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Hierarchical ramp metering in freeways: An aggregated modeling and control approach

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ABSTRACT

This paper develops a model-based hierarchical control method for coordinated ramp metering on freeway networks with multiple bottlenecks and on- and off-ramps. The controller consists of two levels where at the upper level, a Model Predictive Control (MPC) approach is developed to optimize total network travel time by manipulating total inflow from on-ramps to the freeway network. The lower level controller distributes the optimal total inflows to each on-ramp of the freeway based on local traffic state feedback. The control method is based on a parsimonious aggregated traffic model that relates the freeway total outflow to the number of vehicles on the freeway sections.

Studies on aggregated traffic modeling of networks have shown the existence of a well-defined and low-scatter Macroscopic Fundamental Diagram (MFD) for urban networks. The MFD links network aggregated flow and density (accumulation). However, the MFD of freeway networks typically exhibits high scatter and hysteresis loops that challenge the control performance of MFD-based controllers for freeways. This paper addresses these challenges by modelling the effect of density heterogeneity along the freeway and capacity drop on characteristics of freeway MFD using field traffic data. In addition, we introduce a model to predict the evolution of density heterogeneity that is essential to reproduce the dynamics of freeway MFD accurately. The proposed model is integrated as the prediction model of the MPC in the hierarchical control method.

The proposed coordinated ramp metering method shows desirable performance to reduce the vehicles total time spent and eliminate congestion. The control approach is compared with other coordinated ramp metering controllers based on the MPC framework with different traffic prediction models (e.g. CTM and METANET). The outcomes of numerical experiments highlight that the MFD-based hierarchical controller (i) is better able to overcome the modeling mismatch between the prediction model and the plant (process model) in the MPC framework and (ii) requires less computation effort than other nonlinear controllers.

1. Introduction

Ramp metering control is a common operation measure in freeways to regulate flows from on-ramps. There is an extensive literature on ramp metering control. Early works attempted to alleviate local traffic problems using local ramp metering (Papageorgiou et al., 1991). It has been identified that local ramp metering approaches are not always efficient to ameliorate global

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traffic conditions of the overall traffic network (PPapageorgiou and Kotsialosageorgiou and Kotsialos, 2000). Since then, various advanced coordinated ramp metering methods have been developed (e.g. (Chow, 2015)), and a noticeable method among them is the Model Predictive Control (MPC) approach that is based on traffic flow models. MPC framework contains a prediction model that predicts the evolution of traffic dynamics and estimates the optimal control scheme for the time period in which the relevant traffic dynamics occur. This feature enables the controller to take advantage of potentially larger future gains at a current (smaller) cost, so as to avoid myopic control actions. Studies of Kotsialos and Papageorgiou (2004), Hegyi et al. (2005a), Papamichail et al. (2010) presented different optimal approaches of ramp metering that were based on the METANET model. Gomes and Horowitz (2006) presented an optimal freeway ramp metering approach that was based on the asymmetric cell transmission model, which can be efficiently solved by linear programming. Han et al. (2015) presented a linear quadratic MPC approach for ramp metering based on an extended cell transmission model (CTM) which took the capacity drop into account. For a detailed description of METANET and CTM, readers are referred to Kotsialos and Papageorgiou (2004), Daganzo (1994). The aforementioned studies used same models as the prediction model and the process model which represents the reality. However in field applications, there is inherently significant mismatch between the dynamics of the prediction model and the process (plant). Hence, developing a model-based traffic control method that demonstrates robustness to modeling mismatch in the MPC framework will increase the confidence that the proposed approach will also accurately work in practice, where there is always model mismatch. This is a challenging task and is not sufficiently studied in the literature.

This paper seeks potentials in parsimonious macroscopic traffic models for ramp metering to be incorporated in the MPC approach as the prediction model to address the modeling mismatch difficulty. Among them, the Macroscopic Fundamental Diagram (MFD) enable us to develop a hierarchical model-based control method. The MFD provides an efficient tool for expressing aggregated dynamics of traffic networks that links the accumulation (weighted sum of links densities and lengths) and the production (weighted sum of links flows and lengths) of the network (Daganzo, 2007; Geroliminis and Daganzo, 2008). Although a unimodal and low-scatter MFD was observed in a homogeneous region of a city (i.e. with low spatial density heterogeneity), existence of a well-defined MFD in general cases specifically in freeway networks is still an open question, which might undermine the benefits of MFD in modeling traffic dynamics and traffic control applications (Daganzo et al., 2011; Buisson and Ladier, 2009). For example, studies of Mazloumian et al. (2010), Geroliminis and Sun (2011a), Gayah and Daganzo (2011) have shown that urban networks with heterogeneous distribution of density exhibit network flows smaller than those that approximately meet homogeneous conditions. Thus, recent studies focus more on modeling and controlling dynamics of heterogeneity in urban networks (Ramezani et al., 2015; Yildirimoglu et al., 2015). Nevertheless, the MFD-based controllers require less detailed information of traffic states compared to microscopic, mesoscopic, and non-parsimonious macroscopic model-based traffic controllers. The MFD substantially reduces the complexity of traffic models because the packets of vehicular traffic are considered as a single continuum entity (Laval et al., 2017). Furthermore, MFD-based controllers need less computation effort that is beneficial for real-time applications.

The MFD has been utilized to introduce city-scale traffic control strategies, e.g. Perimeter control (Geroliminis et al., 2013), to decrease delays in large-scale urban networks. In the literature, different control approaches have been used to solve the perimeter control problems. For example, classical feedback control approaches have been implemented by Keyvan-Ekbatani et al. (2012, 2015), Kouvelas et al. (2017), Ampountolas et al. (2017), and the model predictive control (MPC) approach has been used to solve the optimal control problems in (Geroliminis et al., 2013; Haddad et al., 2013; Ramezani et al., 2015; Yang et al., 2017). Moreover, methods of MFD estimation are studied in (Leclercq et al., 2014; Laval and Castrillón, 2015; Saberi et al., 2014). Recently, Haddad (2015) designed a robust perimeter controller to systematically take into account uncertainties in MFD-based controllers; Ramezani and Nourinejad (2017) developed a city-scale dispatching of ride-sourcing (e.g. taxi) systems based on the MFD dynamics.

Although MFD-based controllers have been investigated in urban networks, they have not been scrutinized for freeway traffic control. It has been found that a well-defined and low-scatter MFD does not always exist for freeways (Daganzo, 2011). Cassidy et al. (2011) showed that a well-defined and low-scatter freeway MFD can be observed only when traffic is in stable regime (either congested or non-congested) in all lanes and on all links. Studies of Ji et al. (2010), Saberi and Mahmassani (2012), Geroliminis and Sun (2011b) have shown that freeway MFD exhibits hysteresis pattern during the onset and offset of congestion, which represents an adverse effect on the freeway overall performance. In these studies, the heterogeneity of density distribution was perceived as a main factor that causes the hysteresis pattern. Knoop and Hoogendoorn (2013) defined the spatial spread of density as a function of the weighted variance of the densities in all sections, and fitted a third-order polynomial functional form to field traffic data obtained from a Dutch freeway. It was found that by including the density heterogeneity, the accuracy of the MFD improves significantly. In Geroliminis and Sun (2011b), it was found that non-equilibrium states in individual detectors' measurements in freeways, which include transition flows and the capacity drop, also influence the production of the MFD. The traffic patterns in freeway networks have distinct characteristics, e.g., route choice and congestion propagation, that challenge the traffic congestion modeling and management. Thus, understanding and modeling the dynamics of density heterogeneity is crucial for developing MFD-based freeway traffic control schemes. This paper presents a systematic analysis to quantify the effect of determining traffic state factors on MFD and offers a tractable coordinated freeway congestion control method.

The objectives of this paper are twofold related to modeling and control aspects. Regarding the modeling aspect, we introduce a model to capture the evolution of density heterogeneity which is essential to reproduce the dynamics of freeway MFD. Note that the density heterogeneity in this paper refers to the longitudinal heterogeneity along the freeway rather than the lateral heterogeneity across lanes. By analyzing field data, we model the density heterogeneity as (i) a linear function of the average density when no congestion occurs in the freeways and (ii) a non-linear function when congestion occurs. The presented model captures this phenomenon and *predicts* the density heterogeneity. Furthermore, we present a quantitative measure to represent the effect of capacity drop on the MFD, which is fitted to and tested with field data. Regarding the control aspect, we present a hierarchical control