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On the use of Lagrangian observations from public transport and probe vehicles to estimate car space-mean speeds in bi-modal urban networks

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ABSTRACT

The Macroscopic Fundamental Diagram (MFD) has been recognized as a powerful framework to develop network-wide control strategies. Recently, the concept has been extended to the three-dimensional MFD, used to investigate traffic dynamics of multi-modal urban cities, where different transport modes compete for, and share the limited road infrastructure. In most cases, the macroscopic traffic variables are estimated using either loop detector data (LDD) or floating car data (FCD). Taking into account that none of these data sources might be available, in this study we propose novel estimation methods for the space-mean speed of cars based on: (i) the automatic vehicle location (AVL) data of public transport where no FCD is available; and (ii) the fused FCD and AVL data sources where both are available, but FCD is not complete. Both methods account for the network configuration layout and the configuration of the public transport system. The first method allows one to derive either uni-modal or bi-modal macroscopic fundamental relationships, even in the extreme cases where no LDD nor FCD exist. The second method does not require a priori knowledge about FCD penetration rates and can significantly improve the estimation accuracy of the macroscopic fundamental relationships. Using empirical data from the city of Zurich, we demonstrate the applicability and validate the accuracy of the proposed methods in real-life traffic scenarios, providing a cross-comparison with the existing estimation methods. Such empirical comparison is, to the best of our knowledge, the first of its kind. The findings show that the proposed AVL-based estimation method can provide a good approximation of the average speed of cars at the network level. On the other hand, by fusing the FCD and AVL data, especially in case of sparse FCD, it is possible to obtain a more representative outcome regarding the performance of multi-modal traffic.

1. Introduction and background

Multi-modal urban cities are complex systems, where different modes of transport compete for, and share the limited road infrastructure for serving transport demands. These modes interact with each other, creating conflicts at different road infrastructure levels. While there is a vast and well-established literature towards understanding and mitigating vehicular congestion in single-mode networks, the knowledge on multi-modal networks with passenger mobility consideration is in its infancy.

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In traffic flow theory, various concepts have been proposed to macroscopically model the dynamics of urban networks under steady state traffic conditions (Godfrey, 1969; Herman and Prigogine, 1979; Mahmassani et al., 1987). Following these ideas, Daganzo (2007) suggested a macroscopic relationship between the total outflow from the system and the aggregated accumulation, commonly known today as the Macroscopic Fundamental Diagram (MFD), sometimes also called the Network Fundamental Diagram (NFD) (Mahmassani et al., 2013; Saberi et al., 2014a,b). Later, using empirical data from the city of Yokohama, Geroliminis and Daganzo (2008) confirmed the existence of the MFD and derived an analytical approximation method based on variational theory (Daganzo and Geroliminis, 2008). It was inferred that the maximum space-mean flow remains the same and invariant to small changes in demand patterns, if congestion is homogeneously distributed across the network. Additional scientific literature following this direction can also be found in Boyaci and Geroliminis (2011), who attempted to extend the MFD-based analysis into multi-modal networks, or in Leclercq and Geroliminis (2013), who analyzed the impact of route patterns on the traffic performance. Further research on the MFD, inspired by the use of empirical data, showed that the characteristics of an MFD depend on the location of the data collection and measurement of the traffic stream characteristics (Buisson and Ladier, 2009; Geroliminis and Sun, 2011; Ambühl et al., in press).

Using simulation tools, Papageorgiou and Vigos (2008) derived the relationship between time- and space-occupancy in signalized links, employing a Kalman-Filter estimator for the number of vehicles in the link based on the measurements of (at least) three loop detectors (Vigos et al., 2008). Mazloumian et al. (2010) explored how the spatial variability of vehicle density affects the traffic performance at the network level. The authors emphasized that establishing a strategy for decreasing density variations can improve traffic operations. Such conclusions have triggered the development of routing strategies (Knoop et al., 2012), as well as the gating control strategies for a single-region (Yang et al., 2017) and multiple regions (Aboudolas and Geroliminis, 2013; Ampountolas et al., 2017). Girault et al. (2016) explored the effects of signal coordination on the MFD, revealing that good coordination offers limited benefits, but poor coordination can be very detrimental. Impact of the spatial and temporal distribution of congestion on the shape of the MFD was also investigated by Gayah and Daganzo (2011),Saberi and Mahmassani (2012), and Muhlich et al. (2015), with the focus on the evolution and characterization of hysteresis.

Despite the large amount of research efforts that have been placed on investigating different aspects of single-mode networks, research related to the interactions and influence of various modes at the network level in case of mixed traffic remains mostly unexplored in the literature. The current state of the art provides only few studies that have looked at the features of multi-modal operations and the resulting MFD (Arnet et al., 2015), mainly focusing on designing an optimal public transport service (Wirasinghe et al., 1977), special bus lanes (Daganzo and Cassidy, 2008), pre-signals for bus priority (Guler and Menendez, 2014a; Guler and Menendez, 2014b; He et al., 2016), or providing traffic signal priority for public transport (Eichler and Daganzo, 2006; Christofa et al., 2016). Only recently did researchers demonstrate that a well defined relationship between the average vehicle accumulation and flow is also applicable for multi-modal traffic (Geroliminis et al., 2014; Loder et al., 2017). The authors extended the concept of a single-mode MFD to a three-dimensional MFD (3D-MFD), with the consideration of passenger flows and traffic performance of each mode. It was demonstrated that the passenger 3D-MFD (relating the accumulation of cars and buses to the passenger flow) shows a completely different pattern from the vehicular 3D-MFD (relating the accumulation of cars and buses to the total circulating flow of vehicles), highlighting the importance of modeling passenger traffic dynamics for multi-modal systems. The discussion on passenger MFD can also be found in Chiabaut (2015).

Recent research has also analyzed the influence of bus operations on traffic performance (Nikias et al., 2016), gating controls in bi-modal networks (Chiabaut et al., in press), and the space allocation between cars and buses (Gonzales and Daganzo, 2012; He et al., 2018). However, these works did not provide any quantitative approach connecting the impact of dedicated space to the global traffic performance. This was addressed by Zheng and Geroliminis (2013),Ortigosa et al. (2017), and Zheng et al. (2017), who investigated the difference in performance as a function of the space allocation between mixed and dedicated bus lanes.

Due to the limited amount of available data used to develop an MFD, different estimation methods have been proposed (Leclercq et al., 2014). The present paper further elaborates on this by using the trajectory data from both public transport (collected via automatic vehicle location (AVL) devices as in Bertini and Tantiyanugulchai (2004)) and probe vehicles to better estimate the space-mean speed of cars. Empirical data from the city of Zurich is then used to demonstrate the applicability of the proposed methods in real-life traffic scenarios and provide a cross-comparison with the existing MFD estimation methods. Such empirical comparison is, to the best our knowledge, the first of its kind.

2. MFD estimation: research problem and contribution

2.1. Limitation of the existing methods

In reality, having a perfect macroscopic picture of the traffic performance, or in other words, a ground truth MFD, is almost never achievable, as loop detectors are not installed on all streets/links, nor are all vehicles equipped with GPS devices tracking their movement. Instead, only a portion of streets are surveyed and limited number of vehicles are tracked, compelling researchers to use extrapolation methods to estimate the MFD or the extended 3D-MFD. In most cases, the data comes from either loop detectors or GPS-equipped probe vehicles. If none of these data sources is available, traffic information might also come from some other sources, such as adaptive traffic control systems that report density-like measures, which can be potentially used for constructing the fundamental relationships (Dakic and Stevanovic, 2017).

Recently, it has been shown that the incomplete loop detector data (LDD) can be successfully used to inform an MFD perimeter control (Keyvan-Ekbatani et al., 2013; Ortigosa et al., 2014). However, both studies assumed that the detector measurements are not