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Agent-based network transmission model using the properties of macroscopic fundamental diagram

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ABSTRACT

The field of research that has recently come to the fore is the perimeter control, which aims to control traffic demand for a large urban area prior to controlling internal flow inside the area. Such control concept needs to be tested by simulations, hence, it is necessary to develop a model that can appropriately estimate the network-wide flow dynamics. In this paper, agent-based network transmission model (ANTM) is proposed for describing the aggregated flow dynamics over an urban area of multiple large-scale networks. The proposed model is the combination of the cell transmission model (CTM), macroscopic fundamental diagram (MFD), and agent concept. The CTM-based simulation is adopted for the simplicity considering the computation requirements for real-time feasibility. The MFD concept is applied for representing the network properties, and a new approach is taken particularly for estimating network outflow affected by both demand patterns and boundary capacity. The agent concept is applied for representing drivers' travel behaviors. The model is compared with microscopic simulations and shows reasonable accuracy for large areas. In addition, various travel direction choice behaviors are applicable to this model. Various perimeter control policies are applicable as well, thus, the proposed model can be a useful tool for testing various control methods, in terms of reducing the congestion in urban areas.

1. Introduction

Traffic congestion in urban areas is one of the major social problems in these days. In order to mitigate congestion in urban areas, we could increase road capacity by extending the existing infrastructure, or we could reduce traffic demand. The former way is usually not a favorable solution because the cost for such action is relatively expensive and land space is physically limited. The latter way is not an easy solution either, due to limited capability in controlling travels directly (e.g. ramp metering and HOV lane operation) or indirectly (e.g. dynamic toll pricing and route guidance). The growths in urban population and city-centered life patterns make it even more difficult. Therefore, our focus nowadays should be more on increasing the utilization level of the existing infrastructure by considering both supply and demand.

Over the past decades, the field of urban traffic control (UTC) has been studied in various ways for increasing urban mobility. Development of traffic responsive signal control strategies is the main example because urban traffic flow dynamics essentially depend on a given signal control strategy. Various signal control strategies have been developed so far, such as SCOOT (Hunt et al., 1982), SCATS (Lowrie, 1982), OPAC (Gartner, 1983), PRODYN (Farges et al., 1983), RHODES (Mirchandani and Head, 1998), and

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TUC (Diakaki et al., 2002). All of these strategies are applicable to large-scale urban road networks for finding network-wide optimized solutions. However, most of them are known to be less efficient when road network's traffic condition is severely oversaturated with spillback problems. The use of highly complex optimization algorithms is another disadvantage in terms of network-wide application (Keyvan-Ekbatani et al., 2012; Aboudolas and Geroliminis, 2013). Thus, considering the real-time feasibility, the recent trend has moved to developing distributed approaches (McKenney and White, 2013; Timotheou et al., 2015; Ye et al., 2015) or taking advantages of machine learning techniques (El-Tantawy et al., 2013; Khamis and Gomaa, 2014).

An alternative approach for network-wide traffic signal control in a real-time manner is the perimeter control, which aims to control the traffic demand for specified urban networks prior to controlling the internal traffic flow inside each of the networks. Such concept has been developed along with the investigations on the relationship between aggregated network flow and density, called the macroscopic fundamental diagram (MFD). Since the noteworthy investigations on the MFD (Daganzo, 2007; Geroliminis and Daganzo, 2007; Geroliminis and Daganzo, 2008), subsequent studies particularly have been discussing the network's spatial homogeneity condition for well-defined MFD in terms of the practical issue (Buisson and Ladier, 2009; Ji et al., 2010; Mazloumian et al., 2010; Daganzo et al., 2011; Geroliminis and Sun, 2011b; Knoop et al., 2015). Due to many arguments on the impact of spatial inhomogeneity on network production, several efforts have been attempted to address partitioning urban networks into homogeneous zones with low variances of link densities (Ji and Geroliminis, 2012; Saeedmanesh and Geroliminis, 2016; Lopez et al., 2017; Saeedmanesh and Geroliminis, 2017; An et al., 2018). Based on such diverse efforts, the research community considers that the aggregated relationship (network accumulation and production) is recognizable nowadays. The studies on the hysteretic phenomenon of MFD during traffic loading and recovery phases (Gayah and Daganzo, 2011; Geroliminis and Sun, 2011a; Mahmassani et al., 2013; Zhang et al., 2013), the studies on vehicle routing based on urban MFD information (Menelaou et al., 2017a; Menelaou et al., 2017b), and the studies on the vulnerability of network performance in road closure cases (Kim and Yeo, 2016; Kim and Yeo, 2017) are some other subsequent branches of the MFD related researches. As another subsequent branch, various perimeter control approaches have been recently proposed for different control purposes. There are the gating problem for a single network (Keyvan-Ekbatani et al., 2012; Keyvan-Ekbatani et al., 2013a; Csikos et al., 2015; Keyvan-Ekbatani et al., 2015a; Keyvan-Ekbatani et al., 2016), the gating problem for multiple network boundaries (Keyvan-Ekbatani et al., 2013b; Keyvan-Ekbatani et al., 2015b), the problem of one-on-one transfer flow for two networks (Geroliminis et al., 2013; Haddad and Shraiber, 2014), the problem of transfer flow for multiple networks (Aboudolas and Geroliminis, 2013; Ramezani et al., 2015; Haddad and Mirkin, 2017), and the problem of mixed traffic (Haddad et al., 2013). These studies proposed methodologies using the control engineering-based concepts like proportional-integral (PI) control, model predictive control (MPC), or the combination of the two.

In this paper, our focus is more on "how" the various network-wide control concepts can be tested, rather than on "what" control concepts to test. When testing any control concepts, proper prediction on how the changes in the control policy influence the traffic conditions of a bunch of road networks is the crucial point. Nonetheless, for estimating network traffic, several previous studies have been using a concise way, in which the shape of MFD (or outflow) is considered to be a fixed property regardless of demand patterns and supply level of transfer between networks. Since the MFD is the given capability of certain network based on the properties of infrastructure (e.g. road length, network geometry, and intersection signal timings), it can be considered as fixed property at given infrastructure conditions. However, network "outflow" level may change due to demand patterns (the rate of network outbound demand over total travel demand and the proportion of demand towards each side of a network). Note that the term, outflow, means the flow exiting a network towards others and excludes the flow towards the local space (local streets or parking spaces) of network area in this paper. Hajiahmadi et al. (2015) applied multiple MFDs that were saved in a predefined library and used different MFDs by situations, but the predefined MFDs were based on only the signal control policies for internal traffic of a network. Another factor that may influence network outflow is boundary capacity (maximum transfer rate between networks). A few previous studies have considered the boundary capacity (Knoop and Hoogendoorn, 2015; Ramezani et al., 2015), but there is a lack of detailed descriptions on such property in relation to the infrastructural conditions at the intersections of network boundaries. Such description should include the number of connected links, number of lanes, saturation flow rate, and signal cycle length, and green split. Particularly, although the boundary capacity may be changed over time due to the green signal splits at network boundaries, the maximum value of it has been considered as constant. In general, the previous perimeter control studies determined how much of flow should be transferred between networks. However, for such control, the boundary capacity has to be changed due to green splits adjustment in each direction. There is an absence of considering the reduced effect of changes in boundary capacity on network outflow. Hence, the effect of boundary capacity on network outflow should be another issue to be addressed. Furthermore, considering the duration of morning or evening peak hours in urban areas, the traffic prediction horizon has to be large enough (e.g. 3–6 h). It is doubtful that the concise way they used can adequately estimate or predict the traffic states of a group of large-scale networks for such large look-ahead period.

Hence, it is necessary to develop a model that can appropriately predict network-wide flow dynamics even in a long period so that it can be used for more precise tests of various perimeter control concepts. Such model should also be able to practice various tests for different purposes (e.g. single network protection or transfer flow between networks). In this paper, we take a new approach to using the MFD concept for expressing network outflow that changes due to demand patterns and boundary capacity. Based on the new outflow concept, this paper aims to develop a simulation model for large-scale urban road networks. Rather than the micro-simulation, the macroscopic concept is adopted considering the computation requirements for large areas, and it also suits the scope of the simulation purpose of representing aggregated traffic dynamics. We use the concept of the cell transmission model (Daganzo, 1994), which is one of the most intuitive models in describing traffic flow propagation, as the basis for dynamic simulation. Several modifications are made to the cell transmission model (CTM) for our purpose. Instead of a single road section, a whole road network is considered as a cell, and the transmission rule for vehicles follows the newly proposed concept of network outflow. Each cell is