Transportation Research Part B 101 (2017) 245–267

Contents lists available at ScienceDirect

Transportation Research Part B

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

Macroscopic urban dynamics: Analytical and numerical comparisons of existing models

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ARTICLE INFO

Article history:
Received 21 October 2016
Revised 11 April 2017
Accepted 11 April 2017
Available online 2 May 2017

Keywords:
Macroscopic modeling
Single-reservoir
Trip length
Analytical resolution
Piecewise linear functions

ABSTRACT

Large-scale network modeling using the Macroscopic Fundamental Diagram (MFD) is widely based on the single-reservoir model, where the variation of the accumulation of circulating vehicles in the reservoir equals inflow minus outflow. However, inconsistent lags for information propagation between boundaries may be observed with this single accumulation-based model. For example, outflow is reacting too fast when inflow varies rapidly, whereas this information should be carried by vehicles that are never driving faster than the free-flow speed. To overcome this limitation, a trip-based model has been recently proposed, but whose solution cannot be obtained analytically.

In this paper we compare both models under piecewise linear MFD and a piecewise constant demand. These assumptions allow to establish the exact solution of the accumulation-based model, and continuous approximations of the trip-based model at any order using Taylor series. Moreover, a flexible event-based simulation framework is implemented to solve the latter model, making it a promising tool to account for heterogeneity in distance traveled. Thanks to these resolution schemes we are able to measure the inaccuracy of the accumulation-based approach when the demand varies rapidly, and propose a validity domain for this model. Other applications with different trip lengths and supply limitations are also discussed.

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1. Introduction

Large-scale network modeling based on the Macroscopic Fundamental Diagram (MFD) has advanced significantly in recent years. It appears as a viable option for congestion management applications such as perimeter control (see e.g. Haddad and Geroliminis, 2012; Aboudolas and Geroliminis, 2013; Ramezani et al., 2015; Haddad, 2017) and for modeling large cities based on the multi-reservoir framework presented in Hajiahmadi et al. (2013), Knoop and Hoogendoorn (2014), Yildirimoglu et al. (2015) and Kouvelas et al. (2017). The theoretical foundations of all these approaches have been established in Daganzo (2007) and Geroliminis and Daganzo (2007), where the dynamics of a single reservoir is represented by a conservation equation where outflow is determined by the MFD function. This approach will be referred to as the "accumulation-based MFD model". Though it has proved to be an attractive description of large urban areas, this approach still relies on strong hypotheses, which may have non negligible impacts. For example, Xue et al. (2016) show that simplifying an urban system by two reservoirs may lead to a different optimal perimeter-control strategy than when the system is described using classical

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http://dx.doi.org/10.1016/j.trb.2017.04.002
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traffic flow theory. Also, it has been shown in Leclercq et al. (2015) that the accumulation-based model suffers from significant numerical viscosity even when the time step is small. Outflow (respectively inflow) may then overreact to sudden demand surge (respectively supply drop) leading to inconsistent propagation of information between opposite perimeter boundaries. The simplest illustration is an empty reservoir and a demand that starts increasing. The outflow instantaneously also increases creating an immediate reaction that may be interpreted as information that propagates from one boundary to the other at an infinite speed.

Another crucial point concerns the representation of vehicle trip length within the reservoir. It is often assumed constant for all vehicles for the sake of simplicity (see e.g. Haddad and Geroliminis, 2012; Aboudolas and Geroliminis, 2013; Hajiahmadi et al., 2013), but this is not consistent with what is observed when the local dynamics are taken into account (Leclercq et al., 2015). Trip lengths not only depend on the OD (Origin-Destination) matrix but also on the traffic conditions within the reservoir. Yildirimoglu and Geroliminis (2014) first highlight the error made in simulation when using the standard formulation of Daganzo (2007) in comparison with an improved description taking into account the variability of the trip length with respect to OD pairs. Such a description requires that the original single conservation equation that describes the behavior of the reservoir must be split into different vehicle classes, for example per OD pairs, with constant travel distances. The influence of the trip length for the accumulation-based MFD model is thoroughly investigated in Mariotte and Leclercq (2016). Leclercq et al. (2015) propose an alternative modeling framework to Yildirimoglu and Geroliminis (2014) to consider different trip lengths by defining macroscopic routes and jointly solving the related system of conservation equations. Based on an idea of Arnott (2013) and Fosgerau (2015), Daganzo and Lehe (2015) and then Lamotte and Geroliminis (2016) elaborate a simple and elegant reformulation of the single-reservoir dynamics to address the question of variable trip lengths. This reformulation will be further referred to as “trip-based MFD model” since the main idea is to guaranty that all vehicles cover their travel distance within the reservoir by adjusting their instantaneous speed to the current reservoir mean speed defined by the MFD.

In this paper, we compare the accumulation-based and the trip-based MFD models by investigating their analytical and numerical solutions for a piecewise linear MFD and piecewise constant inflows. The analytical solutions of the accumulation-based MFD model can be determined piece by piece while the trip-based MFD model require a continuous approximation based on the entering vehicle discretization. A major insight of our analytical developments is that the accumulation-based has no memory while the trip-based approach accounts for a reaction time. The comparison of the solutions on simple test cases will permit to further analyze the different model properties. In all cases, the trip-based approach appears superior as it better represents wave propagation and travel time evolution within the reservoir. On the other hand, an attempt to define a validity domain for the accumulation-based model application has been proposed. Numerical schemes are also derived for both approaches. Notably, we propose here an event-based solution method for the trip-based model that provides the exact solution when the inflow cumulative curve is kept as a step-function related to the entry of each individual vehicles. This solution method can be easily extended to account for different trip lengths for each driver, which is a significant improvement compared to the accumulation-based model. This means that the trip-based MFD model would be even easier to implement with multiple reservoirs.

The layout of this paper is as follows: we first present the analytical and numerical resolution of the accumulation-based reservoir model. Then we introduce the numerical resolution of the trip-based model and compare its properties with the original model. The event-based numerical scheme for the trip-based approach is also presented there. Finally, we compare the results with the previous method and the accumulation-based model on three case studies: a typical peak-hour demand profile, a supply restriction at the reservoir exit, and a peak demand case with various trip lengths inside the reservoir.

2. Accumulation-based approach

We present in this section the seminal *accumulation-based* approach for describing the dynamics of a single-reservoir system.

2.1. The single-reservoir dynamics

The single-reservoir system dynamics has been extensively presented in Daganzo (2007) and Geroliminis and Daganzo (2007). The basic principle is that an urban network can be described in an aggregate manner with a reservoir characterized by its accumulation $n(t)$, the number of circulating vehicles at time t (in [veh]). The traffic state within the reservoir is given by a well-defined relationship between the travel production P (in [veh.m/s]) and the accumulation $n(t)$. Note that the mean speed V of travelers (in [m/s]) is given by $V(n(t)) = P(n(t))/n(t)$ at every time t (Geroliminis and Daganzo, 2007). As in Lamotte and Geroliminis (2016), $P(n)$ will be referred to as the “production-MFD”, and $V(n)$ as the “speed-MFD”. According to Geroliminis and Daganzo (2007), the trip length L is the same for all travelers and satisfies the following equation:

$$O(n) = \frac{P(n)}{L} \tag{1}$$

where $O(n)$ is the reservoir outflow (in [veh/s]). It may represent either trips ending in the reservoir or trips exiting the area. This equation can be viewed as the application of Little’s formula at the reservoir scale (Little, 1961). In this paper, we first add some further but non restrictive assumptions in order to facilitate analytical calculations. The initial state of

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