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Macroscopic modeling approach to estimate traffic-related emissions in urban areas

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ABSTRACT

This paper integrates a macroscopic dynamic traffic assignment (DTA) model for urban traffic flow with an instantaneous emission model to investigate traffic-related emissions in urban areas of arbitrary shape. It is assumed that homogeneous travelers continuously distributed over the urban areas tend to choose a path to minimize their total travel cost based on instantaneous traffic information. The macroscopic DTA model consists of a two-dimensional hyperbolic system of nonlinear conservation laws with source terms and an Eikonal-type equation used to describe the path-choice behavior of travelers. A solution algorithm for the model is designed as a Runge–Kutta Discontinuous Galerkin method for the hyperbolic system coupled with a fast sweeping method for the Eikonal-type equation on unstructured meshes. A case study investigating macroscopic characteristics of urban traffic flow and predicting exhaust emissions emitted by various types of vehicles in urban areas is conducted to illustrate the applicability of the model and the effectiveness of the algorithm.

Introduction

The contribution of road traffic in urban areas to current global anthropogenic emissions, such as carbon dioxide (CO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC) and particulate matter (PM), is significant (Niemeier et al., 2006). These traffic-induced emissions have enormous impacts on human health and climate change. Therefore, previous research (Ahn et al., 2002; Panis et al., 2006; Smit et al., 2007; Nejadkoorki et al., 2008; Misra et al., 2013; Jie et al., 2013; Yin et al., 2012; Zegeye et al., 2013; Zhu, 2013; Tang et al., 2015; Yu and Shi, 2015) has focused on the contribution of traffic-generated air pollutants (e.g., NO_x, VOC and PM) and greenhouse gases (e.g., CO_2). Various modeling approaches of emission from motor vehicle exhausts including analytical models, numerical models and statistical models (Sharma and Khare, 2001; Smit et al., 2010) have been proposed over the years to evaluate the environmental effectiveness of various traffic management and traffic control strategies.

Most methodologies of calculating traffic-related emissions are based on emissions factors representing emissions emitted by each vehicle category under normal traffic conditions and operational parameters (e.g., the density, average speed and acceleration of traffic flows) representing real-world traffic conditions (Cortés et al., 2008). The literature encompasses two general approaches used to estimate vehicle emissions and fuel consumption (as represented by the CO_2 emissions): the

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macroscopic modeling approach and the microscopic modeling approach (Nejadkoorki et al., 2008). The macroscopic modeling approach uses average aggregate network parameters to estimate network-wide emission rates according to high-level relationships among density, flow, and speed of traffic flows on urban road networks (Dia et al., 2006). This approach is low-accuracy, but allows to compute faster the estimates of emissions. Therefore, macroscopic emission models, such as U.S. federal's MOBILE model (EPA, 2003), California's EMFAC model (CARB, 2007) and European's COPERT III model (Ntziachristos and Samaras, 2000), are useful for estimating the emissions of large-scale areas. However, these models ignore microscopic vehicle movement and could incorrectly estimate emission rates (Misra et al., 2013). The microscopic modeling approach is usually adopted to estimate instantaneous vehicle emission rates using either vehicle engine or vehicle speed/acceleration data. Microscopic emission models, such as the CMEM model (Barth et al., 2000), the VT-Micro model (Ahn et al., 2002), the VERSIT + model (Smit et al., 2007) and the MOVES model (Vallamsundar and Lin, 2011), are considered to be preferable for predicting emissions in urban areas. This is because the density and speed of traffic flows on networks can vary significantly over relatively short distance and time scales (Nejadkoorki et al., 2008).

Vehicle operational parameters that affect greatly the exhaust emissions are generally obtained by traffic surveys and dynamic traffic assignment (DTA) models. The former can most accurately reflect real-time traffic conditions, but is usually carried out on some specific road links and during a specific time period (Xia and Shao, 2005). Therefore, traffic surveys are often insufficient for adequately quantifying the traffic on the whole road network. DTA models that deal with time-varying flows can capture traffic dynamics on urban road networks (e.g., time-dependent travel speeds of vehicles), which is important input data required for the calculation of traffic emissions. There are two basic types of DTA models in literature, i.e., microscopic DTA models and macroscopic DTA models (Jiang et al., 2011). Microscopic DTA models as described in the review articles by Peeta and Ziliaskopoulos (2001), Szeto and Wong (2012), in which each individual vehicle is represented and each road link is modeled separately, are commonly adopted for the detailed planing and analysis of a transportation system. There are obviously difficulties in modeling a large-scale congested urban traffic network with a large number of links. Conversely, macroscopic DTA models (Rossa et al., 2010; Jiang et al., 2011; Tao et al., 2014; Saumtally et al., 2013), in which a dense network is approximated as a continuum on which travelers are free to choose their paths in a two-dimensional (2D) continuous space, are used in regional studies and for modeling highly dense transportation systems. Most of macroscopic DTA models (Rossa et al., 2010; Jiang et al., 2011; Tao et al., 2014) are derived from the classical Lighthill–Whitham–Richards (LWR) models for one-dimensional (1D) vehicular traffic flow and cannot express the acceleration/deceleration dynamics of vehicles. There are also developments combining ideas from both macroscopic and microscopic DTA models (Osorio and Nanduri, 2015).

In consideration of their capability of capturing the effect of traffic variations, DTA models integrated with road traffic emission models can characterize the traffic fluxes and quantify the emission amounts on an urban road network. Consequently, this type of integrated models, which typically consist of a microscopic/macroscopic DTA model and a microscopic/macroscopic emission model (Xia and Shao, 2005; Panis et al., 2006; Pataki et al., 2009; Madireddy et al., 2011; Misra et al., 2013; Jie et al., 2013; Yin et al., 2012; Zegeye et al., 2013; Zhu, 2013; Osorio and Nanduri, 2015; Tang et al., 2015; Yu and Shi, 2015), can serve as an evaluation tool for quantifying the environmental impacts of various traffic management and traffic control strategies. For example, Panis et al. (2006) developed an integrated model, which is described as the network-wide traffic microsimulation model DRACULA coupled with an instantaneous emission model. In this integrated model, new second-by-second emission functions depending on vehicle speed and acceleration are developed based on actual measurements with several instrumented vehicles driving in real urban traffic situations. Misra et al. (2013) adopted an integrated modeling approach by combining the traffic microsimulation model PARAMICS and the CMEM emission model. Jie et al. (2013) used the microscopic simulation model VISSIM coupled with the VERSIT + emission model. The aforementioned methodology is high-resolution, but has an important drawback that a large number of input variables, e.g., driver behavior attributes (vehicle speed and acceleration), vehicle characteristics (weight or mass) and road geometry (grade), may be required (Osorio and Nanduri, 2015). In contrast, less input data is required for the macroscopic DTA models integrated with the microscopic emission models and this integrated approach can also get a balanced trade-off between computational complexity and accuracy (Zegeye et al., 2013). Yin et al. (2012) presented a network-based macroscopic model coupled with the VT-micro model to investigate the relationships among housing allocation, traffic volume, and CO_2 emissions, but this network-based macroscopic model did not consider time-dependent origin–destination (OD) travel demand. In order to estimate network-wide vehicular emissions, Zegeye et al. (2013) proposed a VT-macro model based on a combination of the macroscopic traffic flow model METANET (which is described as nonlinear difference equations for link traffic flow) and the VT-micro emission model. Here, this macroscopic traffic flow model METANET requires detailed data for all road links and intersections included in the road network for the model setup process, and is thus suitable only for road networks with a simple structure.

In order to estimate traffic-related emissions in urban areas, the macroscopic modeling approach is particularly useful for highly populated urban cities with high population and road densities (Yin et al., 2012). In this study, we integrate a macroscopic DTA model for urban traffic flow with an instantaneous emission model to investigate air pollutants and greenhouse gases emitted by various types of vehicles in a dense urban area of arbitrary shape. These two different models are integrated in such a way that the emission model can get speed and acceleration inputs of the traffic flow from the macroscopic DTA model at every simulation time step. The macroscopic DTA model is described as a 2D hyperbolic system of nonlinear conservation laws with source terms under the hypothesis that all vehicles with the same characteristics, e.g. weight, engine type and size, move like a continuous anisotropic medium. The desired direction of motion for drivers is to minimize the

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