Transportation Research Part C 58 (2015) 532–553

Contents lists available at ScienceDirect

Transportation Research Part C

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

Computationally efficient model predictive control of freeway networks

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A R T I C L E I N F O

Article history:
Received 2 October 2013
Received in revised form 12 January 2015
Accepted 16 March 2015
Available online 15 April 2015

Keywords:
Model predictive control
Optimal control
Ramp metering
Variable speed limits
Computationally efficient controllers

A B S T R A C T

A computationally efficient model predictive controller for congestion control in freeway networks is presented in this paper. The controller utilizes a modified Link-Node Cell Transmission Model (LN-CTM) to simulate traffic state trajectories under the effect of ramp metering, variable speed limit control and compute performance objectives. The modified LN-CTM simulates freeway traffic dynamics in the presence of capacity drop and ramp weaving effects. The objective of the controller can be chosen to represent commonly used congestion performance measures like total congestion delay measured in units of vehicle hours. The optimal control formulation based on this modified model is non-convex making it inefficient for direct use within a model predictive framework. Heuristic restrictions and relaxations are presented which allow the computation of the solution using optimal solutions of a sequence of derived linear programs. Mainly, the freeway is cleverly divided into regions, and limited restrictions are placed on solution trajectories to allow us to derive computationally efficient control actions. In the absence of capacity drop, this solution strategy provides optimal solutions to the original optimal control problem by solving a single linear program. The properties of the solution are discussed along with the role of variable speed limits when capacity drop is present/absent. Examples are provided to showcase the computational efficiency of the solution strategy, and scenarios simulated using the modified LN-CTM are analyzed to investigate the role of variable speed limits as a congestion control strategy.

1. Introduction

Traffic congestion can be encountered in metropolitan areas during various time periods across the day or sometimes during the night. An average commuter experiences recurrent congestion during his commute due to presence of system bottlenecks. In addition, non-recurrent events, both planned (road work, public events) and unplanned (accidents) contribute increasingly to the unreliability in commute times. The 2012 annual urban mobility report (David Schrank and Tim, 2012) compiled by the Texas Transportation institute calculated that the average commuter experienced 38 h of delay in 2011, up from 14 h in 1982. In 2011, congestion costs accumulate over $121 billion dollars, which is more than $818 per commuter. The easiest way to combat congestion is through infrastructure expansions. Adding additional lanes and new freeways are not always feasible due to economic, environmental or space restrictions. As a result, transportation engineers increasingly rely on intelligent operational management of the existing infrastructure to improve system efficiency, and traffic control is one such strategy.

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http://dx.doi.org/10.1016/j.trc.2015.03.029

Ramp metering and variable speed limits are two commonly used control strategies to regulate traffic flow and delay the onset of congestion. Ramp metering is a control method which utilizes a traffic light present at the ramp entrance to regulate the traffic entering the freeway. Over the years, many ramp metering algorithms have been developed and deployed. The simplest ones are fixed time of day controllers which specify a fixed rate at any particular time of the day. Percent occupancy control is a widely deployed traffic responsive ramp metering strategy that uses occupancy thresholds to determine the metering rates. Alinea is a popular ramp metering algorithm based on feedback control theory (Papageorgiou et al., 1991). The basic version is an integral controller, which regulates the density downstream of the ramp to be around the target density (which is usually chosen as the critical density). Compared to the percent occupancy scheme, which is a feedforward controller, Alinea is a feedback controller and its field implementations have yielded improved performance (Papageorgiou et al., 1997). Various versions of ALINEA, including the upstream ALINEA (which uses density measurements upstream of the ramp) and FL-ALINEA (which uses flow measurements) have been developed (Smaragdis and Papageorgiou, 2003). Various coordinated ramp metering strategies have been presented in literature and deployed in the field. The most popular ones include Compass, Bottleneck algorithm, SWARM (Systemwide adaptive ramp metering), ZONE algorithm and METALINE, among others (Zhang et al., 2001). Heuristic Co-ordinated ramp metering (HERO), a coordinated ramp metering strategy (Papamichail et al., 2010), was recently deployed successfully in the Monash freeway in Australia. Ramp metering is usually deployed in conjunction with queue overrides and integral queue regulators to prevent spill backs from the ramps to the city streets (Sun and Horowitz, 2005).

Recently, variable speed limits(VSL) have captured the interest of researchers and practitioners as another popular control strategy for traffic regulation in freeways. Variable message signs display the current speed limits, often determined in response to the current road, traffic and weather conditions. In some installations, the posted speeds are advisory, while many require mandatory compliance with enforcement. In most of the installations, the main target objective is to ensure traffic safety, and the VSL's are designed to ensure speed reduction and homogenization in locations with high traffic incidents (van den Hoogen and Smulders, 1994). There are a few studies documenting the direct effect of VSL on aggregate traffic flow characteristics (Papageorgiou et al., 2008). Hegyi et al. (2005), Carlson et al. (2010), Carlson et al. (2010), Heydecker and Addison (2011), and Heydecker and Addison (2010) represent a sample of studies that include VSL as one of the components of congestion control.

Model based predictive controllers use predicted demands along with a model of the freeway network to specify ramp metering rates and/or variable speed limits for freeway traffic control. These strategies typically employ an optimal control/optimization framework to design the control actions to minimize a chosen performance objective function (Burger et al., 2013). Historically, simple models have been used to design optimal strategies (Wattleworth, 1965; Blinkin, 1976; Papageorgiou and Mayr, 1982). With improved computational capabilities, more accurate macroscopic models including first order models (eg. Cell Transmission Models, (Daganzo, 1994)) as well as second order models (METANET – Kotsialos and Papageorgiou, 2004) have become popular choices for freeway optimal control formulations in recent years (Kotsialos et al., 2002; Kotsialos and Papageorgiou, 2004; Gomes et al., 2006; Hegyi et al., 2005; Carlson et al., 2010; Papamichail et al., 2010; Carlson et al., 2010). While the formulation of these optimal control problems is typically easy, the challenge remains in specifying a solution technique which can calculate good quality solutions without being computationally intensive. This is because the optimization problems that arise in these optimal control formulations are large-scale in nature (typically involving thousands of variables, at the least, for even a small freeway section), apart from being nonlinear and non-convex. Applying commonly available solution techniques lead to large computation times (Kotsialos and Papageorgiou, 2004) with no guarantees of global optimality of the solution. The former proves to be a drawback when the controller is embedded as a part of a model predictive framework, since this requires fast optimizations to be executed repeatedly (Kotsialos and Papageorgiou, 2004). Optimal controller formulations based on second order models like METANET (e.g. Kotsialos and Papageorgiou, 2004; Hegyi et al., 2005; Carlson et al., 2010) suffer from these disadvantages.

In contrast, optimal controller formulations based on the Cell Transmission Model show more promise in terms of computational efficiency and global optimality of the generated solution (Ziliaskopoulos, 2000; Gomes et al., 2006). Gomes et al. (2006) present an optimal ramp metering controller based on the Asymmetric Cell Transmission Model (ACTM) along with an efficient solution strategy. The underlying freeway dynamics in the controller formulation is the ACTM, which is presented as a simplification to the CTM. The motivation for this simplification is to provide a higher quality and efficiently computable solution as compared to the original optimal control problem. The authors presented a relaxed version of this optimal ramp metering problem, and proved that the problems are equivalent in terms of the optimal solution trajectory. The relaxed problem is a linear optimization problem, which can be solved efficiently for large freeway networks with long time horizons. While simplified first order models promise computationally efficient and globally optimal solutions, the underlying models do not incorporate phenomena of interest such as weaving and capacity drops. This limits the usefulness of the solutions in many locations where both these effects may be observed (Papageorgiou et al., 2008).

An optimal controller, which ensures global optimality and fast solutions while accounting for weaving and capacity drop is absent. Therefore, we introduce a new model predictive control strategy based on an augmented Link-Node Cell Transmission Model (LN-CTM) (Muralidharan and Horowitz; Muralidharan, 2012). The model predictive controller solves an optimal control problem at each sample step after measuring the state of the freeway. The modified LN-CTM is used to calculate the state evolution of the freeway in the presence of the capacity drop and ramp weaving effects. The optimal controller constructed using the modified LN-CTM model is shown to be non-convex, and strategies that rely on heuristic assumptions are presented to allow the efficient computation of the solution of the original optimal control problem.