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Equilibrium analysis and route guidance in large-scale networks with MFD dynamics

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A B S T R A C T

Recent studies have demonstrated that Macroscopic Fundamental Diagram (MFD), which provides an aggregated model of urban traffic dynamics linking network production and density, offers a new generation of real-time traffic management strategies to improve the network performance. However, the effect of route choice behavior on MFD modeling in case of heterogeneous urban networks is still unexplored. The paper advances in this direction by firstly extending two MFD-based traffic models with different granularity of vehicle accumulation state and route choice behavior aggregation. This configuration enables us to address limited traffic state observability and to scrutinize implications of drivers' route choice in MFD modeling. We consider a city that is partitioned in a small number of large-size regions (aggregated model) where each region consists of medium-size sub-regions (more detailed model) exhibiting a well-defined MFD. This paper proposes a route guidance advisory control system based on the aggregated model as a large-scale traffic management strategy that utilizes aggregated traffic states while sub-regional information is partially known. In addition, we investigate the effect of equilibrium conditions (i.e. user equilibrium and system optimum) on the overall network performance, in particular MFD functions.

1. Introduction

Research on congestion propagation in large urban networks has been mainly based on micro-simulations where traffic dynamics are defined at the link level. However, because of unpredictability of travelers' behavior and high complexity of traffic physical modeling, microscopic simulation models are time consuming and case dependent. In addition, traffic congestion management in large-scale urban systems is currently fragmented and uncoordinated with respect to optimizing the goals of travel efficiency and equity for multiple regions of a city. An alternative, which is investigated in this article, is a regional route guidance strategy, where a network is partitioned into homogeneous regions and drivers are given a regional path to follow (e.g. going through the city center or using the longer route at the periphery). On the other hand, the effect of driver adaptation models on the aggregate network performance is not fully explored. Microscopic simulation models depend on enroute decision mechanisms, where drivers update their routes based on instantaneous travel times at the network. This behavioral assumption may cause uneven distribution of congestion in the network and reduce the network flow especially in the unloading phase where certain parts of the network are already more congested than others. However,

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under equilibrium conditions drivers are expected to make decisions based on experienced travel costs, which may lead to a more homogenous network in both loading and unloading phases. Understanding these interactions for heterogeneously congested cities is a big challenge, which will allow revisiting, redesigning, and integrating smarter traffic management approaches to alleviate congestion with a ''system of systems'' approach.

The traffic modeling in this paper is based on the network macroscopic fundamental diagram (MFD) that provides a unimodal, low-scatter, and demand-insensitive relationship between network vehicle density and space-mean flow in homogeneous urban areas (with small spatial link density heterogeneity) (Geroliminis and Daganzo, 2008). The idea of an MFD with an optimum accumulation belongs to Godfrey (1969) and similar approaches were introduced later by Herman and Prigogine (1979), Mahmassani et al. (1984) and Daganzo (2007). However, urban transportation networks exhibit uneven distribution of congestion which leads to a scattered flow-density relationship. Heterogeneity in congestion distribution can affect the shape/scatter or even the existence of MFD (Buisson and Ladier, 2009; Geroliminis and Sun, 2011). By using a grid network and considering variance of link density (over space) as an independent variable, Mazloumian et al. (2010) shows that MFD remains well-defined in subregions of the urban network. These results are very critical, because MFD concept can be useful for heterogeneously loaded cities, if the network can be partitioned into smaller homogenous areas. The effect of heterogeneity has been recently studied by many researchers with similar conclusions, see for example (Daganzo et al., 2011; Mahmassani et al., 2013b; Geroliminis and Sun, 2011; Doig et al., 2013) and others. Ji and Geroliminis (2012) develops a static partitioning mechanism to minimize the variance of link densities while maintaining a spatially compact shape. Resulting subregions can be used to develop macroscopic traffic control strategies. In case of hierarchical networks with respect to topology, e.g. mixed freeway/arterial networks, hybrid models might be utilized. For example, Haddad et al. (2013) models the urban part of a city with multi-region MFDs, while the freeway network is represented by the Cell Transmission Model (Daganzo, 1994). Transfer flows between the two models guarantee consistency and conservation of flows. More complicated network structures with strong directional flows, limited connectivity, and high variability in trip lengths and connection with MFD modeling and clustering should be further investigated. This is work in progress.

Mahmassani et al. (2013b) and Gayah and Daganzo (2011) investigate the effect of driver adaptation on the shape of MFD through microscopic simulation for different network sizes. They both identify that an increase in driver adaptivity through enroute decision models can influence and shrink the size of hysteresis loops in the network MFD. In addition, Knoop et al. (2012) has developed myopic local re-routing strategies considering the aggregated information from multiple sub-networks. This strategy does not consider the interaction of the vehicles in the following time periods. Leclercq and Geroliminis (2013) investigates approximations of user equilibrium (UE) and system optimum (SO) conditions of a simple network with MFD dynamics and two parallel routes with instantaneous travel times. Their findings reveal that SO improves system performance compared to UE mainly when initial network conditions are not in the congested regime of the MFDs. Nevertheless, the effect of equilibrium flows in real-sized networks has not been tested with MFD dynamics. In addition, stability analysis for MFD dynamics and control has been investigated in Haddad and Geroliminis (2012) and Haddad and Shraiber (2014).

Real-time large-scale traffic management strategies, e.g. multi-region perimeter control (Geroliminis et al., 2013; Haddad et al., 2013; 1), gating (Daganzo, 2007; Keyvan-Ekbatani et al., 2012; Keyvan-Ekbatani et al., 2015)) that benefit from parsimonious models with aggregated network dynamics, provide promising results towards a new generation of smart hierarchical strategies. On the other hand, the estimation of network traffic states for MFD analysis with different types of sensors identifies the applicability of MFD in large scale networks even if limited data exist, see for example (Ortigosa et al., 2013; Gayah and Dixit, 2013; Nagle and Gayah, 2014; Leclercq et al., 2014; Ji et al., 2014). Furthermore, a connection of travel time reliability with network heterogeneity based on MFD concepts have been investigated by Gayah et al. (2013), Mahmassani et al. (2013a), Yildirimoglu et al. (2015).

The primary motivation of the paper is to develop a network-level traffic management scheme to mitigate congestion in urban areas by considering the effect of route choice at an aggregated level. The management scheme is developed based on MFD and consists of a route guidance system that advises drivers a sequence of subregions to assist them in reaching their destination. This study extends the work in Yildirimoglu and Geroliminis (2014) to a route guidance system based on SO conditions. It is worth mentioning that we aim at network-level management strategies, thus the route guidance operates on subregional basis as opposed to conventional link-based route guidance, see for example (Papageorgiou, 1990; Ben-Akiva et al., 1997; Zhou et al., 2008; Ben-Elia et al., 2013; Zhu and Ukkusuri, 2013). The route guidance system can impact the travelers' route decision by providing them with useful information regarding the traffic states of the urban regions. Therefore, drivers can follow a series of subregions that has lower cost (in terms of travel time, fuel consumption, etc.), which might lead to a better overall system performance. The second motivation is to investigate the impact of driver adaptivity on the overall network performance, in particular MFDs. Most of the previous MFD estimations in the literature are based on one-shot simulations where driver adaptivity is incorporated by en-route decision mechanisms (e.g. current best or myopic local re-routing). This study tests the effect of dynamic UE (or DUE) and dynamic DSO (or DSO) flows in the network on the observed MFD functions and the existence of hysteresis loops. This article is the first attempt to integrate equilibrium flow conditions in the network MFD analysis, while different approaches have been utilized in Mahmassani et al. (2013b) (micro-simulation and instantaneous traffic conditions as opposed to equilibrium conditions), Gayah and Daganzo (2011) (a toy network with two rings), and Leclercq and Geroliminis (2013) (two parallel routes).

We investigate the problem where a heterogeneous city, in terms of link density, consists of several smaller and more homogenous subregions, see Fig. 1, where each subregion (1–19) can be represented by a well-defined low scatter MFD.