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The effect of variability of urban systems characteristics in the network capacity

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ABSTRACT

Recent experimental analysis has shown that some types of urban networks exhibit a low scatter reproducible relationship between average network flow and density, known as the macroscopic fundamental diagram (MFD). It has also been shown that heterogeneity in the spatial distribution of density can significantly decrease the network flow for the same value of density. Analytical theories have been developed to explore the connection between network structure and an MFD for urban neighborhoods with cars controlled by traffic signals. However these theories have been applied only in cities with deterministic values of topological and control variables for the whole network and by ignoring the effect of turns. In our study we are aiming to generate an MFD for streets with variable link lengths and signal characteristics and understand the effect of variability for different cities and signal structures. Furthermore, this variability gives the opportunity to mimic the effect of turning movements. Route or network capacity can be significantly smaller than the capacity of a single link, because of the correlations developed through the different values of offsets. The above analysis would not be possible using standard traffic engineering techniques. This will be a key issue in planning the signal regimes such a way that maximizes the network capacity and/or the density range of the maximum capacity.

1. Introduction

Recent studies (Geroliminis and Sun, 2011b; Mazloumian et al., 2010; Daganzo et al., 2011) has shown that networks with heterogeneous distribution of link density exhibit network flows smaller than those that approximately meet homogeneity conditions (low spatial variance of link density), especially for congested conditions. Also, note that the scalability of flows from a series of links to large traffic networks is not a direct transformation. For example, route or network capacity can be significantly smaller than the capacity of a single link as this is expressed by sG/C (s is the saturation flow, G and C are the durations of green phase and cycle). This is because of the correlations between successive arterial links, the creation of spill-back queues and the effect of offsets (Daganzo and Geroliminis, 2008). In case of long links, these effects are negligible and the propagation of traffic is much simpler. Nevertheless, congestion often occurs in the city centers with dense topology of short links.

At the link scale, traffic flows can be unpredictable or chaotic when a network is critically congested because of different driving behavior patterns, the effect of route choice, the fast dynamics of link travel times and origin–destination tables and the computational complexity (too many particles/cars). These observations make the development of global traffic management strategies, to improve mobility for a large signalized traffic network with a microscopic analysis, intractable. An alternative is a hierarchical control structure, where a network can be partitioned in homogeneous regions (with small spatial

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variance of link density distribution) and optimal control methodologies can identify the inter-transfers between regions of a city to maximize the system output, as expressed by the number of trip endings. These policies can change the spatial distribution of congestion in such a way that the network outflow increases. This is a challenging task that requires knowledge on how the network flow for a region of a city changes as a function of topology, control and level of congestion.

The physical tool to advance this research is the macroscopic fundamental diagram (MFD) of urban traffic, which provides for some network regions a unimodal, low-scatter relationship between network vehicle density (veh/km) and network space-mean flow (veh/h). The first theoretical proposition of such a physical model was developed by Godfrey (1969), while similar approaches were also initiated by Herman and Prigogine (1979) and Daganzo (2007). The physical model of MFD was observed with dynamic features through empirical data in congested urban networks in Yokohama (Geroliminis and Daganzo, 2008). Other empirical or simulated analysis for MFDs with low or high scatter can be found in Buisson and Ladier (2009), Daganzo et al. (2011), Geroliminis and Sun (2011a), Gayah and Daganzo (2011), Courbon and Leclercq (2011), Ji et al. (2010), Saberi and Mahmassani, 2012 and others. Nevertheless, it is not obvious whether the MFDs would be universal or network-specific. More real-world experiments are needed to identify the types of networks and demand conditions, for which invariant MFDs with low scatter exist.

To evaluate topological or control-related changes of the network (e.g. a re-timing of the traffic signals or a change in infrastructure), Daganzo and Geroliminis (2008) and, Helbing (2009) have derived analytical theories for the urban fundamental diagram, using a density-based and a utilization-based approaches respectively. The first reference proved, using variational theory (Daganzo, 2005), that an MFD must arise for single-route networks with a fixed number of vehicles in circulation (periodic boundary conditions and no turns). The same reference also gives explicit formulae for the single-route MFD with deterministic topology, control and traffic characteristics (i.e. all intersections have common control patterns, the length of its links and their individual fundamental diagrams are all the same. The reference conjectured that these MFD formulae should approximately expected to hold for homogeneous, redundant networks with slow-changing demand. The methodology estimates the average speed and the maximum passing rate (rate that cars can overpass him) for a large number of observers moving forward or backward and stopping only at traffic lights. Then by considering that each observer can create a "cut" in the MFD, its shape is estimated as the lower envelope of all these cuts.

In this paper we provide several extensions and refinements of the analytical model for an MFD. We explore how network parameters (topology and signal control) affect two key characteristics of an MFD, (i) the network capacity and (ii) the density range for which the network capacity is maximum. We first provide an analytical proof that simplifies the estimation of the density range for which the network capacity is maximum by utilizing only spatial and control parameters of the network. We also investigate how sensitive are these two characteristics in small changes of the parameters. Afterwards, we relax the deterministic character of the parameters and investigate how variations in the signal offsets and the link lengths affect network capacity and density range. These results can be utilized to develop efficient control strategies for a series of signalized intersections as these variations can describe not only differences in network parameters, but also different characteristics in driver behavior. Later, we imitate the effect of incoming turns in a long arterial and we show that these turns can significantly decrease the network capacity even if vehicle density remains unchanged. To precisely describe all the above phenomena we initially provide some analytical proofs for a simplification of the variational theory approach and then we develop a simulator to study the non-deterministic effects.

2. A note on variational theory

Daganzo and Geroliminis (2008) developed a moving observer method to show that the average flow-density states of any urban street without turning movements must be bounded from above by a concave curve. The section also shows that, under the assumptions of variational theory, this curve is the locus of the possible (steady) traffic states for the street; i.e., it is its MFD.

Their method builds on a recent finding of Daganzo (2005), which showed that kinematic wave theory traffic problems with a concave flow-density relation are shortest (least cost) path problems. Thus, the centerpiece of variational theory (as is the fundamental diagram for kinematic wave theory) is a relative capacity ("cost") function (CF), $r(u)$, that describes each homogeneous portion of the street. This function is related to the known fundamental diagram (FD) of kinematic wave theory Q. Physically, the CF gives the maximum rate at which vehicles can pass an observer moving with speed u and not interacting with traffic; i.e., the street's capacity from the observer's frame of reference. Linear CFs correspond to triangular FDs. Daganzo (2005) assumed a linear CF characterized by the following parameters: k_0 (optimal density), u_f (free flow speed), κ (jam density), w (backward wave speed), s (capacity), and r (maximum passing rate). CF line crosses points $(u_f,0)$, $(0,\ s)$, $(-w,r)$ and has a slope equal to $-k_0$. Other applications of variational theory in modeling traffic phenomena can be found in Laval and Leclercq (2008) and Daganzo and Menendez (2005).

A second element of variational theory is the set of "valid" observer paths on the (t,x) plane starting from arbitrary points on the boundary at $t = 0$ and ending at a later time, $t_0 > 0$. A path is "valid" if the observer's average speed in any time interval is in the range $[-w,u_f]$. If $\mathcal{P}$ is one such path, $u_{\mathcal{P}}$ be the average speed for the complete path, and $\Delta(\mathcal{P})$ is the path's cost which is evaluated with $r(u), \Delta(\mathcal{P})$ bounds from above the change in vehicle number that could possibly be seen by observer $\mathcal{P}$. Thus, the quantity:

$$R(u) = \lim_{t_o\to\infty}\inf_{\mathcal{P}}\{\Delta(\mathcal{P}) : u_{\mathcal{P}} = u\}/t_o \quad (1)$$