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# Evaluation of a model predictive control framework for motorway traffic involving conventional and automated vehicles

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ABSTRACT

A Model Predictive Control (MPC) strategy for motorway traffic management, which takes into account both conventional control measures and control actions executed by vehicles equipped with Vehicle Automation and Communication Systems (VACS), is presented and evaluated using microscopic traffic simulation. A stretch of the motorway A20, which connects Rotterdam to Gouda in the Netherlands, is taken as a realistic test bed. In order to ensure the reliability of the application results, extensive speed and flow measurements, collected from the field, are used to calibrate the site's microscopic traffic simulation model. The efficiency of the MPC framework, applied to this real sizable and complex network under realistic traffic conditions, is examined for different traffic conditions and different penetration rates of equipped vehicles. The adequacy of the control application when only VACS equipped vehicles are used as actuators, is also considered, and the related findings underline the significance of conventional control measures during a transition period or in case of increased future demand.

## 1. Introduction

Traffic congestion is associated with a variety of problems that modern societies face. Increased travel times, infrastructure degradation, and excessive environmental pollution are some of the negative consequences of traffic congestion, rendering the need for efficient traffic management stronger than ever. In this context, the development of various types of Vehicle Automation and Communication Systems (VACS) during the last decade may prove beneficial, not only for the individual driver safety and convenience, but also for their employment as important tools of innovative traffic management approaches (Diakaki et al., 2015). It should be noted however that the mere existence of VACS is no guarantee for improved traffic flow efficiency, and, in fact, VACS may even lead to deterioration of the traffic conditions if their introduction is not accompanied by proper traffic management measures. Thus, the development of traffic control strategies that exploit VACS efficiently has been the subject of several works.

In some early works on the subject, Varaiya (1993) proposed the use of intelligent devices in Automated Highway Systems (AHS), where it was assumed that platoons of fully automated vehicles may travel in specifically designed motorways. This complex system was suggested to be controlled through a three-layer control structure, where the decentralized traffic flow control tasks are implemented via roadside and vehicle computers (Rao and Varaiya, 1994). The possibility of semi-automated or fully automated driving, leading to lane assignment problems for AHS, is considered by Kim et al. (2008). Baskar et al. (2011), provide an in-depth analysis of the traffic control measures for Intelligent Vehicle Highway Systems (IVHS) and give an overview of developed control

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schemes that combine roadside controllers and automated platoons.

Besides the decentralized control approaches for AHS, a lot of research has been conducted on the impact of the currently existing driver assistance systems on the motorway traffic flow conditions (see e.g., Rao and Varaiya, 1993; Vander Werf et al., 2002; Davis, 2004). Kesting et al. (2007) proposed an Adaptive Cruise Control (ACC)-based in-vehicle strategy, capable to overcome the potential negative impact of the driver assistance system on the traffic conditions and to improve the overall traffic situation on the motorway. The experiments conducted by Shladover et al. (2012), using real equipped vehicles, have shown that, in case sufficient amount of vehicles equipped with cooperative ACC, the highway capacity can be increased, in contrast to the case of automated ACC systems, which resulted in minor impact on the capacity values. Wang et al. (2014a) presented a control framework whereby vehicles equipped with Advanced Driver Assistance Systems (ADAS) are enabled to set their acceleration based on the prediction of the neighboring vehicles behavior over a time horizon. This control scheme was modified by Wang et al. (2014b), where the possibility of synergistic control actions and information exchange between vehicles is considered with the introduction of cooperative ADAS. In the work by Spiliopoulou et al. (2017), an ACC-based control scheme is presented where the settings of the ACC system are adjusted based on the traffic conditions of specific motorway sections. This traffic control strategy was tested using microscopic traffic simulations and resulted in significant improvements of the average vehicle delay as well as of the fuel consumption rates.

Although the main research interest lies in the exploitation of ADAS systems for longitudinal flow control, some recent studies have emphasized the advantages of cooperative lane-changing with the use of Vehicle-to-Vehicle (V2V) communication systems. Ammoun et al. (2007) presented a lane-changing assisting system, capable to predict the trajectory of the vehicle and to examine risks associated with potential lane change maneuvers based on the information received from the neighboring vehicles. The presented model was validated with real data from tests involving an intelligent vehicle and showed sufficient performance. More recently, a decentralized control framework for cooperative lane-changing was proposed by Nie et al. (2016), where it is considered that connected automated vehicles take lane-changing decisions with the aim of improving the traffic situation in the motorway. The lane-changing decision depends on a state prediction module, which aims at predicting the state of the vehicles related to the automated vehicle in the next time intervals, and a candidate decision generation module, where the candidate decisions of each vehicle are produced based on information received by the neighboring vehicles.

This paper is an extension of Perraki et al. (2017) and adopts the Model Predictive Control (MPC) strategy proposed by Roncoli et al. (2016a) to evaluate various interesting aspects of innovative and conventional traffic control measures for a complex real network in a realistic simulation environment. Specifically, the applicability and effectiveness of the strategy is tested for various combinations of control measures and different penetration rates of equipped vehicles using a complex real infrastructure which is simulated by use of the Aimsun (Transport Simulation Systems, 2014) microscopic traffic simulator, after careful calibration and validation on the basis of real traffic data. The model is fed with real measured demands, creating a realistic and sizable virtual testbed for comprehensive and multi-faceted evaluation. The core of the control strategy is the convex optimization problem proposed by Roncoli et al. (2015b), which includes, as decision variables, actions enabled with the aid of VACS as well as conventional traffic control measures. The optimal control problem formulation is based on a piecewise-linear macroscopic traffic flow model developed by Roncoli et al. (2015a), which is however extended in the present work with the introduction of a piecewise-linear fundamental diagram in order to capture under-critical conditions more efficiently. Moreover, while in the earlier work of Roncoli et al. (2016a) the primary control scheme had been preliminarily tested using microscopic traffic simulation for a limited hypothetical infrastructure, this paper explores the efficiency of the strategy for a challenging and sizable real-life network with the no-control case being the real reference case for the traffic conditions in the motorway. In addition, we examine the case where the conventional control measures are deactivated from the control application, so as to enable conclusions to be drawn regarding the adequacy of the control actions which are exclusively performed by VACS-equipped vehicles.

The rest of the paper is organized as follows. Section 2 gives a brief overview of the optimal control problem and the employed MPC scheme. In Section 3, the case study network is described, along with the behavioral models and the dynamic scenario used in the microscopic simulation. Then, the calibration process is presented, and the simulated speeds are compared to the real measured speeds in order to demonstrate that the microscopic simulation is capable of replicating reality. In Section 4, the setup of the MPC strategy is specified, and the control strategy is applied to the calibrated model for different penetration rates of equipped vehicles. Subsequently, the outcome of a modified control scheme, that considers only the control actions executed by VACS-equipped vehicles, is investigated. Finally, Section 5 summarizes the main findings of the work.

## 2. Model predictive control for integrated and coordinated motorway traffic control

### 2.1. Control framework

Several approaches have been presented in the literature for the problem of optimal coordinated and integrated motorway traffic control (see, e.g., Kotsialos et al., 2002; Hegyi et al., 2005a). The application of these approaches cannot be effectuated in an open-loop manner due to inevitable discrepancies from reality of the employed models and external variable (e.g. demand) prediction. Such discrepancies are mitigated by use of an MPC framework, whereby the optimal control problem is solved repeatedly in real time with updated initial traffic state and demand predictions; while only a small initial part of the computed optimal control trajectories are actually applied, before the next updated optimization. Each optimization features a finite time horizon, which is "rolled" with subsequent optimal control computations, hence the synonym "rolling horizon control" for MPC. Some experiments that highlight the efficiency of MPC for the motorway traffic control problem can be found in Hegyi et al. (2005a), van den Berg et al. (2007), Baskar et al. (2012).