Transportation Research Part C 82 (2017) 88–101

Contents lists available at ScienceDirect

Transportation Research Part C

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

Empirics of multi-modal traffic networks – Using the 3D macroscopic fundamental diagram

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ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form 12 June 2017
Accepted 13 June 2017
Available online 26 June 2017

Keywords:
Macroscopic fundamental diagram
Multi-modal traffic
Public transport
Urban traffic
Mode share

ABSTRACT

Traffic is multi-modal in most cities. However, the impacts of different transport modes on traffic performance and on each other are unclear – especially at the network level. The recent extension of the macroscopic fundamental diagram (MFD) into the 3D-MFD offers a novel framework to address this gap at the urban scale. The 3D-MFD relates the network accumulation of cars and public transport vehicles to the network travel production, for either vehicles or passengers. No empirical 3D-MFD has been reported so far.

In this paper, we present the first empirical estimate of a 3D-MFD at the urban scale. To this end, we use data from loop detectors and automatic vehicle location devices (AVL) of the public transport vehicles in the city of Zurich, Switzerland. We compare two different areas within the city, that differ in their topology and share of dedicated lanes for public transport. We propose a statistical model of the 3D-MFD, which estimates the effects of the vehicle accumulation on car and public transport speeds under multi-modal traffic conditions. The results quantify the effects of both, vehicles and passengers, and confirm that a greater share of dedicated lanes reduces the marginal effects of public transport vehicles on car speeds. Lastly, we derive a new application of the 3D-MFD by identifying the share of public transport users that maximizes the journey speeds in an urban network accounting for all motorized transport modes.

1. Introduction and background

Potential benefits from public transport provision and improvements in urban transportation networks are not limited to reduction in passengers travel time (Hensher, 2001) or congestion relief (Adler and van Ommeren, 2016; Anderson, 2014), but also include an increase in agglomeration economies (Chatman and Noland, 2011). The literature is abundant regarding the share of public transport users (from the set of all users) that maximizes these benefits (Small and Verhoef, 2007; Tirachini and Hensher, 2012). While infrastructure investments for both modes are long-term-oriented, an optimal modal share of public transport users for the short term considers how travel demand should be allocated to existing infrastructure while improving accessibility for all users. Recent advances in understanding network-wide traffic through the macroscopic fundamental diagram (MFD), a well-defined and reproducible relationship between vehicle network accumulation and network production (Geroliminis and Daganzo, 2008), offer a new approach for optimal demand allocation to existing infrastructure. The MFD is considered invariant to small changes in demand, so network topology in combination with traffic control determine its shape (Daganzo and Geroliminis, 2008). Public transport and private cars do not affect congestion

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http://dx.doi.org/10.1016/j.trc.2017.06.009
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equally (Boyaci and Geroliminis, 2011; Chiabaut et al., 2014; Gronau, 2000). To properly account for these two systems, the MFD must be extended to the multi-modal or 3D-MFD (Geroliminis et al., 2014), that integrates transport modes. Although promising, no empirical 3D-MFD has yet been reported. Such empirical study, however, is crucial for further applications of the 3D-MFD in transportation and economics.

In this paper, we present the first empirical estimate of a 3D-MFD at the urban scale, using data from loop detectors and automatic vehicle location devices (AVL) for the city of Zurich, Switzerland. We combine both vehicle and passenger data to statistically estimate the multi-modal interaction effects at vehicle and passenger levels. We compare such interaction effects for two regions in the city of Zurich differing in their share of dedicated lanes for public transport. We find evidence that cars and public transport vehicles do not contribute equally to congestion and that a greater share of dedicated lanes reduces multi-modal interaction effects. Finally, we derive a new application of the 3D-MFD by linking the share of public transport users to the average journey speeds in the city. Using this approach, we then identify the optimal share of public transport users that maximizes journey speeds in an urban area (considering all motorized transport modes).

In the following, we give a literature overview. First, we concentrate on the car MFD, then on the interactions between cars and public transport at a network level, from both vehicle and passenger perspectives, including the concept of the 3D-MFD.

Origins of the MFD can be traced back to network traffic flow theory in the 1960s and are based on work by Godfrey (1969), Herman and Prigogine (1979), Smeed (1961, 1968), Thomson (1967) and Wardrop (1968). In the 1980s, Mahmassani et al. (1984, 1987) and Williams et al. (1987) used simulations to relate average speed, flow and density at the network level. The studies found that the network relationships of these variables are similar to their link-based counterparts. The concept of the macroscopic traffic flow analysis was then re-initiated by Daganzo (2007). Daganzo and Geroliminis (2008) used variational theory to analytically derive the MFD as a characteristic of a network (free flow speed, average link length, link capacity, traffic signal cycle characteristics, jam density, and backward wave speed) and found it to be a well-defined and reproducible curve. Laval and Castrillón (2015) showed with a stochastic approach that the two dimensionless parameters, mean block length to green ratio and the mean red to green ratio, are the main drivers of the MFDs shape. In addition to simulation and analytical estimates of the MFD, the macroscopic relationship has also been observed using empirical data. The MFD has been shown to exist for Yokohama, Japan (Geroliminis and Daganzo, 2008), Toulouse, France (Buisson and Ladier, 2009), Brisbane, Australia (Tsubota et al., 2014), Shenzhen, China (Ji et al., 2014), Sendai, Japan (Wang et al., 2015) and Zurich, Switzerland (Ambühl et al., 2017). Such estimates are typically based on either loop detector data or floating car data, although both data sources have some drawbacks (Ambühl et al., 2017; Buisson and Ladier, 2009; Du et al., 2016), hence efforts have been made to fuse them (Ambühl and Menendez, 2016). So far, the MFD has been applied to traffic control (e.g. Aboudolas and Geroliminis, 2013; Girault et al., 2016; Haddad and Geroliminis, 2012), pricing (e.g. Zheng et al., 2012, 2016), investigation of the network topology's impact on traffic performance (e.g. Knoop et al., 2014, 2015; Muhlich et al., 2015; Ortigosa et al., 2015, 2017a) and to describe the effects of other systems, in particular parking (e.g. Cao and Menendez, 2015; Geroliminis, 2015; Leclercq et al., 2017; Zheng and Geroliminis, 2016).

Although public transport plays an important role in cities, its impact on traffic at the network level has not received much attention in literature. At the link level, analytical approaches have been developed to quantify maximum capacity of mixed traffic and analyze the effects of stop types, dwell times and distances between stops on speeds (Anderhub et al., 2008; Chiabaut, 2015; Chiabaut et al., 2014; He et al., 2017; Köhler et al., 1998; Lüthy et al., 2016) and empirical data has been used to analyze car capacity with and without buses (Arnet et al., 2015). At intersection level, existing literature on multi-modal interactions is rather large, e.g. Guler and Menendez (2014a,b), He et al. (2016) and Moghimidarzi et al. (2016) analyzed bus priority at signalized intersections and Gu et al. (2013, 2014) analyzed the effects on car traffic of bus stops close to an intersection. At the network level, Smeed (1961, 1968) discussed the effects of car and bus interactions on the respective travel times, and the effect of urban design on traffic performance, emphasizing the dilemma between public and private transport modes for both travel times and vehicle occupancies. Work following Smeed's macroscopic relations was almost non-existent for decades, until Boyaci and Geroliminis (2011) discussed urban design and multi-modal capacities at network level, Nikias et al. (2016) quantified the effects of bus operations on the traffic performance of urban networks, and Geroliminis et al. (2014) extended the MFD to a 3D-MFD using simulation data. The maximum vehicular flow in a 3D-MFD occurs when no public transport vehicles operate. When including passenger flows, the 3D-MFD becomes the 3D-passenger MFD (3D-pMFD). The maximum passenger flow in a 3D-pMFD is observed at non-zero provision of public transport. Chiabaut (2015) related the accumulation of passengers per kilometer to passenger flow and discussed the concept of the 3D-MFD for multi-modal arterials from a passenger's point of view, emphasizing the user and system optimum. While analytical approximations for MFDs concentrating on cars (Daganzo and Geroliminis, 2008; Geroliminis and Boyaci, 2012; Leclercq and Geroliminis, 2013) and multi-modal MFDs (Boyaci and Geroliminis, 2011; Chiabaut, 2015; Chiabaut et al., 2014) exist, empirical MFDs have only been obtained for cars so far. Data describing multi-modal relations has been obtained only from simulations of San Francisco and Zurich (Geroliminis et al., 2014; Menendez et al., 2016; Ortigosa et al., 2017b). First applications of the 3D-MFD (and 3D-pMFD) are related to urban space allocation (Zheng and Geroliminis, 2013), parking (Zheng and Geroliminis, 2016) and mode choice (Schreiber et al., 2016).

The remainder of this paper is organized as follows; in Section 2, we describe the case study for Zurich with the available data. In Section 3, we present the empirical 3D-MFD. In Section 4, we propose a model to quantify the effects of bi-modal traffic at the network level. In Section 5, we show the results of the proposed model for both, vehicles and passengers. In