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A three-dimensional macroscopic fundamental diagram for mixed bi-modal urban networks

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ABSTRACT

Recent research has studied the existence and the properties of a macroscopic fundamental diagram (MFD) for large urban networks. The MFD should not be universally expected as high scatter or hysteresis might appear for some type of networks, like heterogeneous networks or freeways. In this paper, we investigate if aggregated relationships can describe the performance of urban bi-modal networks with buses and cars sharing the same road infrastructure and identify how this performance is influenced by the interactions between modes and the effect of bus stops. Based on simulation data, we develop a three-dimensional vehicle MFD (3D-*v*MFD) relating the accumulation of cars and buses, and the total circulating vehicle flow in the network. This relation experiences low scatter and can be approximated by an exponential-family function. We also propose a parsimonious model to estimate a three-dimensional passenger MFD (3D-*p*MFD), which provides a different perspective of the flow characteristics in bi-modal networks, by considering that buses carry more passengers. We also show that a constant Bus–Car Unit (BCU) equivalent value cannot describe the influence of buses in the system as congestion develops. We then integrate a partitioning algorithm to cluster the network into a small number of regions with similar mode composition and level of congestion. Our results show that partitioning unveils important traffic properties of flow heterogeneity in the studied network. Interactions between buses and cars are different in the partitioned regions due to higher density of buses. Building on these results, various traffic management strategies in bi-modal multi-region urban networks can then be integrated, such as redistribution of urban space among different modes, perimeter signal control with preferential treatment of buses and bus priority.

1. Introduction

Transportation systems in real cities are complex with many modes of transport sharing and competing for limited road infrastructure. While there is a vast literature of the dynamics and the modeling of congestion for vehicular traffic, the effect of service stops (like when a bus or taxi stops to board and alight passengers) in the overall performance of a large-scale urban system still remains a challenge. It is intuitive that the effect of these stops in the network capacity is almost negligible during light demand conditions, but nowadays city centers are experiencing high level of congestion and the frequency in

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time and space of these stops is significantly high. While one bus traditionally creates more congestion than a moving car, the additional delay per passenger carrying is smaller for large bus occupancies, making buses a more sustainable mode of transport compared to cars.

To understand the physics of urban mobility, traffic dynamics of multimodal urban networks need to be analyzed under various network structures. As multiple modes compete for limited urban space, conflicts and interactions are developed resulting in congestion. Existing literature on multimodal traffic mainly focuses on the design and operation of special bus lanes (Site and Filippi, 1998; Daganzo and Cassidy, 2008; Li et al., 2010; Tirachini and Hensher, 2011) or optimization of traffic signals with transit priority (Eichler and Daganzo, 2006; Mesbah and Currie, 2011; Christofa et al., 2013). However there is no significant body of work dedicated on the modeling of traffic dynamics and the influence of each mode on the network performance. Most of the existing works fall short either in the scale of application or the treatment of congestion dynamics (small scale and/or static models). For example, the work by Li et al. (2010) estimates traffic state for each mode based on a BPR (Bureau of Public Roads, 1964) type of model, which works only for static conditions. Site and Filippi (1998), Daganzo and Cassidy (2008) and Tuerprasert and Aswakul (2010) utilize the link-scale Fundamental Diagram, which can experience high scatter and therefore cannot provide accurate estimates of speed and travel time at the network level. These somehow detailed models can also be computationally complex when applied at the network scale.

An aggregated modeling for multimodal systems, following the concept of a macroscopic fundamental diagram (MFD), can be a strong alternative if it unveils similar properties as in the single-mode case of vehicular traffic. The idea of an MFD for car-only urban networks was initially proposed by Godfrey (1969) and was re-initiated later in Mahmassani et al. (1987) and Daganzo (2007). The demonstration of its existence with dynamic features and empirical data from Yokohama was recent by Geroliminis and Daganzo (2008). This work showed that the MFD is a property of the network itself (infrastructure and control) if the network is homogeneously congested and not very sensitive to demand, i.e. the space-mean flow is maximum for the same value of critical density of vehicles, for many origin-destination tables. Recent works also highlighted that the spatial distribution of congestion can affect the shape and the scatter of the MFD with higher flows observed for less spatial heterogeneity, e.g. Mazloumian et al. (2010), Geroliminis and Sun (2011), Mahmassani et al. (2013), and Knoop et al. (2013). Analytical theories have been derived for the shape of the MFD as a function of network and intersection parameters, using variational theory for homogeneous and heterogeneous network topologies, respectively (Daganzo and Geroliminis, 2008; Geroliminis and Boyaci, 2012; Leclercq and Geroliminis, 2013). The properties of a well-defined MFD, stability and scatter phenomenon are analyzed through many other simulation studies and experimental tests, such as Buisson and Ladier (2009), Ji et al. (2010), Gayah and Daganzo (2011), Saberi and Mahmassani (2012), and Ji and Geroliminis (2012), Mahmassani et al. (2013). Given the MFD of a network, effective traffic management strategies can be readily developed to mitigate congestion, examples including perimeter flow control in Keyvan-Ekbatani et al. (2012), Haddad et al. (2013) and Aboudolas and Geroliminis (2013) and cordon-based pricing in Zheng et al. (2012). Besides, Gonzales and Daganzo (2012) examined system optimum solutions for a transport system with cars and public transit share spaces for the morning commute problem. The authors solved user and system optimum for the bottleneck model and system optimum for the network model (with an MFD representation).

Building on the knowledge of the single-mode MFD, developing and understanding the dynamics of multimodal networks is promising. In this work, we seek to extend the modeling and the application of the single-mode MFD to a bi-modal (bus and cars) one, with the consideration of passenger flows and traffic performance of each mode. If this type of models holds for further scrutiny in multimodal networks, then network level control strategies can be developed to maximize urban mobility. The dynamics of traffic flow in bi-modal networks are more complicated due to the operational characteristics of buses and the interactions between cars and buses. Despite of this complication, simulation studies on small networks showed that a classical MFD applies (under certain conditions) for bi-modal urban networks as well, see e.g. Gonzales et al. (2011) and Zheng and Geroliminis (2013). However, the influence of each mode in the network dynamics and performance is still missing. This relationship, if known, will facilitate the development of control strategies at various levels, e.g. network bus priority (Christofa et al., 2013) or redistribution of urban space (Zheng and Geroliminis, 2013). Therefore we aim at investigating the relationship among the accumulation of cars and buses, and the traffic throughput or circulating flow of a network. Buses have scheduled service stops in addition to stops caused by traffic and signals, which makes the speed and the flow rate of buses lower than cars. On the other hand, buses carry significantly higher number of passengers. Therefore it is insufficient to simply consider vehicle flows and develop the relevant management strategies for a multimodal network. Zheng et al. (2013) presented initial simulation findings on a three-dimensional macroscopic relation between flow and accumulations for a bi-modal network, and proposed to develop a macroscopic passenger flow model.

A semi-analytical approach building on variational theory was developed to estimate an MFD for networks with cars and buses (Boyaci and Geroliminis, 2011). Buses influence traffic when they stop for passengers to enter or exit at bus stops. These stops were treated as periodic red phases of fictitious traffic signals that decrease the capacity of the road at the bus stop locations. While such a framework can provide important insights for network capacity for different operational characteristics of buses, it cannot directly integrate the heterogeneity in the spatial distribution of buses and cars in the network. To shed some light towards this direction a detailed micro-simulation of a congested bi-modal network is performed for various demand scenarios and a relationship between network flow and accumulations of cars and buses is investigated in the current work.

Both the vehicle flow and the passenger flow dynamics were not studied in detail and have to be further investigated. Furthermore, the ratio of car and bus density is not homogeneously distributed in urban networks (due to different location