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Dynamics of heterogeneity in urban networks: aggregated traffic modeling and hierarchical control

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ABSTRACT

Real traffic data and simulation analysis reveal that for some urban networks a well-defined Macroscopic Fundamental Diagram (MFD) exists, which provides a unimodal and low-scatter relationship between the network vehicle density and outflow. Recent studies demonstrate that link density heterogeneity plays a significant role in the shape and scatter level of MFD and can cause hysteresis loops that influence the network performance. Evidently, a more homogeneous network in terms of link density can result in higher network outflow, which implies a network performance improvement. In this article, we introduce two aggregated models, region- and subregion-based MFDs, to study the dynamics of heterogeneity and how they can affect the accuracy scatter and hysteresis of a multi-subregion MFD model. We also introduce a hierarchical perimeter flow control problem by integrating the MFD heterogeneous modeling. The perimeter flow controllers operate on the border between urban regions, and manipulate the percentages of flows that transfer between the regions such that the network delay is minimized and the distribution of congestion is more homogeneous. The first level of the hierarchical control problem can be solved by a model predictive control approach, where the prediction model is the aggregated parsimonious region-based MFD and the plant (reality) is formulated by the subregion-based MFDs, which is a more detailed model. At the lower level, a feedback controller of the hierarchical structure, tries to maximize the outflow of critical regions, by increasing their homogeneity. With inputs that can be observed with existing monitoring techniques and without the need for detailed traffic state information, the proposed framework succeeds to increase network flows and decrease the hysteresis loop of the MFD. Comparison with existing perimeter controllers without considering the more advanced heterogeneity modeling of MFD highlights the importance of such approach for traffic modeling and control.

1. Introduction

Efficient traffic control and management of large-scale transportation networks still remain a challenge both for traffic researchers and practitioners. Unlike microscopic approaches that usually utilize disaggregate traffic flow models, as

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behavior of each vehicle is modeled in detail, e.g. car following and lane changing models, in this paper, we follow the macroscopic (network level) approach utilizing the Macroscopic Fundamental Diagram (MFD). The MFD aims at simplifying the micro-modeling task of the urban network, where the collective traffic flow dynamics of subnetworks capture the main characteristics of traffic congestion, such as the evolution of space-mean flows and densities in different regions of a city. Nevertheless, the MFD is not a universal law for all network structures and demands and if it is applied in a non-careful way it can hide critical patterns of congestion and result in inefficient control methods.

The MFD provides a unimodal, low-scatter relationship between network vehicle density (veh/km) and network space-mean flow or outflow (trip completion rate) (veh/h) for different network regions, if congestion is roughly homogeneous in the region. Recently, the macroscopic (network) traffic modeling has intensively attracted the traffic flow community. The physical model of MFD was initially proposed by Godfrey (1969) and observed with dynamic features in congested urban network in Yokohama by Geroliminis and Daganzo (2008), and investigated using empirical or simulated data by Buisson and Ladier (2009), Ji et al. (2010), Mazloumian et al. (2010), Zhang et al. (2013) and others. Earlier works had looked for MFD patterns in data from lightly congested real-world networks or in data from simulations with artificial routing rules and static demands (e.g. Mahmassani et al., 1987; Olszewski et al., 1995 and others), but did not demonstrate that an invariant MFD with dynamic features can arise. The observability of the MFD with different sensing techniques have been studied by Leclercq et al. (2014) and Ortigosa et al. (2014).

Studies Mazloumian et al. (2010), Geroliminis and Sun (2011b), Gayah and Daganzo (2011a), Mahmassani et al. (2013), and Knoop et al. (2013) have shown that networks with heterogeneous distribution of density exhibit network flows smaller than those that approximately meet homogeneity conditions (low spatial variance of link density), especially for high network densities. Networks with small variance of link densities have *a well-defined* MFD, i.e. low scatter of flows for the same densities. Heterogeneously congested networks might exhibit points below the upper envelope of an MFD or strong hysteresis loops (see for example freeway networks in Geroliminis and Sun (2011a) and Saberi and Mahmassani (2013)). Recently, in agreement with previous publications in heterogeneity, Mahmassani et al. (2013) proposed and calibrated with simulated data an MFD where the heterogeneity decreases the MFD output with a functional relationship. Following these findings the concept of an MFD can be applied for heterogeneously loaded cities with multiple pockets of congestion, if these cities can be partitioned into a small number of homogeneous clusters. Recent work Ji and Geroliminis (2012) created clustering algorithms for heterogeneous transportation networks with an objective to obtain small variance of link densities within a cluster. Understanding and modeling the dynamics of heterogeneity is a crucial and challenging question that can shed more light on how to develop smarter hierarchical traffic control schemes for large-scale urban networks. This paper moves towards this direction.

The MFD can be utilized to introduce elegant real-time control strategies to improve mobility and decrease delays in large urban networks, that local ones are unable to succeed, see for example Daganzo (2007), Haddad and Geroliminis (2012) and Geroliminis et al. (2013). Perimeter flow control strategies, i.e. manipulating the transfer flows at the perimeter border of the urban region, utilizing the concept of the MFD have been introduced for single-region cities in Daganzo (2007), Keyvan-Ekbatani et al. (2012), Gayah et al. (2014) and Haddad and Shraiber (2014), and for multi-region cities in Haddad and Geroliminis (2012), Geroliminis et al. (2013), and Aboudolas and Geroliminis (2013). Moreover, route guidance strategies with the utilization of MFD have been studied in Knoop et al. (2012) for grid networks without traffic lights. Gayah and Daganzo (2011b) and Leclercq and Geroliminis (2013) also studied simple routing strategies for two-bin or two-route network abstractions.

In Haddad et al. (2013) different control strategies with different levels of coordination have been introduced for metropolitan transportation networks that have a hierarchical structure which consists of freeways and urban roads. Previous works Daganzo and Geroliminis (2008), Geroliminis and Boyacı (2012) and Zhang et al. (2013) have shown that traffic-responsive signal control strategies and different signal settings can change the shape of the MFD and the critical accumulations. While in both works Geroliminis et al. (2013) and Haddad et al. (2013), do not explicitly model the effect of link heterogeneity, in this paper we aim at studying the effect of heterogeneity by introducing a new modeling approach that considers MFD of regions and smaller subregions. This work also models a simple route choice process between paths through subregions, and considers the effect of subregion flow receiving capacity.

The control problems in previous works, e.g. Geroliminis et al. (2013) and Haddad et al. (2013), have been solved by the model predictive control (MPC) approach. It was shown that this control approach can handle different levels of error in traffic demand and noise in MFDs shape. Nevertheless, the model and the plant in the MPC framework were inherently similar, though the errors in demand and the MFD distinguish between the two. A stronger level of dissimilarity between the model and the plant can provide a more convincing evidence for the applicability of such approaches in more realistic and complex networks.

The objectives of this paper are twofold, in modeling and control aspects. First, we further investigate the relation between the heterogeneity and the MFD. With respect to modeling, we investigate the dynamics of heterogeneity and how it can affect accuracy and scatter of a multi-region MFD model, which consists of variables that can be obtained with existing sensor technology. While there is some work how heterogeneity influences the shape of the MFD, there is no theoretical work to investigate how an asymmetric demand pattern can affect the distribution of congestion over time and space and its dynamic behavior. Existing MFD dynamic models as expressed in various publications are hysteresis-free and as a result the developed control frameworks based on such models cannot be trusted when hysteresis appears. With respect to control, our objective is to integrate the dynamics of heterogeneity in the optimization framework and design