Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 23 (2017) 497–516

Transportation Research Procedia

www.elsevier.com/locate/procedia

22nd International Symposium on Transportation and Traffic Theory

An analytical framework to model uncertainty in urban network dynamics using Macroscopic Fundamental Diagrams

Xueyu (Shirley) Gao[a], Vikash V. Gayah[a,*]

[a] *Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA, 16802*

Abstract

Recent studies have proposed using well-defined relationships between network productivity and accumulation—otherwise known as Network or Macroscopic Fundamental Diagrams (MFDs)—to model the dynamics of large-scale urban traffic networks. This provides a computationally efficient way to study these complex systems and facilitates the design and control of novel large-scale traffic management strategies. However, empirical and simulation evidence suggests that MFDs are rarely well-defined. Instead, they exhibit large amounts of scatter and uncertainty, which suggests a range of network productivities may be observed for any given accumulation. This paper examines the impact of this MFD uncertainty and uncertainty in aggregate-level vehicle demands (i.e., vehicle exit and entry rates) on large-scale network behavior. It is shown that these uncertainties can cause fundamentally different aggregate network behaviors than would be expected if they were ignored, including unexpected congestion or gridlock. An analytically derived Markov Chain framework is proposed that can be used to model aggregate network dynamics while explicitly accounting for these types of uncertainties, which are very likely to arise on realistic urban networks. Comparison between the analytical predictions and numerical simulations suggest that the Markov Chain framework can accurately predict traffic dynamics under uncertainty for both single- and multi-region networks. Since this framework relies on the careful discretization of both time and accumulation within individual regions within a network, guidance is also provided on how to best select these discretization parameters for the most accurate results.

Peer review under responsibility of the scientific committee of the 22nd International Symposium on Transportation and Traffic Theory.

Keywords: Macroscopic Fundamental Diagram; urban traffic network dynamics; large-scale network uncertainty; Markov chains

---

* Corresponding author. Tel.: +1-814-865-4014; fax: +1-814-863-7304.
E-mail address: gayah@engr.psu.edu

Peer review under responsibility of the scientific committee of the 22nd International Symposium on Transportation and Traffic Theory.
10.1016/j.trpro.2017.05.028

1. Introduction and Motivation

Relationships between traffic variables measured and aggregated across entire urban networks or regions of cities have been studied intermittently for nearly five decades (Ardekani and Herman, 1987; Godfrey, 1969; Herman and Prigogine, 1979; Mahmassani et al., 1987; Mahmassani et al., 1984; Smeed, 1967; Zahavi, 1972). This topic has recently received renewed interest due to empirical findings that unveiled well-defined relationships between traffic network production (measured by average flow or trip completion rate) and vehicle accumulation (measured by average link density or total number of vehicles currently on the network) (Geroliminis and Daganzo, 2008). The relationship between average network flow and density has come to be known as the Network or Macroscopic Fundamental Diagram (NFD or MFD), while the relationship between trip completion rate and accumulation is called the Network Exit Function (NEF). Later efforts have verified that these relationships arise in other networks using empirical data (Buisson and Ladier, 2009; Tsubota et al., 2014) or simulations of large-scale urban networks (Gayah and Dixit, 2013; Saberi et al., 2012).

Various studies have proposed using MFDs and NEFs to model traffic dynamics in large-scale urban networks. These frameworks rely on dividing networks into regions that exhibit well-defined MFDs/NEFs and using these aggregate-level relationships to predict the evolution of overall traffic behavior within each of these regions. Such frameworks have been combined with control theory, models of transportation economics and other methods to develop large-scale urban traffic control strategies like perimeter flow control or gating (Aboudolas and Geroliminis, 2013; Daganzo, 2007; Haddad and Geroliminis, 2012; Haddad and Mirkin, 2015; Haddad et al., 2012, 2013; Keyvan-Ekbatani et al., 2012; Keyvan-Ekbatani et al., 2013, 2014), area-wide congestion pricing (Geroliminis and Levinson, 2009; Gonzales and Daganzo, 2012; Simoni et al., 2015; Zheng et al., 2012), space allocation (Daganzo et al., 2012; Zheng and Geroliminis, 2013), street network design (Gayah and Daganzo, 2012; Ortigosa et al., 2015) and vehicle routing (Knoop et al., 2012; Yildirimoglu and Geroliminis, 2014).

Unfortunately, MFDs and NEFs obtained from empirical or simulated data are rarely well-defined. Instead, they exhibit a large amount of scatter or uncertainty that suggests a network might experience a range of productivities—as opposed to a specific value—for a given amount of traffic in a network. For example, even in the quintessential MFD originally unveiled for Yokohama, Japan, observed average network flows fluctuate by up to 10% of the mean value for some densities (Geroliminis and Daganzo, 2008). This scatter is inherent and cannot be eliminated. Naturally arising instabilities in urban traffic networks can cause vehicles to tend towards inhomogeneous spatial distributions, which results in scattered and unpredictable MFDs, especially when the network is congested (Daganzo et al., 2011; Gayah and Daganzo, 2011a; Gayah and Daganzo, 2011b; Mazloumian et al., 2010). While this can be alleviated by having vehicles route more adaptively to avoid localized pockets of congestion (Daganzo et al., 2011; Mahmassani et al., 2013), implementing adaptive traffic control (Gayah et al., 2014; Zhang et al., 2013) or carefully partitioning a network to ensure more homogeneous vehicle distributions (Ji and Geroliminis, 2012; Ji et al., 2014), it cannot be avoided altogether. Variation in network properties, such as block lengths and signal timings, can also produce MFDs with significant scatter or uncertainty (Laval and Castrillón, 2015).

The majority of MFD-based modeling frameworks do not take this uncertainty into account and instead rely on a direct mapping between network accumulation and productivity. However, as will be shown in this paper, the presence of this uncertainty can have large impacts that fundamentally change expected network behavior. Failure to account for the changes in behavior brought about by uncertainty can lead to poor control decisions and unintended consequences, such as congestion or gridlock. A few studies have incorporated MFD uncertainty into gating/perimeter control frameworks (Geroliminis et al., 2013; Haddad, 2015; Haddad and Mirkin, 2015). However, these only consider the impacts of uncertain MFDs in a local range when determining optimal gating control decisions. Some of these existing studies also rely on the presence of accurate traffic state estimation to adjust perimeter inflow values when unexpected behaviors arise. However, these frameworks are not generic: they are only useful to tune gating parameters and cannot be used to describe general network dynamics when uncertainty is present.

In light of this, the present paper proposes an analytical framework that can be used to model aggregate network dynamics governed by MFDs while accounting for various uncertainties that might arise. This includes uncertainty in vehicle entries into the network (i.e., demands) and vehicle exits from the network (i.e., the MFD itself). The framework relies on discretizing the state space and the continuous relationships that govern traffic state dynamics