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Modeling of the dispersion of motorway traffic emission for control purposes

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ABSTRACT

In this paper a novel simple dynamic model is suggested for the dispersion of motorway traffic emissions. The motivation for the research is to develop a model with low computational demand so that it can serve as a basis for a model based controller that is able to keep pollutant concentrations under legislation limits. The dispersion process is characterized as a distributed parameter system (DPS) in which the law of mass conservation holds. The elements of the mathematical model (the assumptions of the initial value problem) are specified using topological considerations, and the boundary conditions originate from the macroscopic traffic emission framework developed by the authors earlier. The developed engineering model, with applying the Gaussian plume model, is transformed to a discrete time nonlinear concentrated parameter state-space model form using lumping and finite difference approximations. For the suggested model a verification and numerical stability analysis is carried out. A sensitivity analysis of the existing motorway control measures (i.e. ramp metering, variable speed limits) is performed to justify the choice of a future control structure.

1. Introduction

The dispersion of vehicular emissions is a significant environmental problem. Therefore, its dynamic modeling and use in designing pollution-aware traffic controllers is of primary importance. The model has to be as accurate as possible, yet numerically simple enough to be used for control design purposes.

The importance of traffic emission modeling was recognized long ago. In Kulkarni et al. (1996), the relationship between traffic intensity and emissions are analyzed using the spin glass phenomenon analogy. In Koenig et al. (1996) a method is proposed for the analysis of traffic demands in terms of emissions and travel times, and it is also shown for an example of a commute-related traffic increase. In Bachman et al. (2000) the aggregated emission of vehicle individuals is recognized to be a distributed parameter system, and the data is collected using a Geographic Information System (GIS) framework.

For the modeling of aggregated emissions, a microscopic approach can be taken as well. A good example for this is Jie et al. (2013), using the microscopic simulator VISSIM, and the emission model Versit+. In Zegeye et al. (2013), an integrated model is suggested for the modeling of motorway emissions and fuel consumption based on the model VT-Micro (see Rakha et al., 2004). In this work the output of the integrated emission model is not interpreted on a macroscopic level as a distributed parameter system (by using the spatial and temporal variable of the process), but by average vehicle emission levels

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on separate road links. On the other hand, the model VT-Micro is developed only for a few vehicle classes, commonly used in the USA. In Csikós and Varga (2012), a macroscopic modeling framework is introduced for the description of motorway emissions, as a distributed parameter system. For the modeling of the pollution of a vehicle individual, the average speed model COPERT (see Ntziachristos et al., 2000) is used. The effects of motorway control on traffic emissions have been investigated too. The effect of speed limit control is compared to the effect of road pricing in Yang et al. (2012) in terms of traffic performance and emission. For the optimal speed limits, an algorithm is suggested in Wang (2013) but here no emission model is considered explicitly.

To obtain the pollutant concentration values near motorways, the dispersion of the exhaust emissions has to be modeled. Traffic emission dispersion models are mainly developed for urban networks: so-called street-canyon models (see e.g. Buckland and Middleton, 1999 and Tominaga and Stathopoulos, 2011) describe the accumulation of concentration of pollutants being stuck in the canyons of urban streets. These models are not adaptable for freeways because of the fundamentally different topology. Several dispersion models – i.e. Gaussian plume models (see e.g. Johnson et al., 1973; Benson, 1979) or CFD models (e.g. Gosman, 1999) – are applicable for the freeway topology providing high resolution description of the pollutant dispersion, but these models are not suitable for control design purposes because of their high computational demands. The numerical properties of CFD modeling is evaluated in He et al. (2011), and the high computational demands are highlighted. In Zegeye et al. (2011) a grid-based dispersion model is suggested for traffic control purposes, but the specification of boundary conditions using emission values is not discussed.

In this paper a novel model is suggested for the dispersion of motorway traffic emissions. The motivation for the research is to later develop a model based control that is able to keep pollutant concentrations emerging in inhabited areas in the proximity of a motorway stretch under legislation limits, and in case of a shockwave threat, the prevention of shockwave formation by possibly using the controller presented in Csikós et al. (2013). Thus, a simple yet accurate model is needed to characterize the dispersion of exhaust gases. Assuming isothermal conditions, the dispersion process is described as a distributed parameter system (DPS) in which the law of mass conservation holds. The elements of the mathematical model (the assumptions of the initial value problem) are specified using topological considerations, and the boundary conditions originate from the macroscopic traffic emission framework introduced in Csikós and Varga (2012). The developed partial differential equation is converted to a set of ordinary differential equations by lumping the system. These differential equations are then reformalized by finite difference approximation resulting in a model being discrete both in space and time. Then an analytical approximation of the decay rate (modeling the dissolution of pollution) is proposed.

The paper is organized as follows. First the preliminaries on macroscopic traffic and emission modeling are summarized in Section 2. The derivation of the dispersion model dynamics is detailed in Section 3. Hereafter, the joint traffic – emission dispersion model system is stated in Section 4. The analysis of the model is carried out in Section 5. For the suggested model a verification and numerical stability analysis is presented here. Furthermore, a sensitivity analysis of the existing motorway control measures (i.e. ramp metering, variable speed limits) is performed to justify the choice of the future control structure.

2. Preliminaries on macroscopic traffic and emission modeling

Motorway traffic is most commonly described by macroscopic traffic models. This approach describes traffic as a compressible fluid neglecting individual vehicle dynamics and describing it by aggregated variables. Road traffic variables are bivariate functions of space (x) and time (t): traffic flow (denoted by $q(x,t)$ in units [veh/h]), traffic density (denoted by $\rho(x,t)$, in units [veh/km]) and space mean speed of traffic (denoted by $v(x,t)$, in units [km/h]). These continuous variables are approximated by discrete values in time and space by loop detector measurements (for measurement resolutions see Cremer and Papageorgiou, 1981). Emission of the traffic needs to be characterized in the same manner i.e. as a variable of both space and time. According to the dynamical equations first- and second- and higher-order models exist. A discrete interpretation of the continuous first-order models of Lighthill and Whitham (1955) and Richards (1956) is given by the Cell Transmission Model (CTM) (Daganzo, 1994). The second-order models of Payne (1971) and Whitham (1974) is formalized in discrete spatiotemporal manner by the model METANET, introduced in Messmer and Papageorgiou (1990). In our work, a modified version of METANET is used.

2.1. Macroscopic modeling of motorway traffic

The considered traffic system is a motorway stretch divided to N_s segments of similar length. Control is realized using metered ramps r_i and variable speed limits $VSL_i, i = 1,\dots,N_s$. Upstream flow (q_0), mean speed of the upstream traffic (v_0), ramp demands ($d_i, i = 1,\dots,N_s$) and downstream density (ρ_{N_s+1}) are considered disturbances. System dynamics are modeled by the second order continuum model (see Papageorgiou et al., 1980). Macroscopic variables are obtained by direct measurements (e.g. the traffic flow and traffic speed) or may be derived from measurements (e.g. traffic density, which can be calculated from the occupancy measurements of the loop detectors (see Papageorgiou and Vigos, 2008)).

2.1.1. Engineering model

Equations of the second-order traffic flow model regarding segment i of length L_i during a discrete time step k of length T are as follows: