Transportation Research Part C 46 (2014) 309–325

Contents lists available at ScienceDirect

Transportation Research Part C

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

Hybrid model predictive control for freeway traffic using discrete speed limit signals

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ARTICLE INFO

Article history:
Received 15 April 2013
Received in revised form 11 June 2014
Accepted 24 June 2014

Keywords:
Traffic control
Model predictive control
Hybrid control
ITS
Freeway

ABSTRACT

In this paper, two hybrid Model Predictive Control (MPC) approaches for freeway traffic control are proposed considering variable speed limits (VSL) as discrete variables as in current real world implementations. These discrete characteristics of the speed limits values and some necessary constraints for the actual operation of VSL are usually underestimated in the literature, so we propose a way to include them using a macroscopic traffic model within an MPC framework. For obtaining discrete signals, the MPC controller has to solve a highly non-linear optimization problem, including mixed-integer variables. Since solving such a problem is complex and difficult to execute in real-time, we propose some methods to obtain reasonable control actions in a limited computation time. The first two methods (θ-exhaustive and θ-genetic discretization) consist of first relaxing the discrete constraints for the VSL inputs; and then, based on this continuous solution and using a genetic or an exhaustive algorithm, to find discrete solutions within a distance θ of the continuous solution that provide a good performance. The second class of methods split the problem in a continuous optimization for the ramp metering signals and in a discrete optimization for speed limits. The speed limits optimization, which is much more time-consuming than the ramp metering one, is solved by a genetic or an exhaustive algorithm in communication with a non-linear solver for the ramp metering. The proposed methods are tested by simulation, showing not only a good performance, but also keeping the computation time reduced.

1. Introduction

Traffic congestion on freeways is a critical problem due to its negative impact on the environment and many other important consequences like higher delays, waste of fuel, a higher accident risk probability, etc. In the last decades, a lot of research has been focused on making a better use of the available traffic infrastructure, since solutions like the construction of new freeways are not always viable to implement in the short-term due to technical, political, legal, or economic reasons. It has been reported in the literature under different conditions that dynamic traffic control is a good solution to decrease congestion (Hegyi, 2004; Muralidharan and Horowitz, 2012; Hegyi and Hoogendoorn, 2010). In general, dynamic traffic control uses measurements of the traffic conditions over time and computes dynamic control signals to influence the behavior of the

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http://dx.doi.org/10.1016/j.trc.2014.06.005
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drivers and to generate a response in such a way that the performance of the network is improved, by reducing for example the delays, emissions, etc.

Variable speed limits, ramp metering, and route guidance are some of the most often used examples of freeway traffic signals that can be used to dynamically control traffic. These measures have been already successfully implemented in USA, Germany, Spain, the Netherlands, and other countries (van den Hoogen and Smulders, 1994; Papageorgiou et al., 1990; Hegyi and Hoogendoorn, 2010). When selecting the control signals, among the available options described in the literature, the methods based on the use of advanced control techniques like Model Predictive Control (MPC) (Camacho and Bordons, 2004) have by simulation proved to substantially improve the performance of the controlled traffic system (Frejo and Camacho, 2011; Muralidharan and Horowitz, 2012; Frejo and Camacho, 2012; Hegyi, 2004). In the current paper, we focus on control using variable speed limits (VSL) together with ramp metering (see Fig. 1). In most of the works about VSL computed with MPC, the VSL signals are assumed to have continuous values, meaning that the real VSL panels implemented in the network should display to the driver those values (Muralidharan and Horowitz, 2012; Frejo and Camacho, 2011; Hegyi, 2004; Zegeye et al., 2012; Gomes and Horowitz, 2006). However, in the real implementations of VSL panels, the displayed signals are just allowed to take a limited set of discrete values. For example, in the Dutch freeway A12 the signals of the panels are just allowed to take values in the set $\{60, 80, 100\}$ km/h (Hegyi and Hoogendoorn, 2010). Moreover, for safety reasons, some extra constraints should be considered like a limited variation over time (for each panel) and a limited variation over space (consecutive panels) so to avoid drastic changes in speed (Hegyi et al., 2005b; Castelan-Carlson et al., 2011).

The following works have proposed ways to deal explicitly with discrete VSL. In Hegyi et al. (2008), it is proposed a discrete VSL controller based on shock wave theory. In Canudas de Wit (2011), a traffic model with variable length segments is used to compute a simple best-effort controller that reduces congestion considering VSL signals that can only be decreased or increased by steps of 10 km/h. Both controllers, (Hegyi et al., 2008 and Canudas de Wit, 2011), use simple control laws that are not explicitly designed to optimize a performance index of the network. In Hegyi et al. (2005b) and Castelan-Carlson et al. (2011) the VSL are discretized (by rounding, ceiling, or flooring) after computing them in a continuous way. These papers conclude that the performance of the discretized speed limits was comparable with the continuous case. However, those results depend on the network configuration and the demand conditions, as in our case study we found some important loss of performance due to the discretization (Frejo et al., 2013). So, in this paper, we consider explicitly the effects of using discrete signals for the VSL panels in an MPC framework. Subsequently, we propose new efficient algorithms for the computation of discrete VSL signals together with continuous ramp metering rates.

Section 2 briefly introduces the general concepts of traffic model METANET, of Model Predictive Control, and the safety and operational constraints that appear in a real VSL implementation. Section 3 introduces the common characteristics of the proposed methods to obtain discrete signals using the continuous solution for the VSL panels. In Section 4, an exhaustive and a genetic procedure are used to obtain feasible discrete solutions within a θ distance to the continuous solution provided by the MPC controller. Section 5 proposes methods to obtain the MPC solution by solving iteratively a continuous optimization for the ramp metering and a discrete optimization for the VSL without using the continuous MPC solution. Again, an exhaustive algorithm and a genetic algorithm are proposed. The scenario and the numerical results are presented and discussed in Section 6. Finally, Section 7 shows a summary of the results and the conclusions.

2. Freeway traffic control using model predictive control

2.1. Traffic model METANET

In this paper, we have selected the traffic model METANET (Papageorgiou et al., 2010). However, it is important to note that the methods we propose are independent of the traffic model used, so they can be equivalently applied using other

Fig. 1. VSL implementation on A13. Delft, The Netherlands.