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A multi-class model-based control scheme for reducing congestion and emissions in freeway networks by combining ramp metering and route guidance ☆

C. Pasquale [a], S. Sacone [a], S. Siri [a,*], B. De Schutter [b]

[a] Department of Informatics, Bioengineering, Robotics and Systems Engineering, University of Genova, Italy
[b] Delft Center for Systems and Control, Delft University of Technology, The Netherlands

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ABSTRACT

The paper proposes a multi-class control scheme for freeway traffic networks. This control scheme combines two control strategies, i.e. ramp metering and route guidance, in order to reduce the total time spent and the total emissions in a balanced way. In particular, the ramp metering and route guidance controllers are feedback predictive controllers, i.e. they compute the control actions not only on the basis of the measured system state, but also on the basis of the prediction of the system evolution, in terms of traffic conditions and traffic emissions. Another important feature of the controllers is that they have a multi-class nature: different classes of vehicles are considered and specific control actions are computed for each class. Since the controllers are based on a set of parameters that need to be tuned, the overall control framework also includes a module to properly determine the gains of the controllers. The simulation analysis reported in the paper shows the effectiveness of the proposed control framework and, in particular, the possibility of implementing control policies that are specific for each vehicle type.

1. Introduction

Different traffic control strategies have been studied by researchers in the last decades in order to improve the travelling conditions of the drivers in freeway networks. Successful strategies are ramp metering, variable speed limits, route guidance, as well as combined strategies which are based on the application of different control measures (Papageorgiou et al., 2003; Hegyi et al., 2009). In the present work, a multi-class and multi-objective combined ramp metering and routing control strategy is proposed for a freeway network, in order to reduce the total time spent and the total emissions in a balanced way.

Analysing the wide literature on freeway traffic control, it is worth noting that most of the research works are devoted to the sole reduction of congestion phenomena, i.e. to the minimisation of the total time spent by the drivers in the traffic network, which has been proven to be equivalent to maximise the throughput in the system (Papageorgiou and Kotsialos, 2002, 2004; Burger et al., 2013). However, in the last years, many other aspects have received great attention for enhancing the mobility of people and the quality of traffic systems, such as the reduction of pollutant emissions, noise, and environmental deterioration, as well as the increase of safety. Hence, also in the design of traffic control schemes for realising sustainable

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* Corresponding author.
E-mail address: silvia.siri@unige.it (S. Siri).

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traffic systems, these environment-related aspects can be explicitly taken into consideration. For instance, in the works by Zegeye et al. (2013), Liu et al. (2014a) and Pasquale et al. (2015b), ramp metering or combined control strategies are studied to take into account the reduction of traffic congestion as well as the decrease of emissions. These objectives are also pursued by the controllers proposed in this paper which aim to balance the two objectives in a freeway network by means of proper ramp metering and routing control actions.

The combination of ramp metering and routing control strategies exploited in this paper is motivated by their high effectiveness in freeway networks. Ramp metering is one of the most common freeway traffic control strategies, which regulates the traffic flow entering the freeway mainstream by using traffic lights positioned at the on-ramps (Papageorgiou and Papamichail, 2008). Route guidance is another common traffic control technique which has been broadly applied in large freeway networks to suggest the drivers the best paths to follow in specific traffic conditions (Ben-Akiva et al., 2001). Many real applications have shown that ramp metering and routing control are effective strategies, which surely show their highest potential when combined together (Kotsialos et al., 2002).

One of the features of the work developed in this paper is that different classes of vehicles are explicitly considered, i.e. cars, trucks, or specific vehicles, which present different dynamic behaviours and have different environmental impacts on the freeway system. In particular, not only the macroscopic dynamic model used in this paper to represent the evolution of the freeway network is of the multi-class type, but also the considered controllers are designed in order to define specific control actions for different vehicle classes. The idea of proposing a multi-class regulator is rather recent and has been developed in few research works, such as for instance by Pasquale et al. (2015b), Caligaris et al. (2007), Schreiter et al. (2011) and Liu et al. (2017). It is important to emphasise that the use of a multi-class macroscopic model allows to represent the traffic system behaviour more accurately than with a one-class model which assumes that the whole traffic is a homogeneous fluid. This is true for instance in case a high percentage of trucks is present in the freeway traffic system, since trucks have a strong impact on the overall traffic flow for many reasons (because of their high dimensions and low operating capabilities, because their presence has a psychological impact on the drivers of nearby vehicles, and so on). Moreover, the use of a multi-class traffic model is particularly adequate for roads with multiple lanes, as it normally happens in freeways, in which fast vehicles can overtake slow vehicles, thus generating different flows sharing the same infrastructure.

In addition, setting separate control actions for the different classes of vehicles can represent a further opportunity to make the freeway traffic system perform more efficiently, for instance by assigning different priorities to the different vehicle categories. In practice, controlling separately the different vehicle classes via ramp metering means that separate lanes and signals must be present at on-ramps, as it is already practiced in some countries for cars and trucks (New Zeland Transport Agency, 2011; Burley and Gaffney, 2013). In the present work, we assume that the considered freeway is provided with dedicated on-ramps for each class of vehicles. As for route guidance, different indications must be given to the different vehicle typologies, normally displayed on Variable Message Signs (VMS). Note that the increasing availability of on-board devices enables the implementation of routing indications communicated directly to vehicles and further motivates the distinction of the traffic flow in different vehicle classes.

The design requirements of the proposed control scheme are the following:

- effective use of system state measurements and predictions;
- definition of dedicated control actions (ramp metering and route guidance) for different vehicle classes;
- improvement of the system performance defined as the combined reduction of travel times and traffic emissions;
- computational effort suitable for an on-line implementation.

To meet these requirements, a feedback predictive control scheme has been designed in which the control action is computed on the basis of the measured system state and, also, on the prediction of the system evolution. The aim of the regulators is to reduce travel times and traffic emissions through specific control actions for different vehicle classes. Finally, the last requirement has led to the choice of a control scheme in which no on-line optimisation is required, differently from what has been done in other works in which Model Predictive Control (MPC) techniques have been adopted (e.g. by Karimi et al., 2004; Sacone and Siri, 2012; Muralidharan and Horowitz, 2015; Ferrara et al., 2015b). Indeed, in MPC schemes a large-scale nonlinear optimisation problem should be solved on-line, with a high computational load affordable only in small freeway networks.

The paper is organised as follows. In Section 2 a detailed literature review is carried out. Section 3 is devoted to present the multi-class macroscopic traffic model adopted in this paper, while the considered macroscopic VERSIT+ emission model is analysed in Section 4. The proposed multi-class and multi-objective control framework is introduced in Section 5, whereas its main components, i.e. the controllers and the gains selector, are described in detail in Section 6 and in Section 7, respectively. Some simulation results are discussed in Section 8, and conclusive remarks are drawn in Section 9.

2. Literature review

In the following, a detailed review of the literature is reported for the main topics of the proposed work, i.e. multi-class traffic flow models, emission models, as well as ramp metering and route guidance control. The section ends with the detailed description of the paper contributions.