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Two-class freeway traffic regulation to reduce congestion and emissions via nonlinear optimal control

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A B S T R A C T

The objective of this paper is the regulation of freeway traffic by means of optimal control techniques. A first innovative aspect of the proposed approach is the adopted objective function in which, besides the reduction of traffic congestion (which is typically considered in traffic control schemes), the minimization of traffic emissions is also included. Moreover, a multi-class framework is defined in which two classes of vehicles (cars and trucks) are explicitly modelled, and specific control actions for each vehicle class are sought. This results in the formulation of a multi-objective optimal control problem which is described in the paper and for which a specific solution algorithm is developed and used. The algorithm exploits a specific version of the feasible direction algorithm whose effectiveness is demonstrated in the paper by means of simulation results.

1. Introduction

Phenomena of recurrent and nonrecurrent congestion in freeway systems can be relieved by applying proper control techniques, that have been studied by researchers for some decades. A very successful and widespread control measure is ramp metering, which allows to control the traffic flow entering the freeway mainstream by using traffic lights at the on-ramps. Ramp metering is applied to achieve maximum mainline throughput downstream of the ramp (local control) or, more generally, optimal traffic conditions in the freeway network (networkwide approaches) (Papageorgiou and Papamichail, 2008). One of the first effective ramp metering strategies is the local feedback traffic controller ALINEA (Papageorgiou et al., 1991), dating back to the Nineties, that has been applied in many freeways all over the world. It has been shown that ALINEA, despite being a local controller, is quite effective in increasing the motorway throughput (Papageorgiou et al., 2007). During the years, ALINEA has been further extended, resulting in a proportional-integral version, called PI-ALINEA (Wang et al., 2010), or through a coordination of the local ramp-metering actions, thus enabling the linked control of the inflow from consecutive on-ramps (Papamichail and Papageorgiou, 2008).

Different traffic control methodologies have been developed in the last decades, also including approaches based on optimization or optimal control algorithms (Kotsialos and Papageorgiou, 2004). In some works, the problem of controlling a freeway is formulated as a discrete-time constrained nonlinear optimal control problem (see Kotsialos et al. (2002) and the references therein), whose numerical solution is often hard to find by directly using the available Nonlinear Programming codes, because of the problem dimensions and complexity. A very efficient numerical solution has been adopted in

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the optimal freeway traffic control tool AMOC (Kotsialos et al., 2001; Papageorgiou and Kotsialos, 2004), by using the so-called feasible direction algorithm. Then, more sophisticated control architectures have been investigated, again based on AMOC, such as for instance the three-layer hierarchical control approach described in Papamichail et al. (2010) and the mainstream traffic flow control scheme proposed in Carlson et al. (2010).

Optimal control algorithms may be embedded in Model Predictive Control schemes, using real-time measurements (feedback) as initial states. For instance, in Hegyi et al. (2005) and Bellemans et al. (2006) nonlinear MPC frameworks adopting the macroscopic model METANET (Papageorgiou et al., 1990) for prediction are presented and described. Also in these works, nonlinear optimization problems have to be solved, since the considered prediction model is nonlinear, thus efficient numerical solution algorithms are needed to enable on-line application for large freeway networks. In other approaches, e.g. (Ferrara et al., 2012; Groot et al., 2011; Maggi et al., 2013), the considered prediction models are rewritten in linear form by adding integer and binary variables to the finite horizon optimal control problem, which turns out to have a mixed-integer linear or quadratic programming form.

In most of the research works dealing with ramp metering control the main objective of the controller is to minimize congestion, often measured in terms of total time spent by the drivers in the traffic network (Papageorgiou and Kotsialos, 2002). However, the congestion reduction is not the only important objective to pursue, since there are other aspects to be considered in traffic control schemes, such as the minimization of traffic emissions. For instance, in Csikós et al. (2011) a control approach to minimize both travel times and traffic emissions on freeways is discussed, while (Csikós et al., 2013) presents a dynamic model for the dispersion of freeway traffic emissions. Moreover, Zegeye et al. (2012)) proposes a parameterized MPC approach where the travel times and the traffic emissions are minimized jointly, and in Zegeye et al. (2013) an MPC scheme is considered in which the macroscopic traffic flow models and the microscopic emission and fuel consumption models are properly integrated.

In order to explicitly consider traffic emissions as an objective to be minimized, models for evaluating hot exhaust emissions are needed. Emission models have been studied for some decades (Horowitz, 1982) and can be classified according to the geographical scale, the accuracy of the model, and the nature of the emission calculation approach. Among others, simple but very widespread models are the so-called average-speed emission models which assume that the average emission factor for a certain pollutant and a given type of vehicle only depends on the average speed during a trip (Barlow and Boulter, 2009). Different average-speed models have been studied and progressively updated including new vehicle classifications and new emission factors, on the basis of real measured data obtained from different sources (Ntziachristos and Samaras, 2000; Ntziachristos and Kouridis, 2007).

In this paper, we propose a freeway traffic control approach which considers, as control objectives, both the minimization of traffic emissions and the reduction of traffic congestion. A similar idea was proposed in previous works (Pasquale et al., 2014a,b), where the control scheme was based on a local regulator inspired by ALINEA. In this work, instead, an optimal control problem is formulated and solved by applying the feasible direction algorithm and, in particular, a specific version of this algorithm which adopts the derivative backpropagation method RPROP, the effectiveness of which has been widely proven for different traffic control applications (Papageorgiou and Kotsialos, 2004).

A further characteristic of this work is that a two-class macroscopic traffic model and a two-class controller are considered, i.e. two classes of vehicles (cars and trucks) are explicitly modelled and the control scheme is designed in order to define specific control actions for each vehicle class. First of all, the use of a two-class traffic model allows to represent the system behaviour more accurately than with a one-class macroscopic model that considers the whole traffic as a homogeneous fluid. Moreover, from the point of view of control, it is possible to devise separate control actions for the two vehicle classes, for instance by differently weighing the presence of cars and trucks in the freeway system; in practice, this calls for separate on-ramp lanes and signals for cars and trucks, something that is anyhow routinely practiced in some countries (e.g. in The Netherlands and in Australia). Some multi-class models can be found in the literature, such as for instance in Hoogendoorn and Bovy (2001) introducing a gas-kinetic traffic flow model using a platoon-based multi-class description of traffic flows, and in Wong and Wong (2002) where the LWR model is extended to include heterogeneous drivers. A more recent multi-class model is FASTLANE, a first order traffic model which considers state-dependent passenger car equivalents (van Lint et al., 2008). Moreover, some Model Predictive Control approaches for multi-class ramp metering can be found in Deo et al. (2009), Schreiter et al. (2011), and Liu et al. (2014). The two-class model presented in this paper extends the model proposed in Caligaris et al. (2009), which was based on the macroscopic traffic flow model METANET.

This paper is organized as follows. Section 2 introduces the modeling framework, i.e. describes the two-class traffic model, the emission model and the performance indicators used in the paper. Section 3 is devoted to the optimal control problem formulation, whereas Section 4 describes the numerical solution algorithm adopted in this work. Then, in Section 5 some simulation results are reported and discussed, and the conclusions are drawn in Section 6.

2. The modeling framework

This section reports, first of all, the two-class macroscopic traffic flow model adopted for representing the freeway dynamic behaviour, then, the average-speed emission model considered in the paper and, finally, some performance indicators which are considered of particular interest for this work. Some of these indicators are used in the subsequent definition of the proposed control scheme.

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