Transportation Research Part D 59 (2018) 174–191

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

A hybrid model predictive control for traffic flow stabilization and pollution reduction of freeways

Alfréd Csikós[a,*], István Varga[b], Katalin M. Hangos[a]

[a] Institute for Computer Science and Control, Systems and Control Laboratory, Hungarian Academy of Sciences, Kende utca 13-17, 1111 Budapest, Hungary

[b] Budapest University of Technology and Economics, Department of Control for Transportation and Vehicle Systems, Stoczek utca 2., 1111 Budapest, Hungary

A B S T R A C T

In this work a control system is developed and analyzed for the suppression of moving jamwaves and the reduction of pollutant concentrations near motorways. The system is based on the second-order macroscopic freeway traffic model METANET, joined by an emission dispersion model, introduced in a previous work of the authors. For the control tasks dedicated controllers are designed, both using the nonlinear model predictive control method. The control objectives require a distinction in the utilized control measures, thus different controllers are designed and used in predefined control modes. The first mode of the controller is responsible for keeping pollutant concentrations below prescribed limits under stable conditions. The second mode of the controller is working in case of a shockwave threat, aiming for traffic stabilization. Between the control modes switching is based on an appropriate rule set that satisfies the stability of the controlled system. The hybrid controller structure is realized by a finite automata. A complex case study is presented for the evaluation of the suggested controller.

1. Introduction

The dispersion of vehicular emissions is a significant environmental problem: the pollution of certain exhaust gases (i.e. CO, HC and NO_x) is responsible for serious health issues. Therefore, reduction of pollutant concentrations at inhabited areas near motorways is of vital importance in modern transport engineering. In our research, we aim to develop a motorway control system for a combined task: in addition to traffic stabilization, the controller should be capable of keeping pollutant concentrations below limits in the vicinity of motorways.

The effect of traffic management systems on vehicular emissions have been investigated both in motorways and urban networks by several authors in the past decades, see Szeto et al. (2012). The exploitation of vehicular emission models in traffic engineering research can be realized on different levels. The first level is the *use of ITS (Intelligent transportation systems) data for offline or online emission modeling*. Offline modeling efforts imply data-based analysis of the relationship between flow conditions and emission. Smit et al. (2008) examine the effect of mean speed distributions on traffic emission inventories. In Liu et al. (2011), the correlation of traffic patterns and emission data are analyzed, aiming to understand the relationship between daily flow level patterns and emissions. In Gokhale (2012), the environmental effect of synchronised flow patterns at intersections is analyzed. Fontes et al. (2015) compare the Eulerian and Lagrangian simulation approaches and their effect on the fidelity of emission inventories.

Online emission modeling results focus on the use of real-time data and this approach serves to establish control strategies

* Corresponding author.
E-mail addresses: csikos.alfred@sztaki.mta.hu (A. Csikós), ivarga@mail.bme.hu (I. Varga), hangos@mta.sztaki.hu (K.M. Hangos).

https://doi.org/10.1016/j.trd.2018.01.006

Available online 20 February 2018
1361-9209/

including emission performances as control criteria. Chen et al. (2014) analyze the substitution of vehicle trajectory data to emission models resulting in average emission factors, normalized for vehicle unit. Chang et al. (2013) propose a bottom-up vehicle emission model to estimate CO_2 emissions using real-time data. The proposed method uses loop detectors and floating car data to express average emission factors of local fleet compositions. Ryu et al. (2013) suggest a method to use probe vehicle data (or floating car data) to express average emissions emerging at link units. Zegeye et al. (2013) apply macroscopic traffic variables for the cycle-variable model VT-Micro (Rakha et al., 2004) to express real-time average emission factors of traffic.

On the middle-level, emission models are used for the *analysis of the environmental impact of ITS tools*. In Carolien et al. (2007) a microscopic simulation platform is developed for the analysis of traffic control measures. Papers of Ma et al. (2014) and Jazcilevich et al. (2015) propose systematic assessment methodologies of ITS solutions, including their impact on emissions. Analyses are carried out regarding the influence of traffic intensity, signal coordination schemes and signal parameters on the gaseous emissions in urban networks by Coensel et al. (2012) and Gori et al. (2015). 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.

The *incorporation of emission models to the control design* is the highest level of use of emission models in traffic engineering. This was first done by Zegeye et al. (2009). The work of Mahmod et al. (2013) gives a comparative analysis of ITS measures (i.e. demand control, restriction of vehicle classes, and speed limit control) for a single intersection. The paper points out that constraining traffic demand clearly reduces emissions, while the reduction of speed limits lead to the increase of emission of certain pollutants. A special traffic assignment problem, minimizing network emissions is addressed by Long et al. (2016). Based on the Link Transmission Model, the problem is solved by means of mixed integer linear programming. A variable speed limit control scheme is designed to reduce emission factors on freeways by Liu et al. (2012). The data transferred by vehicle-to-vehicle (V2V) technologies can be best exploited for cycle variable or higher level emission models, an interesting control approach in this field is presented by Alsabaan et al. (2013).

It has to be pointed out, that although several approaches have been suggested to use emission models in traffic control analysis and synthesis, none of these approaches define a macroscopic description for the spatiotemporal distribution of emissions. This description, based on the average-speed vehicle emission modeling framework is derived by Csikós and Varga (2012).

All the above works focus on emission modeling, expressed in terms of emission factors. For the pollutant behaviour of exhaust gases, *roadside dispersion models* can be applied. Shorshani et al. (2015) examine dispersion under calm wind conditions, following the Gaussian plume approach. A control-oriented dispersion model is presented by Zegeye et al. (2011) with a grid-based approach. The pollution is considered as a soft constraint, and a multi-objective control approach for traffic performance improvement and pollution reduction is proposed.

Inclusion of dispersion dynamics into control design is not straightforward. Handling pollutant concentrations as soft constraints in multi-objective design offers a general approach, however, in case of extreme demands and traffic jams it may lead to suboptimal solutions. On the other hand, topological attributes of the polluted areas need to be incorporated into control design as well. These points can be most effectively solved by separating the considered control problems, namely: (i) stabilizing traffic flow; (ii) keeping pollutant concentrations under specified limits under stable traffic conditions. Therefore, in the current paper, instead of a multi-objective control design, a hybrid approach is presented: separate controllers are developed for the above given control problems. Between the two controllers switching is realized by a supervisor controller, formalized as a finite automata that applies a set of rules that provides stability of the switching mechanism.

Our work relies on the dispersion model proposed in Csikós et al. (2015), where a sensitivity analysis of the model is also carried out supporting a preliminary statement of control objectives for pollution reduction. By integrating the emission dispersion model to the second-order motorway model METANET (Papageorgiou et al., 1990), a joint system is obtained for which the hybrid controller is designed. Ramp metering and variable speed limit (VSL) control input values are optimized by means of the nonlinear model predictive control (NMPC) technique, see in Grune and Pannek (2011). For the evaluation of the suggested controller, a complex case study is presented, in which performances of the control modes and the switching behaviour are analyzed.

The paper is structured as follows: after the introductory section, in Section 2 the macroscopic traffic and emission models are summarized alongside the emission dispersion model. Following an overview of the system model, control design is detailed in Section 3. The controller performance is analyzed in a case study, presented in Section 4. The computational properties of the proposed control system are discussed in Section 5. Finally, conclusions are drawn.

2. Methods and tools

Motorway traffic is most commonly described by macroscopic models using aggregated variables, which are bivariate functions of space and time. This distributed parameter system approach (DPS, see Hangos and Cameron, 2001) is extended to the modeling of motorway traffic emissions as well: i.e. emission is stated as a variable of both space and time, expressed as a function of the macroscopic traffic variables. In this section the modeling aspects are summarized for traffic flow, traffic emissions and the dispersion of exhaust pollution.

2.1. Motorway traffic model

The considered traffic system is a motorway stretch divided to N_s segments of similar length.[1] Control of the system is realized by

[1] Segment lengths $L_i, i = 1,...,N_s$ may be chosen arbitrarily as long as the numerical stability condition of Courant et al. (1928) is satisfied for given sampling time T, i.e. $v_{free}\frac{T}{L_i} < 1, i = 1,...,N_s$. The free flow speed v_{free} is equal to the highest velocity that a particle (i.e. a vehicle) in the flow may carry.