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Integration of a cell transmission model and macroscopic fundamental diagram: Network aggregation for dynamic traffic models

Zhao Zhang [a], Brian Wolshon [b,*], Vinayak V. Dixit [c]

[a] Department of Industrial Engineering, Tsinghua University, Beijing 100084, China
[b] Gulf Coast Center for Evacuation and Transportation Resiliency, Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, United States
[c] School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia

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ABSTRACT

Network size can have a significant impact on the computational performance of traffic simulation models. Due to this, methods to reduce network size can be valuable when analyzing large networks. In this research, a novel model integrating a Cell Transmission Model (CTM) with the Macroscopic Fundamental Diagram (MFD) for urban networks is proposed and its effects analyzed. The concept that underlies this work is that a road network can be classified into two types of networks: the first includes roads that are modeled using CTM, and the second are components of the network that can be aggregated into large self-contained cells that also maintain properties of the MFD. To test the proposed model and its computational efficiency, a case study involving an evacuation is introduced. The network and its demand, built from the Southeast Louisiana Hurricane Katrina evacuation event, were modeled using a combination of CTM and MFD. The spatio-temporal profiles of volume and speeds on key routes and destinations from the proposed model were compared to observed data from the event. The results suggest that the model was able to realistically capture the observed shock wave phenomena, and reproduce the spatio-temporal characteristics of the evacuation traffic. This simple methodology has considerable potential to improve computational efficiency in dynamic traffic assignment models, particularly for those large-scale networks and processes, while ensuring that the traffic dynamics are realistically modeled.

1. Introduction

Traffic simulation models are widely recognized as useful tools in transportation planning and operations (Gazis, 2002). They are used as a fundamental decision-support tools for most, if not all, transportation problems. In general, transportation simulation models are categorized by the level detail at which they represent traffic processes and are classified as microscopic, mesoscopic and macroscopic (Cousins et al., 2009). The selection of any one of the types of simulation models is based on the needs and goals of the analysis. Microscopic simulation models typically produce output measures at high levels of fidelity, but require correspondingly greater levels of input detail and computing time. Macroscopic model need less

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* Corresponding author.
E-mail address: brian@rsip.lsu.edu (B. Wolshon).

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input but do not produce output at highest levels of specificity. Mesoscopic models lie within a range of performance between macro and micro.

Because of its ability to represent conditions that are infrequent or even non-existent in real life, traffic modeling has also been widely used in evacuation planning and strategy analysis. Ranging from hazards associated with nuclear power plant emergencies (Sheffi et al., 1982; Hobeika and Kim, 1998), hurricanes (Cova and Johnson, 2003; Dixit and Radwan, 2009; Zhang et al., 2013b; Zhang et al., 2014a; Zhang et al., 2014b) and wildfires (Cova and Johnson, 2002).

Under most emergency plans evacuation traffic is routed to large cities where sheltering options exist to host fleeing populations. However, road networks in most destinations are not designed to accommodate the sudden and overwhelming demand that arrives during mass evacuations. This can result in congestion in the destination network, which in turn, can create backups that can extend for many miles on approaching evacuation routes (Dixit and Radwan, 2009). Though such phenomena have been observed repeatedly, limited literature exists on the issue of network condition at termination nodes. Most simulation studies tend to assume "ideal destinations", where vehicles leave the analysis network as soon as they reach the destination, irrespective of the number of vehicles already present in the destination road network. Empirical observation in locations such as Baton Rouge, Louisiana during Hurricane Katrina showed that this is an unreasonable assumption because vehicle accumulation in the downstream and destination road networks created significant impacts on entering and pass-through evacuation routes. On the contrary, detailed modeling of the destination networks could significantly enhance the time required to model and run such scenarios. For these reasons, it has been suggested that future models should more realistically represent evacuation traffic conditions to include destination network capacity, accumulation, and average network flow.

Daganzo (2007) investigated optimal strategies to improve city mobility through gridlock control. The paper proposed a relationship between the outflow (exit function $(G(n))$) and the number of vehicles in the network. The paper derived a differential equation (Eq. (1)) describing the number of vehicles in the network, based on the inflow $(f(t))$ and outflow $(G(n))$.

$$\frac{dn}{dt} = f(t) - G(n(t)), \quad \text{for } t > 0 \tag{1}$$

These relationships were used to determine an optimal control strategy (A–B strategy) to control inflows so as to maximize outflow.

Following the theoretical work by Daganzo (2007), Geroliminis and Daganzo (2008) conducted simulation experiments with the San-Francisco network, and empirically showed the existence of a Macroscopic Fundamental Diagram (MFD) in a large urban area. In addition the paper also described the behavior of inflow with respect to accumulation. They showed that inflow remained constant up to a certain degree of accumulation and then started to decrease. More detailed investigations on MFD in urban networks (Daganzo et al., 2011) and freeway networks (Geroliminis and Sun, 2011a) demonstrate that the phenomena of "clockwise hysteresis loops", which have been attributed to inhomogeneity in networks.

Buisson and Ladier (2009) attempted to analyze factors influencing the shape of MFD by relaxing some of the homogeneity assumptions made by Geroliminis and Daganzo (2008). They used data collected in Toulouse, France to show that heterogeneity, type of network, intersection distance had significant influence on the MFD curve. Mazloumian et al. (2010) was the first study to quantify the impact of spatial heterogeneity on the shape of MFD using computer simulation. Geroliminis and Sun (2011b) presented the correlation between adjacent roads and an analytical derivation of the spatial distribution of congestion. Gayah (2012), Gayah and Daganzo (2011a,b), Leclercq and Geroliminis (2013) and Knoop et al. (2012) studied the effects of traffic demand, turning maneuvers and route choice on MFD. Zhu et al. (2012) verified that the shape of MFD curve is influenced by network topology, traffic demand,and traffic load pattern based on traffic data collected in Beijing, China.

Researchers have also studied optimal traffic control policies like signal control (Zhang et al., 2013a), gating (Keyvan-Ekbatani et al., 2012, 2013) and optimal perimeter control (Haddad and Geroliminis, 2012; Geroliminis et al., 2013) based on MFD analysis. Gayah and Dixit (2013) proposed a method to use travel speed information collected by circulating probe vehicles to indirectly estimate network densities in real time and shows hysteresis patterns. Gayah et al. (2014) showed that the clock wise hysteresis relationship between average flow and average density is also linked to the variance of travel time. The latest research on MFD demonstrated the intrinsic factors influencing the shape of MFD and applications of MFD on road network control at a macroscopic view.

The research by Dixit and Radwan (2011) was perhaps the first to introduce and use MFD to study and optimally control evacuation traffic. As shown in the literature, homogeneity in traffic is needed for a well-defined MFD. During evacuation, homogeneity does not exist at an origin or along evacuation routes, since vehicles are predominantly using routes and lanes that exit the network. However, this is not true of the destination primarily because of the background traffic associated with individuals carrying out their daily activities, and the final destinations of the evacuees (hotels, restaurants and other final or intermediate destinations) being homogenously located throughout the network. Therefore, a homogeneity assumption at a destination is reasonable, however, this is not true at the origin. Further, incorporating the MFD with a mesoscopic model could potentially provide improvement in computation while providing a reasonable replication of the traffic dynamics.

Cell Transmission Models (CTMs) (Daganzo, 1994, 1995) have been used to model traffic dynamics using macroscopic traffic flow characteristics. The strength of this modeling approach is its ability to reproduce LWR model and the flexibility in transportation modeling, and therefore has been widely used in mesoscopic dynamic traffic assignment models. In addition, CTM has high computing efficiency and provides accurate simulation results especially in on/off ramp analyze. Muñoz et al. (2003) modified CTM and used cell densities as state variables instead of cell occupancies. This permitted the use of