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First-order traffic flow models incorporating capacity drop: Overview and real-data validation

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ABSTRACT

First-order traffic flow models of the LWR (Lighthill-Whitham-Richards) type are known for their simplicity and computational efficiency and have, for this reason, been widely used for various traffic engineering tasks. However, these first-order models are not able to reproduce significant traffic phenomena of great interest, such as the capacity drop and stop-and-go waves. This paper presents an overview of modeling approaches, which introduce the ability to reflect the capacity-drop phenomenon into discretized LWR-type first-order traffic flow models; and also proposes a new approach. The background and main characteristics of each approach are analyzed with particular emphasis on the practical applicability of such models for traffic simulation, management and control. The presented modeling approaches are tested and validated using real data from a motorway network in the U.K.

1. Introduction

Among numerous phenomena characterizing traffic flow behavior, one of the most known and puzzling is the so-called capacity drop. This phenomenon breeds the reduction in the mainstream flow of a motorway when a queue starts forming upstream of a bottleneck location (Banks, 1991; Hall and Agyemang-Duah, 1991). Bottleneck locations can be motorway merge areas, areas with particular infrastructure layout (such as lane drops, strong grade or curvature, tunnels, etc.), areas with specific traffic conditions (e.g., strong weaving of traffic streams), areas with external capacity-reducing events (e.g. work-zones, incidents) etc. (Chung et al., 2007; Dixon et al., 1996; Smith et al., 2003). If the arriving demand is higher than the bottleneck capacity, i.e., the maximum flow that can pass during a certain time period, the bottleneck is activated, i.e., congestion is formed at the bottleneck location and spreads upstream. Empirical observations show that, whenever a bottleneck is activated, the maximum outflow that materializes (also called discharge flow) may be some 5 to 20 percent lower than the nominal bottleneck capacity. The capacity drop is then defined as the difference between these two values of flow, i.e., the capacity and the discharge flow. Certainly, the capacity drop reflects infrastructure performance degradation, leading to increased congestion space-time extent and accordingly longer vehicle delays. To avoid or delay the activation of

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a bottleneck, and the related capacity drop phenomenon, various traffic control measures have been proposed and applied (Cassidy and Rudjanakanoknad, 2005; Papageorgiou et al., 1991, 2003).

Designing and testing efficient traffic control strategies, or assessing their performance, require the usage of traffic flow models that are able to reproduce the motorway traffic conditions with satisfactory accuracy, specifically to reproduce infrastructure degrading phenomena such as the capacity drop. Macroscopic first-order traffic flow models of the Lighthill-Whitham-Richards (LWR) type (Lighthill and Whitham, 1955; Richards, 1956), where the dynamics are described by the conservation equation of vehicles only, represent a valuable tool for the study of traffic behavior, as they are simple, yet effective in reproducing not only free-flow conditions, but also wave formation and propagation under congested conditions. However, they do not allow for capturing more complex traffic phenomena, such as the capacity drop. In order to incorporate this important feature, different approaches have been proposed, which include higher-order extensions and first-order extensions; the former include second-order traffic flow models, while the latter are formulated via introduction of complex fundamental diagrams (Zhang, 2001).

Various second-order macroscopic traffic flow models have been proposed (e.g., Payne, 1971; Messmer and Papageorgiou, 1990; Aw and Rascle, 2000; Zhang, 2002; Whitham, 2011; Delis et al., 2014), which contain an additional dynamic equation to describe the speed evolution, being thereby capable to reproduce traffic instabilities, such as stop-and-go waves, as well as the capacity drop phenomenon at active bottlenecks. Second-order models have been consistently found in diverse calibration exercises to reflect more accurately real traffic data (Cremer and Papageorgiou, 1981; Papageorgiou et al., 1989; Michalopoulos et al., 1992; Frejo, 2015; Spiliopoulou et al., 2014; Fan and Seibold, 2013). On the other hand, also second-order traffic model present some drawbacks, such as: (i) they may (under rare circumstances, as shown by Helbing and Johansson, 2009) produce negative speeds or flows (see Daganzo, 1995a); (ii) they usually include a higher number of parameters (some of which without clear physical significance), that need to be appropriately calibrated; and (iii) any optimization problem built upon second-order models is characterized by a nonlinear formulation, which implies a higher computation effort and the impossibility to guarantee convergence to a global optimum (Kotsialos and Papageorgiou, 2004). With respect to the last drawback, also first-order models include non-linearities, which, however, may be more efficiently tackled, while defining an optimization problem, by using computationally-efficient mixed-integer linear formulations (Ferrara et al., 2015) or, under specific assumptions, by using only linear or piecewise linear constraints (Ziliaskopoulos, 2000; Roncoli et al., 2015a).

The LWR model is composed by a single partial differential equation reflecting the conservation of vehicles and a steady-state flow-density relationship known as the Fundamental Diagram (FD) of traffic flow. While analytical solutions of the LWR model can be obtained for simple traffic settings using the method of characteristics, a significant amount of literature proposes and extends discrete approximations of the continuous LWR model applying the Godunov discretization scheme (Godunov, 1959), where the FD is transformed into two flux functions known as the demand (flow that can be sent from upstream) and the supply (flow that can be received downstream) functions (Lebacque, 1996). The most referenced among these discretized models is the Cell Transmission Model (CTM) (Daganzo, 1994), where the flow is expressed as a function of density via the definition of a triangular FD, and the space and time increments are selected according to the free speed. Remarkably, CTM realistically predicts shockwave propagations, while all the parameters have a physical interpretation, which also implies that they can be easily calibrated using real traffic data (Munoz et al., 2004). Furthermore, it has been employed for the study of different applications, such as dynamic traffic assignment (Lebacque et al., 1996; Ziliaskopoulos, 2000), traffic prediction, signal control and ramp metering (Alecsandru et al., 2011; Gomes and Horowitz, 2006; Zhang et al., 1996). Finally, CTM is characterized by relatively low computational requirements (Gomes and Horowitz, 2006; Lo, 2001) and it can be easily employed for large-scale motorway and urban network simulation (Lebacque et al., 1996).

It should be noted that CTM is not the only computationally efficient and reasonably accurate discretized first-order model. Models such as the Point-Queue (PQ) model, proposed by Smith (1984) and Kuwahara and Akamatsu (1997), as well as the Link Transmission Model (LTM), proposed by Yperman et al. (2006), have been seen as effective tools for traffic flow representation. As discussed by Nie and Zhang (2005), although the PQ model results in less computational cost and leads to equivalent results for a number of initial/boundary conditions, compared to CTM, its solutions differ in cases of queue spill-backs, since the PQ model does not consider the physical length of the queue. Moreover, as discussed by Jin (2015b), LTM, in which the demand and supply functions are defined from cumulative flows, appears to be less computationally demanding but more memory consuming, in comparison with CTM.

Despite the increasing interest from the research community in integrating capacity drop in LWR-type first-order models, a limited number of effective approaches have been proposed, and only a few are actually tested using real traffic data to evaluate their behavior in case a bottleneck is activated. This study, as an extension of the work by Kontorinaki et al. (2016) in various respects, aims to fill this gap, gathering the state-of-the-art related to capacity drop modeling within LWR-type models (first-order extensions), contributing with further insights about their implications, and testing their capability to reproduce correctly the desired traffic pattern at an active bottleneck due to on-ramp merging. In particular, a discretized space-time modeling framework, which comprises CTM as a special case, is used. This is because CTM (and its extensions) serves as basis for most of the proposed capacity drop approaches, which use a discretized space-time framework. It should be noted that each approach introduces additional terms and parameters to the original CTM, and that the computational efficiency of all approaches remains virtually unaltered.

The selection criteria for the CTM-based approaches that are described and analyzed in this paper are two: First, the selected models should include a low number of parameters, which implies a limited effort in calibration and easier ap-