Transportation Research Part C 62 (2016) 117–132

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Hierarchical model predictive control for multi-lane motorways in presence of Vehicle Automation and Communication Systems

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ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form 16 November 2015
Accepted 16 November 2015
Available online 30 November 2015

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

ABSTRACT

A widespread deployment of vehicle automation and communication systems (VACS) is expected in the next years. This may lead to improvements in traffic management efficiency because of the novel possibilities of using VACS both as sensors and as actuators, as well as of a variety of new communications channels (vehicle-to-vehicles, vehicle-to-infrastructure) and related opportunities. To achieve this traffic flow efficiency, appropriate studies, developing potential control strategies to exploit the VACS availability, are essential. This paper describes a hierarchical model predictive control framework that can be used for the coordinated and integrated control of a motorway system, considering that an amount of vehicles are equipped with specific VACS. 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 effectiveness and the computational feasibility of the proposed approach are demonstrated via microscopic simulation for a variety of penetration rates of equipped vehicles.

1. Introduction

The problem of traffic congestion in and around densely inhabited areas has a strong economical and social impact. One possible solution is the construction of wider road infrastructures, with an enormous economical cost and significant environmental consequences. On the other hand, the currently existing motorways are actually underutilised, especially in the periods of high demand due to congestion (Papageorgiou et al., 2003). A possible way to overcome this situation is the development and implementation of proper traffic control measures and strategies with the aim of reducing traffic congestion and increasing the overall capacity of traffic networks.

In the last two decades, a significant and increasing steadily 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 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.

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http://dx.doi.org/10.1016/j.trc.2015.11.008
0968-090X/

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 may travel on specifically designed motorways. This complex system was suggested to be controlled via a multi-layer control structure, where the traffic-level control strategies are included in a decentralised link-layer. One of the first works addressing link-layer control strategies was proposed by Rao and Varaiya (1994). More recently, Baskar et al. (2012) proposed a model predictive control (MPC) approach 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 solve 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. Hall and Lotspeich, 1996; Ramaswamy et al., 1997; 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; also, a number of structural assumptions were made to limit the (otherwise vast) space of potential lane-path assignments.

On the other hand, the coordinated and integrated exploitation of conventional traffic control actuators, such as road-side traffic signals and variable message signs (VMS) for route guidance, variable speed limits (VSL), and RM, has been proposed in several papers. Some approaches are based on the formulation of appropriate optimisation problems, envisioning their application within an MPC scheme (Kotsialos et al., 2002; Hegyi et al., 2005a; Gomes and Horowitz, 2006; Papamichail et al., 2010; Frejo et al., 2014; Chow, 2015; Ferrara et al., 2015). Nevertheless, the intrinsic complexity of these approaches may be an impediment for real-time application 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 problems. Other control strategies where designed following an analysis of some properties of traffic dynamics, e.g. Hegyi et al. (2005b), Sun and Horowitz (2005), Zhang et al. (2006), Hegyi et al. (2008), Muralidharan and Horowitz (2012), Torné et al. (2014).

The purpose of this paper, that represents an extension of Roncoli et al. (2014), is the development of a hierarchical 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, compared to conventional systems. In particular, according to the nomenclature on automated motorway traffic control (see, e.g., Varaiya, 1993), this paper deals with the so-called "link layer", aiming at smoothing and improving traffic conditions. Therefore, problems at higher levels (e.g., route assignment) or at lower levels (e.g., car-following laws) are assumed to be properly addressed by other (external) systems. It is supposed that 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. In Fig. 1, the envisioned scenario is sketched. 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. Since the application of this methodology in a real motorway environment will not be possible for several years to come, because of the necessary amount of vehicles equipped with appropriate devices, the best opportunity to realistically test the proposed control strategy is by use of a microscopic traffic simulator; this latter aspect is the main issue considered in this paper.

The paper is structured as follows: Section 2 describes the proposed control framework. In Section 3, the microscopic simulation environment is described, while in Section 4 the obtained simulation results are presented and compared with a reference no-control case. Section 5 concludes the paper, highlighting the main results and introducing some challenging research tasks for the future.

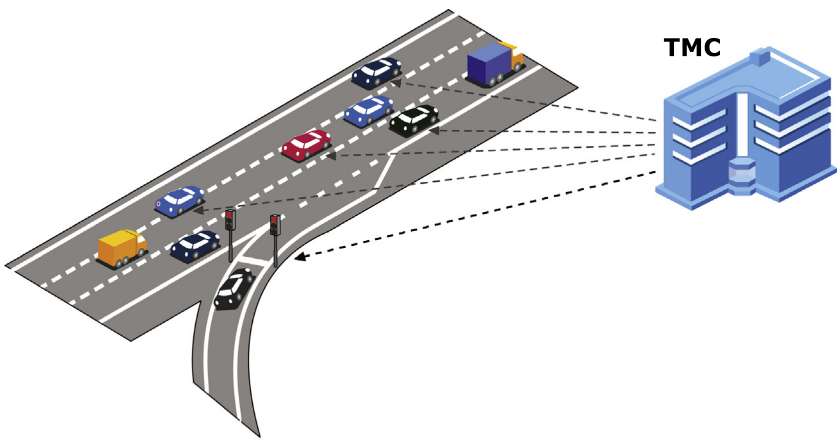

Fig. 1. The envisioned scenario, where vehicles communicate with a TMC, that computes and dispatches control actions.