulates the inflow from the on-ramps to the motorway mainstream and is currently applied on many motorways (see, e.g. Papamichail et al., 2010); the corresponding control variable $r_{i,j}(k^R)$ [veh/h] denotes the controlled ramp outflow, where the ramp is located at segment i, lane j, during control interval $(k^R, k^R + 1]$, 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 Variable Speed Limits (VSL): The use of VSL for traffic management has been exploited in an increasing number of research works; (Smulders and Helleman, 1998; Carlson et al., 2010). In this work, a different VSL may be imposed for each segment-lane of the motorway by ordering the speed of VACS-equipped vehicles, aiming finally at achieving a specific (optimal) mainstream flow value; the longitudinal optimal flows for segment i, lane j are defined by $q_{i,j}(k^Q)$ [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], that denote the amount of vehicles moving from lane j to lane $\bar{j}$ ($\bar{j} = j \pm 1$), remaining within the same segment i, during control interval $(k^F, k^F + 1]$, where $k^F = \left\lceil \frac{kT}{T^F} \right\rceil$ and T^F is the control step for LCC.

The dynamics for densities $\rho_{i,j}$ [veh/km] for each segment-lane (i, j), are given by the conservation equation (1):

$$\rho_{i,j}(k+1) = \rho_{i,j}(k) + \frac{T}{L_i}\Big[q_{i-1,j}(k^Q) + r_{i,j}(k^R) - q_{i,j}(k^Q) - \gamma_{i,j}(k)\sum_{j=1}^{J} q_{i-1,j}(k^Q) \qquad (1)$$

$$+ f_{i,j+1,j}(k^F) + f_{i,j-1,j}(k^F) - f_{i,j,j-1}(k^F) - f_{i,j,j+1}(k^F)\Big]$$

$$w_{i,j}(k+1) = w_{i,j}(k) + T[d_{i,j}(k) - r_{i,j}(k^R)] \qquad (2)$$

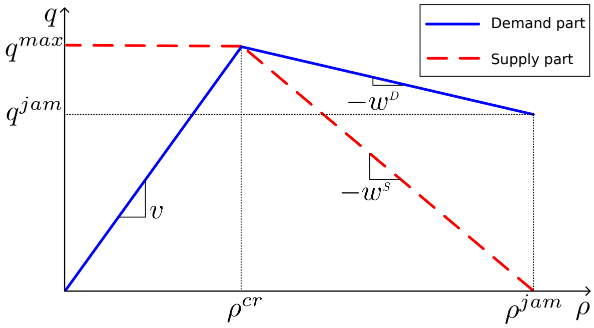

Fig. 2. The demand and supply functions of the used fundamental diagram: the flow q leaving a link is constrained, in congested state ($\rho > \rho^{cr}$), by a linearly decreasing line (with slope $-w^D$), generating a reduction of capacity in congestion, mimicking the capacity drop phenomenon.

where $\gamma_{i,j}(k)$ are estimated turning rates at off-ramps. A graphical representation of the variables related to the segment-lane entity is provided in Fig. 1. The possibility of performing RM actions may lead to the creation of queues $w_{i,j}$ [veh] at on-ramps, defined by the dynamics (2), where $d_{i,j}(k)$ [veh/h] is the external (predicted) demand feeding the model.

As mentioned earlier, longitudinal flows are considered as control variables which can be realised via appropriate VSL actions. Therefore, these control variables are constrained from above by the longitudinal flow values that would prevail without VSL, i.e. by their uncontrolled values. The latter are obtained according to a discretised first-order traffic flow model with piecewise linear fundamental diagram (FD) based on a modified Godunov discretisation that includes specific terms to account for the capacity drop phenomenon (Roncoli et al., 2015a). It is well-known that the Godunov-discretised longitudinal flow of first-order traffic flow models may be viewed as the minimum between a demand function (which depends on the upstream-segment density) and a supply function (which depends on the downstream-segment density). In the used formulation, the capacity drop is considered via a modification of the demand function; specifically, if the upstream density is over-critical, the demand function is not constant and equal to capacity (as in the ordinary Godunov-discretised model), but is linearly decreased in dependence of the density, according to an approach first proposed by Lebacque (2003), see Fig. 2; also, the entering flow from an on-ramp (if any) and from the adjacent segments (lateral flows) are modelled to decrease capacity, since the related acceleration or braking of vehicles usually perturb the mainstream traffic flow. Lateral flows are also considered as control variables, which are constrained only by the available flow and space.

As mentioned earlier, the optimisation problem for coordinated and integrated motorway traffic control in presence of VACS has a convex QP form. The quadratic cost function is composed by linear terms reflecting the Total Time Spent (TTS), which is the most crucial control objective, and penalising lateral (lane-changing) flows; and 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; in particular, the weights related to lateral flows may be tuned in order to encourage lane-changes at specific segment-lanes, e.g. upstream of on-ramps or lane-drops.

In summary, the problem dynamics (linear equality constraints) comprise the linear conservation equations (1) and (2); while linear inequality constraints take into account the piecewise-linear terms related to longitudinal (derived from the previously described FD) and lateral flows (as linear functions denoting the available vehicles in the sending segment-lane and the available space in the receiving segment-lane) 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 developed QP problem may be found in the original papers by Roncoli et al. (2015a) and Roncoli et al. (2015b).

Data retrieved from the motorway system, either from spot detectors or from equipped vehicles, must be processed in order to obtain necessary information to be used by the optimisation problem. With conventional vehicles, all the data available are retrieved from road-side traffic sensors, that are placed at specific locations of the motorway (sometimes quite distant from each other). The presence of VACS with V2I capability provides the opportunity to extend and enhance the real-time measurement capabilities via available vehicle information from on-board sensors, such as vehicle speed, position, 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 unprecedented accuracy, richness, and granularity of available real-time information which opens new avenues for real-time estimation of the traffic state. Related traffic state estimation approaches have been reported (e.g. Herrera and Bayen, 2010; Yuan et al., 2012; Seo et al., 2014; and Bekiaris-Liberis et al., 2015).

Also, 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; classic forecasting models are based on measurements and historical data elaboration (Zhou and Mahmassani, 2007). Again, a high penetration of VACS may give the possibility of improving the knowledge on the number of vehicles that are approaching a specific area, permitting to improve the demand prediction accuracy.

Moreover, the output of the optimisation problem is not directly ready for implementation in the motorway network: the optimal results must be converted into applicable control tasks sent to actuators, that may be infrastructure-based (e.g. using traffic lights in the RM case) (Papageorgiou and Papamichail, 2008), or installed within vehicles (with V2I capabilities).

The application of VSL can be improved by an appropriate use of VACS. In fact, supposing that a sufficiently high number of vehicles is equipped with V2I communication, each equipped vehicle can receive a specific speed limit that can be implemented within its internal throttle and brake controller (Wang et al., 2015). In this case, the spatial granularity of the action is customisable by the control system, permitting to arbitrarily modify the application areas and lanes without expensive modifications of the infrastructure. A further step in this direction is the integration within Adaptive Cruise Control (ACC) or Cooperative ACC, 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 centre. 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 for other, spontaneous lane-changes 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 inherent feedback MPC.

3. Experimental setup

The proposed control methodology has been implemented and tested within the microscopic traffic simulator AIMSUN (TSS - Transport Simulation Systems). The standard configuration of this tool is based on car-following and lane-changing behavioural models derived from the Gipps Model (Gipps, 1981 and Gipps, 1986). However, these models have been reported to have two considerable drawbacks: first, the Gipps car-following model is often not reproducing a realistic capacity drop at the head of congestion (Wang et al., 2005); second, the ability to accurately capture the merging behaviour in a critical flow regime has been criticised (Chevallier and Leclercq, 2009). In order to overcome the first issue, the Gipps car-following model has been replaced here with the Intelligent Driver Model (IDM) (Treiber et al., 2000), as applied by Ntousakis et al. (2014), 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 more realistic merging situations. The modified model was visually observed to produce a realistic merging behaviour under many different scenarios and flow levels.

The ACC system is one of the novel vehicle technologies that has already been deployed in the market. While it was designed mainly to enhance driver comfort and passengers' safety, it also affects the dynamics of traffic flow. Commonly, a two-level control structure is defined (Liang and Peng, 1999), where the higher level deals with calculating the necessary or desired acceleration, depending on the inter-vehicle distance (range) to the leading vehicle and the difference in the corresponding speeds (range rate); while the lower level deals with the conversion of the accel-

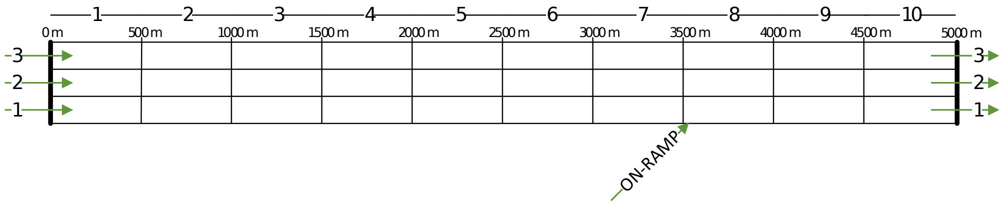

Fig. 3. The motorway stretch used as test-bed for microscopic simulations.

eration, computed at the higher level, into throttle or brake commands. The literature about different ACC strategies is rather vast; a review may be found in the work by Ntousakis et al. (2014). In our case, the following controller is implemented, derived from Liang and Peng (1999):

$$\dot{x}_i^* = \min\left\{v_i^*, \dot{x}_i + T \min\left\{a_i^{max}, \max\left[a_i^{min}, K_s\left(\dot{x}_{i+i} - \dot{x}_i\right) + K_d\left(x_{i+i} - x_i - h_i^d \dot{x}_i\right)\right]\right\}\right\} \tag{3}$$

where the index i indicates the vehicle containing the ACC system and $i + 1$ its "leader", namely the vehicle directly in front of it. Variables x and $\dot{x}$ denote, respectively, the current position and speed of a vehicle; T is the control step (e.g. 100 ms); a_i^{min} and a_i^{max} are the bounds for acceleration; K_s and K_d are the controller gains, to be tuned in order to guarantee string stability and maximise performance (in this work, $K_s = 1.70$ and $Kd = 1.12$, are used, as proposed by Liang and Peng, 1999); the adjustable parameters are the desired time-headway h_i^d, which influences the desired distance from the preceding vehicle, and the desired speed v_i^*. The desired headway is a value that can be chosen by a driver based on personal preferences; suggested values vary in the range between 0.5 s and 2.0 s. The main parameters that can be affected while performing MTFC via VSL is the desired speed: in this work it is supposed that the optimal speed derived from the optimisation problem (Section 2) is sent to equipped vehicles that apply it within their internal control law. To account also for drivers' preferences, a maximum desired speed v_i^d is also considered, according to:

$$v_i^* = \min\left(v_i^d, v_i^{VSL}\right) \tag{4}$$

In the LCC case, all spontaneous lane-changes are inhibited for equipped vehicles; instead, it is assumed that equipped vehicles keep the TMC updated with information related to available gaps for the left and right lanes; then the TMC assigns lane-changing actions aiming at establishing the optimal flows for each segment-lane, sending commands to the vehicles that have the highest gap, thus trying to minimise the impact on the traffic conditions.

4. Network description and reference case

A motorway stretch of 5 km in length, composed of three lanes ($j = 1, 2, 3$ from the shoulder lane to the median lane), with an on-ramp placed at 3.5 km from the motorway entrance, is considered. 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 entrance. The network is space-discretised, obtaining 10 homogeneous sections of 500 m in length, whereby the on-ramp is placed in segment 8, as shown in Fig. 3. The entire simulation horizon is 50 minutes. The average traffic demand is set according to a trapezoidal shape; 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 (the proposed experiment includes 10 replications), which may be deemed to emulate a recurring traffic pattern appearing on different days.

A number of simulations has been performed to calibrate and evaluate the proposed control strategies. First, the macroscopic model and the optimisation problem are calibrated and tuned using one single replication of the stochastic microscopic simulator; then the obtained results are validated using additional simulation replications; subsequently different scenarios characterised by different assumptions on equipped vehicles are simulated, and the results are reported in the next section.

Specifically, different scenarios are defined considering different penetration rates of equipped vehicles and different parameters for the ACC strategies; specifically, three penetration rates (1%, 5%, and 20%) and three different

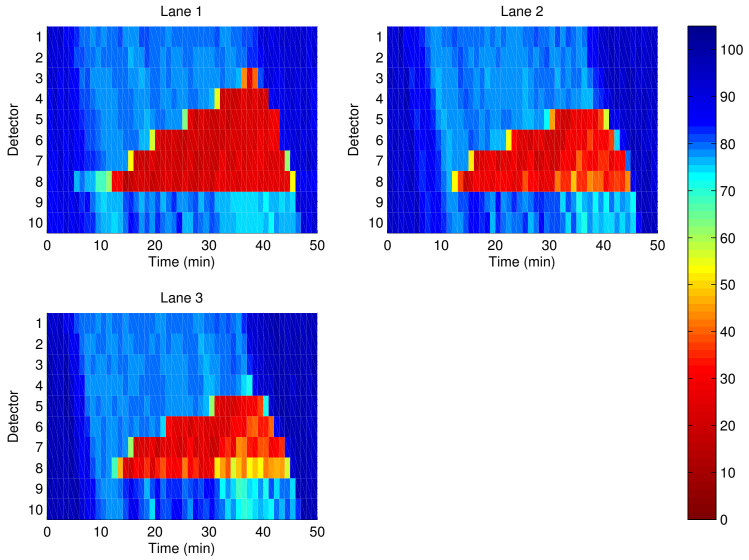

Fig. 4. Contour plots for the mean speed (km/h) in the no-control case.

values for the time-headway of the ACC systems (h_i^d = 0.7 s, 1.3 s, and 2.0 s) are used. For each scenario, a case in which control actions are not applied is first tested, representing the reference case for the performance evaluation of the proposed control strategy. In these no-control cases, a fixed speed limit is set at 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.

In all tested no-control scenarios, a strong congestion appears at the on-ramp merge segment, covering an upstream part of the simulated motorway stretch. Considering a basic case, in which only manually-driven vehicles are travelling within the network, an average $TTS = 269.7$ veh·h is obtained. Other no-control TTS results for different penetration rates and headways used by ACC-equipped vehicles are provided in Table 1. In case the headway is 2.0 s, even with different penetration rates, the traffic performance is quite similar, meaning that this behaviour is rather close to manual vehicles. On the other hand, for smaller ACC headways, the difference is more evident, leading to an amelioration of traffic conditions for higher penetration rates.

The contour plots (by lane) in Fig. 4 show the congestion pattern related to one scenario (penetration rate 5%, h_i^d = 1.3 s) for one replication characterised by a TTS close to the average value. Congestion is created at lane 1 of the merge segment 8 after about 12 minutes because of the high demand both from the mainstream and the on-ramp; then it quickly spreads over the three lanes and spills back, reaching up to section 3. At t = 38 min, because of the demand reduction, the congestion extent gradually decreases, disappearing completely from all lanes after t = 45 min.

5. Control results

The optimisation problem described in Section 2 is adjusted and calibrated considering the network topology and the traffic pattern, in order to reproduce similar congestion phenomena. An optimisation horizon of 10 minutes has been set for the MPC problem, that corresponds to the time necessary to drive along the whole stretch at a speed of 30 km/h, which is a reasonable assumption according to Burger et al. (2013). The update period for the optimisation problem is 1 minute. The demand during the optimisation horizon is set using the average between the mean values and a constant value corresponding to an exponential smoothing of the actual measured demand.

The maximum admissible queue length for RM is 20 veh. This value is considered within the optimisation problem; nevertheless, since demand cannot be perfectly predicted, peaks of demand may generate an unexpected surge of vehicles queuing; thus, to avoid a spillover of the ramp queue, a queue management algorithm (Spiliopoulou et al., 2010) is applied at the on-ramp which may override the optimal RM decisions, if necessary, during the simulation. All

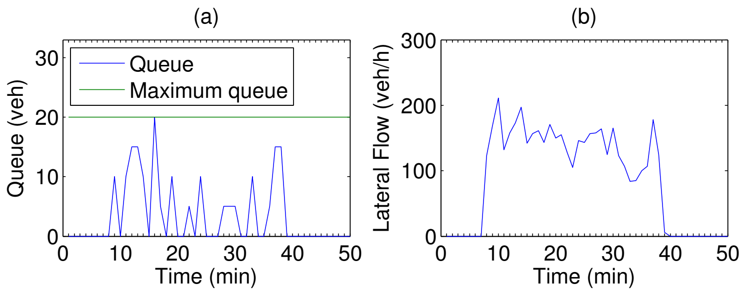

Fig. 5. (a) The queue generated at the on-ramp; and (b) the lateral flow assigned to segment 6 from lane 1 towards lane 2, for one replication in case control is applied.

the weighting coefficients of the optimisation cost function were tuned and kept constant during the entire simulation; in particular, a lower cost for lane-changing is set for segment 6, from lane 1 towards lane 2, thus encouraging equipped vehicles to anticipate the lane-changes that are expected due to the subsequent merging on-ramp.

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), which is much lower than the update period (1 min) of the optimisation problem and hence readily feasible also for real-time applications.

According to the performed simulations, the proposed methodology is capable to improve the traffic conditions for all the designed scenarios. From Table 1, which contains the corresponding numerical results, it can be observed that for all the tested penetration rates and ACC headways, the average TTS is rather similar, meaning that also a low penetration rate is sufficient to accomplish the assigned control tasks. On the other hand, since the no-control case has strong variations for the different cases, the relative improvement has also strong variations, being smaller whenever the no-control case is characterised by a less severe congestion. Moreover, the obtained results indicate that, when applying the proposed control strategy, the traffic conditions may be improved (in particular, the network throughput may be increased) even in the cases of a large ACC headways (e.g. 2 s). This implies that, with opportune macroscopic traffic control strategies that influence the behaviour of equipped vehicles, the overall capacity of the traffic system can be increased, even in case "safer" settings are used for ACC equipped vehicles.

Again, the contour plot for speed, related to one single replication considering penetration rate 5% and $h_i^d = 1.3$ s, is examined in more detail: an overall increase of speed can be seen by inspection of Fig. 6, which finally causes the TTS improvement. These results are achieved via integrated and synergistic application of all the three available control actions. Specifically:

- RM actions are performed during the peak demand period (between $t = 10$ min and $t = 40$ min). Figure 5a displays the queue generated at the ramp.
- Appropriate LCC actions take place in segment 6 between lane 1 and lane 2 (that is characterised by a lower penalty cost for lateral flow) in order to facilitate vehicles entering from the ramp to merge and avoid an excessive increase of vehicles in the merge area; corresponding values are shown in Fig. 5b.
- MTFC actions are performed mainly in lane 2 of segments 6 and 7 from $t = 22$ min to $t = 40$ min, which limit the mainstream flow arriving in the merge area. This creates, as it is shown in Fig. 6, some slight controlled congestion, that, in combination with the RM and LCC actions, avoid the traffic breakdown and increase the throughput thanks to the mitigation of the capacity drop at the merge area.

6. Conclusions

The paper presents an MPC approach for solving a coordinated and integrated motorway traffic control problem in presence of VACS-equipped vehicles. 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

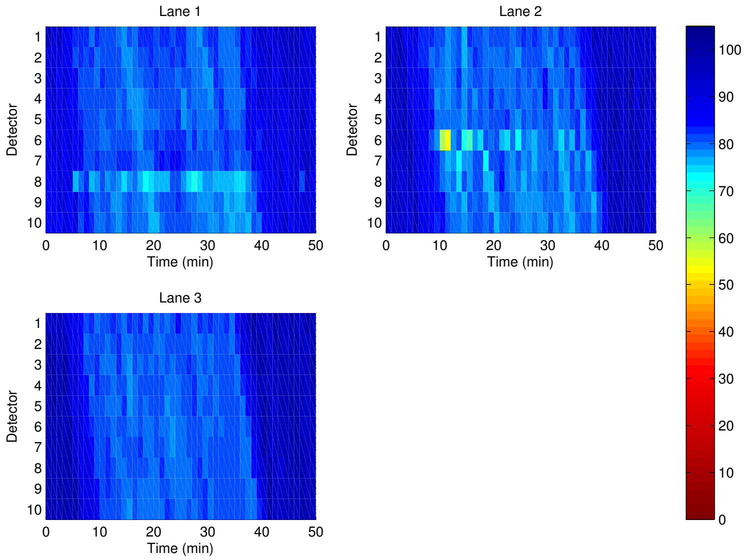

Fig. 6. Contour plots for the mean speed (km/h) in case the results of the optimisation problem are applied.

Table 1. Comparison of the average TTS results (over 10 replications) for all the tested scenarios.

	Headway 0.7			Headway 1.3			Headway 2.0		
	No-control	Control	Impr.	No-control	Control	Impr.	No-control	Control	Impr.
Penetration rate 1%	260.9	213.4	18.2%	272.4	213.4	21.7%	262.6	213.7	18.6%
Penetration rate 5%	249.8	213.0	14.7%	252.6	213.2	15.6%	259.2	214.6	17.2%
Penetration rate 20%	225.5	212.0	6.0%	230.2	212.6	7.6%	261.0	220.7	15.4%

traffic problem, that can be applied also for large-scale systems. The method calls for very low computation times and guarantees 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 different percentages of vehicles are assumed to be equipped with specific devices that feature ACC and lane changing advisor systems, assuming also V2I communication capabilities. In addition, it is shown that the detrimental effects (capacity reduction) due to the choice of a high headway in ACC systems may be mitigated by using an appropriate control strategy acting at a macroscopic level.

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