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Macroscopic traffic model for large scale urban traffic network design

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ABSTRACT

This paper presents a flexible macroscopic traffic model that is applicable for large scale urban traffic network simulations. The proposed approach combines several advantages. First, the discretized partial differential equation of the macroscopic model is solved numerically with low computational effort. The spatial and temporal resolution of the discretization are tuning parameters to balance computational effort with model accuracy. Second, the model allows arbitrary functional forms of the fundamental diagram defined by a small number of parameters. Thereby, moving density gradients (jam fronts) are represented accurately. The model parameters are physically meaningful and can readily be estimated from measurement data. Third, two general types of intersection handling are proposed and can be combined with different merge models. The first intersection approach is a binary traffic light, similar to real traffic lights. Detailed insights concerning queue length, flow across intersections and routing decisions can be investigated. The second approach is a continuous valve-like approach that allows investigation of averaged effects and large scale interaction and feedback effects. Fourth, the proposed model scales linearly with spatial and temporal resolution as well as network size and can be partially solved in parallel to increase computational efficiency. To demonstrate the above mentioned qualities of the presented model, two realistic example situations and a comprehensive study on the scaling properties are provided.

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1. Introduction

In the last decades urban traffic is steadily increasing, causing large jammed regions in urban traffic networks. This not only limits life quality but causes significant economic loss due to lost time in traffic and increases air pollution. As a consequence, ways to optimize traffic flow in both urban regions and along highways are an active topic of research. Methods generally aim at accurate traffic prediction and smart routing. However, methods to optimally utilize existing infrastructure, i. e. deriving control algorithms for traffic networks, are scarce. In this work, a macroscopic traffic model that can be utilized to develop and test control algorithms for intelligent network control in large scale traffic applications is proposed.

Inherent in every modeling task, a trade-off between modeling effort, model accuracy and computational effort must be balanced. The proposed model has the following characteristics:

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Nomenclature

BC	boundary condition
FD	fundamental diagram
α	foresight coefficient
$\mathcal{D}$	spatial computational domain
f	reduction coefficient
i	cell index
n	index of time step
ϕ	traffic flow in vehicles $\cdot\, s^{-1}$
ρ	traffic density in vehicles $\cdot$ m
s	traffic signal flow multiplicator
t, Δt	time, temporal increment
t_{green}	green time
t_{cycle}	cycle time
$\boldsymbol{\theta}$	vector of model parameters
θ	model parameter
$\mathcal{T}, \Upsilon$	traffic regulation matrix, turn rate matrix
v	driving speed in m $\cdot\, s^{-1}$
x, Δx	length of road, spatial increment

- It is based on a non-linear partial differential equation (PDE) that can be solved numerically with low computational effort
- It is capable of representing (moving) density shock waves where the accuracy is defined by the spatial and temporal resolution of the discretization
- It is tuned by a small set of physically meaningful model parameters that can be estimated from measurement data
- The computational effort scales linearly with temporal and spatial discretization and the network size
- Its modularity allows an efficient work flow in real life applications, e. g. developing and testing control algorithms

In this work a macroscopic traffic simulation approach is proposed. Traffic density is treated like a compressible fluid, hence, can be described by the transport equation, a non-linear PDE. Existing macroscopic traffic models, such as the Cell Transmission Model (CTM proposed in [1,2] are well established in highway traffic prediction and analysis. The model parameters of the CTM represent a triangular flux function specifying the forward and backward wave propagation speed and the critical and maximum traffic density. The model has been extended to allow traffic density estimation [3]. Recently, the Stochastic CTM (SCTM) has been developed to account for the stochastic nature of inflow and outflow as well as fluctuations in the model parameters [4,5]. The (extended) CTM is well suited for highway traffic state estimation and prediction. To distribute the computational load of large network simulations cloud computing techniques [6] and auto-scaling methods [7] have recently been developed. A flux function describes the relationship between traffic mass flow and density. In a different parameterization but otherwise equivalent the Fundamental Diagram (FD) [8] describes the relationship between driving speed and traffic density. It is well known from both measurement data and literature [9,10] that the FD is a general, nonlinear function. The CTM's limitation to triangular flux functions is overcome by the traffic model presented in this work, where no limit on the shape of the flux function is imposed. Thereby, shock waves at jam fronts can be represented accurately. This is important for the application in urban traffic network simulations, where the flux functions are often better approximated by non-convex functions of arbitrary shape.

For the proposed model the set of parameters that define the functional form of the FD are the model parameters. It is important to note that the exact parameterization of the functional form is not critical. However, in this work a particular choice of parameters is proposed, such that model parameters are physically meaningful. A method to estimate the model parameters from measurement data is proposed in [11].

With regard to the computational effort the proposed macroscopic traffic model fares well compared to other concepts. For each road in the network the transport equation is discretized and solved numerically with a first-order Godunov finite volume approach. The spatial and temporal resolution are coupled via the Courant–Friedrichs–Lewy (CFL) condition and provide a tuning parameter for the trade-off between model accuracy and computational effort. The computational effort scales linearly with the number spatial cells and temporal increments. Note that the complexity of the traffic situation with regard to changing boundary conditions, evolution of jam fronts, etc. has no impact on computation time. Furthermore the proposed model can be partially solved in parallel in each time step: the discretized transport equation can be solved individually for each road within the traffic network.

Microscopic traffic models represent the other end of the spectrum with respect to modeling effort. Each vehicle is modeled and tracked individually. A driver model (car-following-model) for each vehicle is defined [12], providing the advantage that mixed-mode traffic can be specified readily. A major drawback is the large number of model parameters that are difficult to estimate and require a considerable calibration effort. Due to the high computational load, microscopic models are

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