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A mesoscopic integrated urban traffic flow-emission model

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ABSTRACT

Due to the noticeable environmental and economical problems caused by traffic congestion and by the emissions produced by traffic, analysis and control of traffic is essential. One of the various traffic analysis approaches is the model-based approach, where a mathematical model of the traffic system is developed/used based on the governing physical rules of the system. In this paper, we propose a framework to interface and integrate macroscopic flow models and microscopic emission models. As a result, a new mesoscopic integrated flow-emission model is obtained that provides a balanced trade-off between high accuracy and low computation time. The proposed approach considers an aggregated behavior for different groups of vehicles (mesoscopic) instead of considering the behavior of individual vehicles (microscopic) or the entire group of vehicles (macroscopic). A case study is done to evaluate the proposed framework, considering the performance of the resulting mesoscopic integrated flow-emission model. The traffic simulation software SUMO combined with the microscopic emission model VT-micro is used as the comparison platform. The results of the case study prove that the proposed approach provides excellent results with high accuracy levels. In addition, the mesoscopic nature of the integrated flow-emission model guarantees a low CPU time, which makes the proposed framework suitable for real-time model-based applications.

1. Introduction

Emissions produced by vehicles in urban traffic areas, especially when traffic becomes congested and vehicles start to idle in long queues, significantly increase the level of harmful substances in the air such as carbon monoxide (CO) and dioxide (CO_2), hydrocarbon (HC), and nitrogen oxides (NO_x) (Sjodin et al., 1998; Anderson et al., 1996; Barth and Boriboonsomsin, 2008; Barth et al., 1996). This may be dangerous, especially in sensitive urban areas, e.g., in the neighborhood of hospitals, nursing homes for the elderly people, schools, etc. Additionally, another consequence of congested urban traffic is increased fuel consumption and the expenses it imposes on societies. According to a report published by the Center for Economics and Business Research (2014), the expected costs caused by traffic in the UK, US, Germany, and France might increase by up to 46% by 2030 w.r.t. 2013.

To mitigate the problems regarding increased emissions and fuel consumption in urban traffic networks, model-based analysis and control may be used. Model-predictive control (MPC) (Maciejowski, 2002) is a model-based control approach that has proven to be efficient for traffic networks (see Diakaki et al. (2002, 2003), Aboudolas et al. (2010), van den Berg et al. (2007), and Bellemans et al. (2006) for the application of MPC in urban traffic networks and freeways). Therefore, from

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an environmental and an economical point-of-view, it is important to develop and to improve urban emission models that give an estimate of the current and possible future emission and fuel consumption levels.

Based on the level of detail, different traffic models (including flow and emission models) can be categorized as microscopic, mesoscopic, and macroscopic. If the model is focused on more details and takes into account the behavior of individual vehicles in the network, it is called a microscopic traffic model (Pipes, 1953; Gazis et al., 1961; Qi et al., 2004). Some traffic models express the average behavior of the vehicles as a fluid. These models are known as macroscopic traffic models (see e.g. Messmer and Papageorgiou, 1990; Ntziachristos et al., 2009). There is also a third category for traffic models, known as mesoscopic models (Hoogendoorn and Bovy, 2001), which partly use the characteristics of microscopic and macroscopic models, i.e., the level of detail for a mesoscopic model is less than a microscopic and greater than a macroscopic traffic model.

The focus of this paper is on the introduction and development of a new framework for integrating and interfacing any macroscopic urban traffic flow model that updates the total number of vehicles in the links and the number of vehicles standing in the queues as the states of the traffic network (e.g., the S-model by Lin et al. (2012)) with any microscopic emission model that uses both the speed and the acceleration of the individual vehicles in order to compute the emission and the fuel consumption levels (e.g., VT-micro by Ahn et al., 1999 and VERSIT+ by Ligterink et al., 2009). The proposed approach will result in a new mesoscopic integrated urban traffic flow-emission model that provides a balanced trade-off between high accuracy and low computation time. The resulting model belongs to the mesoscopic category considering the following characteristic given for mesoscopic traffic models by Hoogendoorn and Bovy (2001); mesoscopic models specify the behavior of traffic by groups of vehicles/drivers, were the interactions of these vehicles/drivers are described in a low level of detail.

In order to compute the emission levels, several models from different classes (i.e., microscopic, mesoscopic, and macroscopic) have been developed (e.g., see the macroscopic models by Ntziachristos et al. (2009) and by Csikós et al. (2015), the mesoscopic models by Rakha et al. (2011) and by Gori et al. (2013), and the microscopic models by Ahn et al. (1999), Ligterink et al. (2009), and by Chen and Yu (2007)).

Some macroscopic models provide a high computation speed (such as COPERT by Ntziachristos et al. (2009), which is based on the average speed of the vehicles, and the macroscopic model by Csikós et al. (2015), which is based on the total travel distance and the average speed), while they ignore the effect of acceleration and deceleration of the vehicles. This may bring issues for the accuracy of the results, especially in urban traffic areas with signalized intersections. More specifically, experiments show that in case of positive acceleration, and in particular for the emissions of NO_x, the minimum of the emissions (in g/km) as a function of speed does not always correspond to the urban traffic free-flow speed. Hence, minimizing the total delays of the vehicles does not necessarily lead to minimization of the emissions. Hence, in our proposed framework, we take into account the effect of the acceleration and deceleration of the vehicles to improve the accuracy of the results for urban traffic networks.

The mesoscopic model developed by Rakha et al. (2011) provides promising results w.r.t. the microscopic model VT-micro (the errors are within the range of 10–27%). In the current paper, we aim to improve the accuracy of these results to an even higher level for a mesoscopic model that is resulting from our proposed integrating framework. Hence, we start from a microscopic point-of-view, by considering the time-speed trajectories of individual vehicles in the traffic network. Then we distinguish some groups of vehicles with similar traffic behaviors and we define a (possibly virtual) representative vehicle for each group. Afterwards, we use a microscopic emission model such as VT-micro or VERSIT+ to compute the instantaneous emissions of the representative vehicle for each specific traffic behavior (free-flow, idling, decelerating, accelerating). By multiplying the resulting emissions by the total number of vehicles in each group and by the average time of the given behavior, we obtain a mesoscopic emission model.

The simulation results show that the relative error of the computed emissions by our proposed mesoscopic approach are less than 6%. Hence, we have successfully improved the results w.r.t. (Rakha et al., 2011). Compared with the mesoscopic model proposed by Gori et al. (2013), which is limited to signalized intersections and ignores the decelerating behavior of the vehicles, our framework is more general and can be used for both signalized and non-signalized traffic networks. As mentioned earlier, we do not ignore the decelerating behavior by the vehicles. Gori et al. (2013) consider two different traffic scenarios in an urban traffic network, i.e., the under-saturated and the saturated scenarios. We add a third scenario, i.e., the over-saturated scenario, which helps us to provide more accuracy.

Chen and Yu (2007) develop a microscopic simulation platform by integrating the microscopic traffic simulation VISSIM and the microscopic modal emission model CMEM. The aim of their work is to mostly provide a platform to assess the effect of different aspects in a traffic network on the amount of emissions. Our focus in this paper is mostly on providing a mathematical model for computation of emissions that can be applied in model-based analysis and control of traffic.

Previous work on integrating traffic flow and emission models include the work by Zegeye et al. (2011), where METANET (Messmer and Papageorgiou, 1990), a macroscopic freeway flow model, and VT-micro is are integrated. For urban traffic, an integrated flow and emission model has been developed by Lin et al. (2013), where the S-model is integrated with VT-micro to form a simple integrated model that suits real-time control applications. The proposed macroscopic model has a low computation time and in a case study given in (Lin et al., 2013) shows satisfactory results when used as the internal model of a model-predictive controller. Inspired by the macroscopic integrated model given by Lin et al. (2013) and by Zegeye et al. (2011), in the current paper we develop a general mesoscopic framework to integrate macroscopic traffic flow models and microscopic emission models (i.e., our proposed framework is not limited to specific flow and emission models). The aim is to provide even more accuracy, while keeping the computation speed still high. Therefore, similarly to the work by Lin et al. (2013), we divide the possible traffic states in an urban traffic network into three different scenarios, i.e., under-