Transportation Research Part B 70 (2014) 255–268

Contents lists available at ScienceDirect

Transportation Research Part B

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

On the impacts of locally adaptive signal control on urban network stability and the Macroscopic Fundamental Diagram

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A R T I C L E I N F O

Article history:
Received 15 May 2014
Received in revised form 23 September 2014
Accepted 23 September 2014

Keywords:
Macroscopic Fundamental Diagram
Traffic network instabilities
Traffic congestion
Urban mobility
Adaptive traffic signal control

A B S T R A C T

Urban traffic networks are inherently unstable when congested. This instability causes a natural tendency towards spatially inhomogeneous vehicle distributions and less consistent and reproducible relationships between urban traffic variables. It is important to find ways to mitigate this unstable behavior since well-defined relationships between average network flow and density – the MFD – are useful to aid network design and control.

This paper examines the impacts of locally adaptive traffic signals – e.g., those that allocate green times proportionally to upstream approach densities – on network stability and the MFD. A family of adaptive signal control strategies is examined on two abstractions of an idealized grid network using an analytical model and an interactive simulation. The results suggest that locally adaptive traffic signals provide stability when the network is moderately congested, which increases average flows and decreases the likelihood of gridlock. These benefits increase with the overall adaptivity of the signals. However, adaptive signals appear to have little to no effect on network stability or the MFD in heavily congested networks as vehicle movement becomes more constrained by downstream congestion and queue spillbacks. Under these conditions, other strategies should be used to mitigate the instability, such as adaptively routing drivers to avoid locally congested regions. These behaviors are verified using more realistic micro-simulations and are consistent with other observations documented in the literature.

1. Introduction

Researchers have studied aggregate urban traffic models for nearly fifty years (e.g., Smeed, 1966; Godfrey, 1969; Zahavi, 1972). Godfrey (1969) appears to have been the first to propose a unimodal relationship between the average network flow and density that realistically describes the entire range of potential traffic conditions. This idea was later refined using theoretical, empirical and simulation-based studies of macroscopic network behavior (Herman and Prigogine, 1979; Ardekani and Herman, 1987; Mahmassani et al., 1984, 1987; Olszewski et al., 1995 among others).

The theoretical basis for the existence of well-defined relationships between urban traffic variables was provided in Daganzo (2007). This work postulated that average network flow and density are related by a well-defined unimodal curve, known more commonly now as the Macroscopic Fundamental Diagram (MFD), provided that vehicles are uniformly distributed across space. This conjecture was later verified analytically (Daganzo and Geroliminis, 2008) and empirically using data from Yokohama, Japan (Geroliminis and Daganzo, 2008). Since then, a number of studies have shown that the MFD has tremendous potential to inform the design and control of urban traffic networks (e.g., Geroliminis and Levinson, 2009; Daganzo

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http://dx.doi.org/10.1016/j.trb.2014.09.010
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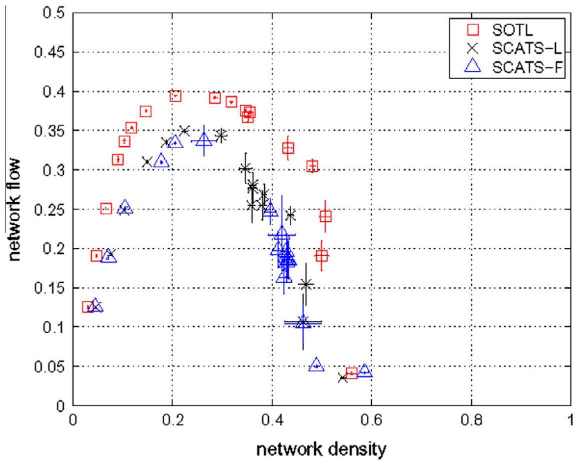

Fig. 1. Aggregate flow-density relationship for three different adaptive control schemes. (source: Zhang et al., 2013).

et al., 2012; Gayah and Daganzo, 2012; Zheng et al., 2012; Keyvan-Ekbatani et al., 2012; Haddad et al., 2013; Keyvan-Ekbatani et al., 2013).

However, network-wide relationships between flow and density are not always well-defined – significant amounts of scatter may arise in which multiple flows are observed for a given value of density (Mazloumian et al., 2010). Hysteresis patterns may also arise for which flows during the onset of congestion are significantly different from those during the dissipation of congestion (Buisson and Ladier, 2009). Similar patterns also emerge in the MFD of freeway networks (Geroliminis and Sun, 2011a; Saberi and Mahmassani, 2013). Daganzo et al. (2011) and Gayah and Daganzo (2011a) provide an explanation for this behavior: congested multi-route networks are inherently unstable and this instability causes traffic to naturally tend towards spatially inhomogeneous vehicle distributions. This innate instability arises in the simplest networks with multiple routes and may persist and grow with time until the network completely gridlocks. Haddad and Geroliminis (2012) examined the ability of network-wide perimeter metering control to mitigate instabilities in two-region networks, but the study ignores congestion inhomogeneities that are likely to arise within a region. Such inhomogeneous congestion distributions are likely to arise in both under- and over-saturated networks (Doig et al., 2013) and significantly affect the shape and functional form of the MFD (Knoop et al., 2013). Although inhomogeneous vehicle distributions do not preclude the existence of a well-defined MFD, congestion patterns must at least be reproducible for an MFD to be useful (Geroliminis and Sun, 2011b).

Fortunately, well-defined MFDs still often arise in real networks. One potential explanation is that drivers tend to adaptively route themselves to avoid localized pockets of congestion. This helps to mitigate the innate instability and should result in more consistent congestion patterns and MFDs (Daganzo et al., 2011; Gayah and Daganzo, 2011a). The impacts of adaptive driving behavior have been verified in large-scale simulations of realistic traffic networks (Saberi et al., 2014; Mahmassani and Saberi, 2013). However, drivers do not always have sufficient information or the ability to route themselves adaptively. Thus, it would be useful to know if other strategies can be used to provide stability within a network.

One strategy with the potential to create more homogeneous vehicle distributions is the implementation of locally adaptive traffic signal control schemes that allocate green time based on existing traffic conditions.[1] Dynamic algorithms have long been used to efficiently allocate green time between competing directions at individual signalized intersections based on real-time data (e.g., Miller, 1963; Robertson and Bretherton, 1974; Diakaki et al., 2002). It is possible that traffic signals that adapt to local intersection demands may help to uniformly distribute congestion across an entire region by prioritizing movements from more congested areas and restricting movement from less congested areas. This should result in more consistent MFDs and higher average network-wide flows when a network is congested.

A recent study provides some evidence to this effect (Zhang et al., 2013). This study found that congestion inhomogeneity did not always grow with time when three adaptive signal control schemes were implemented in a cellular automata simulation of an urban network. The presence of adaptive signal control was also found to significantly influence the functional form of the MFD, particularly in the congested regime. As illustrated in Fig. 1, the more flexible scheme (SOTL) provides higher average flows in the congested branch of the MFD than the less flexible schemes (SCATS-L and SCATS-F). However, in all cases very low flows representing near gridlock conditions still occur when the network is heavily congested (e.g., for densities greater than 0.5). Thus, it appears that adaptive signals provide a stabilizing influence for some congested densities but not all.

The purpose of this paper is to examine the effects of locally adaptive traffic signals on network-wide traffic relationships in a more systematic and theoretical way to see if the results of Zhang et al. (2013) should generally be expected. Adaptive signals and adaptive driver routing are also compared to see which mitigates this instability more robustly. To do this, traffic

[1] The term adaptive here is used in the traffic engineering sense and is not related to adaptive control from a control theoretic perspective.