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Evaluation of a multimodal urban arterial: The passenger macroscopic fundamental diagram

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ABSTRACT

This paper aims to extend the concept of macroscopic fundamental diagram (MFD) to combine different transportation modes. Especially, we propose a unified relationship that accounts for cars and buses because the classical MFD is not sufficient to capture the traffic flow interactions of a multimodal traffic. The concept of passenger macroscopic fundamental diagram (p-MFD) is introduced. With this new relationship, the efficiency of the global transport system, i.e. behaviors of cars and buses, can be assessed. Intuitively, the p-MFD shape strongly depends on the mode ratio. Thus, user equilibrium and system optimum are studied and compared. Finally, this relationship is used to design bus system characteristics and to identify the optimal domains of applications for different transit strategies.

1. Introduction

Cities and transit agencies worldwide have to face an accelerating demand for mobility as people continue to flock to urban areas seeking access to greater economic, educational, and social opportunities. This poses a challenge to optimally distribute city space to multiple transportation modes. To this end, management strategies have to be dynamic, multiscale, and simultaneously applied to individual cars and other transportation modes (such as public transport).

The core element of such management strategies is a global evaluation function of the transportation network. This function must quantify the performance of the whole system that can combine different transportation modes (individual cars, buses, trams, trucks, etc.). This is thus a challenge to capture the traffic dynamics of a complex network mixing these modes. It turns out that cities are complex and intricate systems. Therefore, they are impossible to model in perfect detail. The approach taken in this paper is to look at the transportation network at a macroscopic level. It is important to notice that the approach of the paper is very idealized. Indeed, the challenge here is to propose a modeling framework as general as possible. Then, it could be applied to a relatively wide range of situations and refined based on the characteristics of these situations.

To this end, we resort to an aggregated and parsimonious model to evaluate the transportation network performance. Such a model provides a better understanding and valuable insights on arterial traffic dynamics. The macroscopic fundamental diagram (MFD) can play this role. Indeed, on their seminal works (Godfrey, 1969; Mahmassani et al., 1984; Daganzo, 2007; Geroliminis and Daganzo, 2008), the authors pointed out a major insight: the MFD is an intrinsic property of the network itself and remains invariant when demand changes. The MFD is thus a reliable tool for traffic agencies to manage and evaluate solutions to improve mobility. Haddad and Geroliminis (2012), Keyvan-Ekbatani et al. (2012), Aboudoulas and

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Geroliminis (2013), De Jong et al. (2013), Chiabaut (2014), Haddad and Shraiber (2014), Ramezani et al. (2015) furnished a very good example of how MFDs can be used to model and quantify *ex ante* effects of control. Moreover, recent works (Boyaci and Geroliminis, 2011; Geroliminis and Boyaci, 2012; Leclercq and Geroliminis, 2013; Xie et al., 2013) propose an accurate method to analytically estimate the MFD for an arterial based on its characteristics (number of lanes, traffic signal parameters, etc.) and the characteristics of the public transport system (Chiabaut et al., 2014).

However, one of the remaining lacks of the MFD is that it only expresses the performance of the system as far as vehicles are concerned. Consequently, the average number of passengers present in each transport mode is not taken into account. Eichler and Daganzo (2006) presented the first instance trying to overcome this drawback. They seek to calculate average the pace for each mode. However, the number of passengers is roughly accounted for and the analysis stays very qualitative according to the authors themselves. Thus we propose in the paper to extend the concept of MFD in order to take into account the number of passengers using the transportation network and not only the number of vehicles. This new relationship is called the passenger macroscopic fundamental diagram (p-MFD). Zheng and Geroliminis (2013), Geroliminis et al. (2014) and Chiabaut et al. (2014) have simultaneously introduced the first principles of this relationship.

The mode choice of travelers should be considered as well. It is intuitive that the effect of the ratio of people using public transport rather than individual cars will impact the performance of the transportation network. The p-MFD makes it possible to address this issue and to understand how traffic conditions are modified by the mode choice of passengers. Different equilibriums can be investigated, notably user and system optimums. The ultimate goal of research toward this direction is to develop a strategy that makes people switch from a mode to the other.

The paper is organized as follow: Section 2 introduces the notion of passenger macroscopic fundamental diagram (p-MFD). Section 3 deeply investigates the impacts of modal choice and makes it possible to analytically compare user and system optimums. Section 4 focuses on the application of the p-MFD to network transportation services optimization. Finally, Section 5 proposes a discussion.

2. Passenger fundamental diagram (P-MFD)

In this first section, we extend the definition of MFD to propose a unified relationship that combines all the modes of an urban transportation network: cars, buses, metro, etc. The idea is to relate the number of passengers within the network to space-mean speed of these passengers according to a specific mode choice model. For the sake of simplicity, we first focus on two modes only: individual cars and buses. It is intuitive that, even in this simplest case, the classical MFD is not sufficient to evaluate the performance of the whole network because a bus counts for a unique vehicle. Notice that the methodology presented hereafter is general and can be extended to multiple modes.

2.1. Case study

As mentioned earlier, recent works suggest that there is a consistent relationship between the average network vehicle density and average network flow. Such a relationship is called a MFD. Consequently, we consider in the remainder of the paper an idealized city. Roads shape a very meshed urban network with signalized intersections (see Fig. 1a). We also assume that the flows are uniformly distributed among origins and destinations (Leclercq et al., 2014). Under this assumption, car traffic dynamics is well reproduced by a MFD $q(k)$ giving the space-mean flow of cars $q_c = q(k)$ (veh/h) on each link as a function of the space-mean density of the links within the city k (veh/km) (see Fig. 1b). Notice that the MFD can now be easily estimated accounting for the effect of buses and control strategies (Geroliminis and Boyaci, 2012; Leclercq and Geroliminis, 2013; Chiabaut et al., 2014). It is also worth noticing that the lower case letters refer to variables expressed in terms of vehicles whereas the upper case letters correspond to variables expressed in terms of passengers. We also assume that the maximal occupancy of a car is ρ_c (pax/veh). Notice that, for a realistic purpose, we consider that the maximal occupancy is equal to the observed average occupancy (1.2 pax/veh) rather than the effective maximal occupancy (5 pax/veh). We first assume a trapezoidal car MFD for the sake of simplicity. This form is convenient to coarsely mimic the influence of traffic signals. The parameters are the free-flow speed u (km/h), the critical speed u_c, the maximal flow capacity q_x and the jam density k_x. The congested wave speed is denoted $w = u \cdot q_x / (u \cdot k_x - q_x)$. We assume that all the links are composed of n lanes ($n = 3$).

We first consider that the public transport system is only composed of buses that share the same roads as the car traffic. We also assume that trips of users can always be realized either by individual car or public transport system. The transit system is characterized by the bus time-headway h (h) and the maximal speed of the buses u_t. We also assume that the maximal occupancy of a bus is ρ_t (pax/bus) and that the buses are mixed with car traffic and no lanes are dedicated to them. Moreover, we consider that the average occupancies of both modes and the number of buses in operation do not depend on the traffic conditions and the mode choice. It turns out that, for a given time-headway h the number of buses n_{bus} in operation is $n_{bus} = L/(h \cdot v_t)$ (Hans et al., 2014a) where L (km) is the length of the bus lines of the transportation network and v_t the average speed of the transit system. Physically, it corresponds to static timetables. Finally, Table 1 provides a nomenclature for the different variables and main parameters utilized in the paper. It also provides the values that have been used to draw illustrations.