Transportation Research Part C 69 (2016) 527–547

Contents lists available at ScienceDirect

Transportation Research Part C

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

Network operation reliability in a Manhattan-like urban system with adaptive traffic lights ☆

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ARTICLE INFO

Article history:
Received 29 April 2015
Received in revised form 6 December 2015
Accepted 19 January 2016
Available online 5 February 2016

Keywords:
Network operation reliability
Adaptive traffic light
Traffic breakdown
Gridlock

ABSTRACT

Traffic breakdown to global gridlock occurring in congested traffic network makes the serious traffic congestion even much worse. This paper has proposed to use Network Operation Reliability (NOR) to quantitatively depict the probabilistic feature of traffic breakdown to global gridlock. The Nagel–Schreckenberg cellular automaton model has been used to simulate the traffic flow in a Manhattan-like urban network. A simple adaptive traffic light strategy has been proposed. It has been shown that if vehicles choose to use geometric shortest path, the adaptive traffic signals are able to remarkably enhance the NOR and sometimes the average velocity and the arrival rate as well. The vehicle distribution has been investigated, which has heuristically explained the enhancement of the NOR. A simple perimeter control strategy has been shown to fail to enhance the NOR. Finally, we show that if the time shortest path information could be provided and updated timely, then the NOR can be remarkably enhanced but the adaptive traffic signals have only trivial effect on NOR.

1. Introduction

Traffic congestion in transportation network is serious almost all over the world. A series of proposals to lessen congestion have been presented, such as congestion pricing (Yang and Bell, 1997; Verhoef, 2002) that has been adopted in Singapore and London, the travel restriction based on license plate tail number as adopted in Beijing, advanced traveller information system (ATIS) like variable message sign (VMS) board (Gan and Ye, 2013; Jindahra and Choocharukul, 2013), the variable speed limit, the ramp metering and so on (Papageorgiou et al., 2003; Frejo and Camacho, 2012; Carlson et al., 2011).

In network traffic flow, recently it has been found empirically that the average flow and average density are related by a unique, reproducible curve, which is named as Macroscopic Fundamental Diagram (MFD) (Geroliminis and Daganzo, 2008). Utilizing the MFD, optimal control methodologies such as perimeter and boundary flow control strategies, hierarchical control that considers network heterogeneity as well as cooperative traffic control have been studied (Aboudolas and Geroliminis, 2013; Geroliminis et al., 2013; Haddad et al., 2013; Haddad and Shraiber, 2014; Haddad, 2015; Keyvan-Ekbatani et al., 2015; Yildirimoglu et al., 2015; Yildirimoglu and Geroliminis, 2014; Ramezani et al., 2015).

☆ This article belongs to the Virtual Special Issue on: Recent Advances in Transportation Management and Control.

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http://dx.doi.org/10.1016/j.trc.2016.01.006

In urban traffic networks, the traffic signals control the flows of vehicles at signalized intersections. Therefore, the optimization of traffic signal plans is one major target of intelligent transportation system research. The traffic signal systems can be classified into two types: static systems and dynamic ones. In static systems, the pre-timed signal might have been optimized via off-line optimization approaches, using historically measured data. However, the systems are problematic since the historical data do not accurately reflect the current traffic conditions.

In the dynamic systems, the traffic signal timing reacts adaptively to real-time traffic conditions based on a responsive technique in which real-time measured data is used. As a result, it is expected that the adaptive traffic signals are able to enhance the performance of traffic networks.

Researchers have proposed many adaptive traffic signal strategies and tested them at isolated intersection and traffic networks (see e.g., El-Tantawy et al., 2013; Zheng and Recker, 2013; Zhang et al., 2013; Brilon and Wietholt, 2013; Maslekar et al., 2013; Mckenney and White, 2013; Xin et al., 2013; Mirchandani and Head, 2001; Lo, 1999; Trabia et al., 1999; Abdulhai et al., 2003; Spall and Chin, 1997; Balaji and Srinivasan, 2010; Yu and Recker, 2006; Cai et al., 2009; Gartner and Stamatiadis, 1998; Mirchandani and Zou, 2007; Fang and Elefteriadou, 2008; Kouvelas et al., 2014; Varaiya, 2013; Diakaki et al., 2002, 2003; Gayah et al., 2014). It has been shown that adaptive traffic signals could improve the traffic network performance (e.g., increasing average velocity, reducing average delay and achieving higher capacity).

This paper studies the effect of adaptive traffic signal on the performance of traffic network from a different perspective. It has been shown that when the network density is large, traffic breakdown to global gridlock with zero flow will occur (Daganzo et al., 2011; Mazloumian et al., 2010; Gayah et al., 2014). Since the traffic flow has a probabilistic nature to breakdown into global gridlock, we propose an index "network operation reliability" (NOR) to quantitatively describe this kind of performance of traffic network. Our studies show that the adaptive traffic signal is able to significantly enhance the NOR under certain circumstance.

The paper is organized as follows. In the next section, the simulation model is introduced. In Section 3, we have presented the simulation results to show the probabilistic nature of traffic network's breakdown into global gridlock. The effect of adaptive traffic signal on the NOR is discussed in Section 4. Section 5 makes discussion on the effect of various factors on the NOR. Finally, conclusion and future work are given in Section 6.

2. Model

We study traffic flow in urban traffic network in which all the intersections are signalized. We use the Nagel–Schreckenberg cellular automaton model (Nagel and Schreckenberg, 1992) to simulate the motion of vehicles. For simplicity, we consider a Manhattan-like urban system as shown in Fig. 1(a), which has also been previously studied in the literature, see e.g., Gayah et al. (2014), Ortigosa et al. (2015), and Zhang et al. (2013). The network consists of $N \times N$ square lattice. Any two successive intersections are connected by two lanes, one for each direction, which are both divided into cells. Vehicle driving is restricted to the right lane. In each traffic phase, the traffic lights stay green for one ingoing street and red for the other ingoing streets (yellow light is not considered). When the green light is on, vehicles on the corresponding ingoing street can go straight ahead, turn left or right, or make a U-turn.

Vehicles, except for the leading ones in each lane, travel in the system following the Nagel–Schreckenberg rules as follows:

a. Acceleration: $v_i \to \min(v_{\max}, v_i + 1)$;
b. Deceleration: $v_i \to \min(d_i, v_i)$;
c. Random brake: $v_i \to \max(v_i - 1, 0)$ with a braking probability p;
d. Movement: $x_i = x_i + v_i$.

Here $v_{\max}$ is the maximum velocity of vehicles, x_i is the position of the ith vehicle and d_i is the number of empty cells ahead of the ith vehicle.

The update rules for the leading vehicles on each street are:

a. Traffic light is green
   * If the desired outgoing street is in jam or the intersection is occupied at the moment, d is the number of empty cells ahead to the intersection.
   * Otherwise, d is the number of empty cells ahead to the last vehicle of the desired outgoing street.
b. Traffic light is red
   * d is the number of empty cells ahead to the intersection.

Initially, the vehicles are distributed in the network randomly. Each vehicle is given with a randomly selected destination. When a vehicle reaches its destination, a new destination is chosen randomly from the system. This is just like a taxi. When it arrives at the destination, the passengers get off and new passengers get on and go to new destination (assume that there are always new passengers getting on once passengers get off).