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Macroscopic traffic flow model validation at congested freeway off-ramp areas

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ABSTRACT

The reported study tests, validates and compares two well-known macroscopic traffic flow models in the special, but quite frequently occurring case, where congestion is created due to saturated freeway off-ramps. In particular, the comparison includes the first-order model CTM (Cell Transmission Model) and the second-order model METANET. In order to enable a reliable and fair comparison, the traffic flow models are first calibrated by use of real traffic data from Attiki Odos freeway in Athens, Greece. The resulting models are validated using various traffic data sets, different than the one used for their calibration; the models are then evaluated and compared with respect to their accuracy in the reproduction of congestion created at freeway off-ramp areas.

1. Introduction

During the last decades, several mathematical models for the road traffic flow have been proposed. Depending on the level of detail they use, the models are classified as macroscopic or microscopic (see Hoogendoorn and Bovy (2001) for an overview on traffic flow models). Traffic flow models may be employed for the planning of new, upgraded or modified road infrastructures; as well as for the development and testing of traffic flow estimation algorithms, of traffic control strategies and other operational tools (Kotsialos and Papageorgiou, 2000). The models include a number of physical or non-physical parameters, with unknown values, which should be appropriately specified, in case of real applications, so as to reproduce the network and traffic flow characteristics with the highest possible accuracy. The macroscopic traffic flow models include a lower number of parameters compared to microscopic models; also, they have an analytical form, which allows their usage for various significant traffic engineering tasks (estimation, control strategy design) beyond simulation.

The macroscopic models consider the traffic flow as a compressible fluid and describe it via aggregate variables, such as flow, density and mean speed, using partial differential equations. Macroscopic models are categorized as first-order, second-order or higher-order models, according to the number of differential equations they include. The first-order models, among them the LWR model (Lighthill and Whitham, 1955; Richards, 1956) being the most popular, include one partial differential equation (PDE) which describes the mass (vehicle) conservation law; while they consider a static relation between mean speed and density, which is known as the fundamental diagram. Although the first-order traffic flow models are able to reproduce both free-flow conditions and traffic congestion, they do not allow for mean speed variations, other than those implied by the fundamental diagram. In other words, they do not take into account factors such as the impact of vehicle

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acceleration or deceleration and the drivers' reaction time; in particular, they are not able to reproduce the capacity drop phenomenon which is observed at congested freeway areas and, also, the stop-and-go waves that appear at freeway bottlenecks. The second-order models, the oldest among them being the Payne model (Payne, 1971), include, except for the conservation equation, one more PDE which describes the dynamics of mean speed. These models have the potential to replicate real traffic phenomena with higher accuracy, as they are able to reproduce the capacity drop and the stop-and-go waves occurring during congestion. Finally, they include a slightly higher number of parameters, compared to the first-order models, some of which have no direct physical meaning and should therefore be calibrated on the basis of real traffic data for best accuracy.

As a matter of fact, the only exact equation in traffic flow modeling is the conservation equation; while the description of mean speed is essentially empirical and closely related to the specific infrastructure and traffic conditions. Therefore, before employing a traffic flow model (either a first- or a higher-order model) in practice, it is important to first calibrate it against real traffic data. The calibration procedure aims to appropriately specify the model parameter values, so that the representation of the network and traffic flow characteristics is as accurate as the model structure allows. Within the vast literature on macroscopic traffic flow modeling, there are surprisingly few studies addressing or actually conducting model calibration and validation against real data, such as Grewal and Payne (1976), Cremer and May (1986), Helbing (1996), Sanwal et al. (1996), Kotsialos et al. (2002), Ngoduy et al. (2004), Frejo et al. (2012), Monamy et al. (2012), Ngoduy and Maher (2012), Poole and Kotsialos (2012); and even fewer studies undertaking, in addition to validation, also a comparison of different models, such as Cremer and Papageorgiou (1981), Papageorgiou et al. (1989), Michalopoulos et al. (1993).

The original model PDEs cannot be directly computed in digital computers, which calls for the employment of appropriate numerical schemes. From an engineering application point of view, the final space–time discretized models should be as simple as possible and have nice analytical properties (e.g. have an explicit state-space form, contain continuous and differentiable functions), which would allow for simple and transparent computation codes, convenient discretization intervals, short computation times; as well as for direct application of powerful mathematical methods (e.g. Kalman filtering, optimization, optimal control) (Kotsialos and Papageorgiou, 2000; Papageorgiou, 1998). Since the original PDEs are largely empirical, it may not be necessary to apply special effort and employ complex numerical schemes for their accurate discretization. Instead, an approximate, but explicit and analytical, space–time discretized model may first be derived from the PDEs; to be used eventually as a self-contained modeling tool for practical applications. It is this practical tool (rather than the original PDEs) which is then calibrated and validated against real data to establish and demonstrate the accuracy level of representing real dynamic traffic phenomena.

The goal of the current study is to compare the two most frequently used macroscopic traffic flow models regarding the reproduction of traffic congestion which originates from freeway off-ramp areas. Traffic congestion in these areas is usually created either due to the high freeway exit flow, higher than the off-ramp flow capacity; or due to the spillback of an off-ramp queue into the freeway mainstream. In the latter case, an off-ramp queue may have been created due to a capacity-reducing circumstance, e.g. due to a downstream urban traffic light. Traffic congestion originating from off-ramp areas is a particular, but quite frequent case of (recurrent) congestion, appearing usually at urban or peri-urban freeways during the peak periods. This kind of congestion is difficult to deal with, since there is no direct way to control the freeway exit flow; and this is probably the reason why this frequent traffic flow degradation is rarely addressed in the traffic control literature. The emergence of traffic flow models that are able to reproduce such cases with satisfactory accuracy is deemed important, as it may trigger the development of innovative traffic control strategies that face the problem of congestion at freeway off-ramp areas.

The paper is organized as follows: Section 2 presents the selected macroscopic traffic flow models, which contain a number of unknown parameters. Section 3 describes the model calibration and validation procedure which aims to appropriately specify the parameter values of the models so that they represent the network and traffic flow characteristics of a specific site as best as possible. Section 4, presents the considered freeway stretch and the traffic data used in the current investigations; followed by Section 5 which includes the calibration results and the comparison of the resulting models regarding their ability to reproduce traffic congestion at saturated off-ramp areas. Finally, Section 6 concludes with the main remarks on the study's results.

2. Macroscopic traffic flow models

The macroscopic traffic flow models are classified as first-, second- or higher-order models, depending on the number of the included differential equations. For the current study, two selected space–time discretized macroscopic traffic flow models, one first-order and one second-order, are validated and compared regarding the representation of traffic conditions at congested freeway off-ramp areas. The selected first-order model is the CTM (Cell Transmission Model) (Daganzo, 1995a, 1995b; see also Lebacque, 1996), which is a discretized (and simplified) version of the LWR model; while the selected second-order traffic flow model is METANET (Messmer and Papageorgiou, 1990; Papageorgiou et al., 2010), which is a discretized and enhanced version of the Payne model. These models fulfill the simplicity and convenience requirements mentioned earlier: they have a space–time discrete, explicit, analytical state-space form and allow for convenient discretization intervals. Hence, it is not surprising that they are by far the most frequently utilized macroscopic traffic flow models and have been used by multiple research groups for a variety of traffic engineering tasks, such as simulation, dynamic traffic