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Real-time modeling and control objective analysis of motorway emissions

Alfréd Csikós[a,*], István Varga[b]

[a]*Department of Control and Transport Automation, Budapest University of Technology and Economics. Bertalan L. u. 2., H-1111 Budapest, Hungary.*
[b]*Systems and Control Laboratory, Computer and Automation Research Institute, Hungarian Academy of Sciences. Kende u. 13-17, H-1111 Budapest, Hungary.*

Abstract

In this paper a real-time macroscopic modeling framework of road traffic emissions is suggested based on an average-speed emission model. A model function is created to describe the spatiotemporal distribution of motorway traffic emissions using loop detector data only which is suitable for emission dispersion and immission modeling. The proposed model is built using macroscopic traffic variables, and derivation is shown both on microscopic and macroscopic levels, in the latter case showing relationship with traffic performance functions as well. The suggested model function is validated in a VISSIM/MatLab simulation environment, applying COPERT IV average speed model in the proposed framework, compared to a microscopic emission model (Versit+*Micro* is used via the VISSIM add-on called EnViVer). Based on the suggested model, control objectives are stated for a multi-criteria model-based control. During the cost function analysis, pollutants are distinguished in terms of the areal extension of their effects and a diverse modeling approach is carried out for pollutants causing global and local effects. The cost function is analyzed for steady-state flow conditions.

Keywords: traffic emission; macroscopic emission modeling; freeway traffic; control objective function; model validation

1. Introduction

Modern policies require traffic being a process that is optimal both in terms of social costs (i.e. costs caused by delays, high fuel consumption, local health effects of pollutants) and environmental aspects (local and global

* Corresponding author. Tel.:+3614633089. *E-mail address:* csikos.alfred@mail.bme.hu

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effects of gaseous emission (acid rain, global warming)). While traffic control strategies have been widely used to moderate delays and prevent traffic congestions, emission and fuel consumption optimization have only got into limelight in the short past. In order to formulate control objectives for emission optimization the understanding of the nature of traffic emission is essential.

Emergence of road traffic pollution and fuel consumption can be estimated by a variety of models and methods. These models are classified by several criteria. Based on the scale of input variables, emission models fall into two main categories: microscopic and macroscopic models. Microscopic models use instantaneous driving pattern data (speed and acceleration) to estimate instantaneous vehicle fuel consumption and emission rates (i.e. CMEM, VERSIT+) (see Hirschmann ez al., Smit et al. (2007)). Macroscopic models (HBEFA, Copert) (see CARB (1991), Ntziachristos et al. (2000)) use aggregated traffic variables (such as *VKT* - vehicle kilometers travelled and emission factors) to estimate network-wide fuel consumption and emissions of long time periods. This modeling approach was motivated by the need of emission inventories (e.g. Smit et al. (2010) and Yao et al. (2011)), control possibilities of road traffic were not considered. However, in the traffic control framework, real-time data are available thus a detailed analysis of the problem is needed. In Xia et al., Zegeye et al. (2009) emission models of different levels are used for control purposes, and although these models rest on theoretic considerations, the analysis of emission functions in these works are not profound. Dispersion of pollution is considered in Zegeye et al. (2011), but the real-time amount of emitted pollutants spreading from spatiotemporal segments are not modeled precisely.

Traffic control interventions are usually commanded at certain localities, based on the real-time conditions of the local traffic. In our research, we aim to turn traffic emission into a traffic control criterion. Current paper suggests a macroscopic emission model function that provides real-time information of traffic emissions and also can be formalized as cost functions for a control framework. The model is introduced on freeway traffic as motorways turn over a significant transport performance, and loop detector measurements provide fairly exact information of current traffic conditions. High emission levels are typical of motorways because of their speed range. In addition, the lack of frequent stops and the high traveling speeds mean that the effect of accelerations can be neglected which justifies the use of average speed models. The proposed macroscopic modeling framework uses an average-speed emission model and real-time traffic variables to describe the spatiotemporal emergence of emission. The information of real-time emission distribution in space and time is most useful for control purposes, but also in case of emission dispersion and immission modeling (e.g. Briant et al.). The control objective functions created from the suggested macroscopic model function distinguish the global and local effects of the pollutants.

The suggested model is presented in four sections. After the introductory section, preliminaries regarding emission modeling and macroscopic traffic description are summarized. In Section 3 the macroscopic model function is introduced which is validated using VISSIM/EnViVer simulations in Section 4. Then, in Section 5 control objective functions for emission criteria are formalized. Finally, in Section 6 conclusions and further research directions are stated.

2 Preliminaries

2.1 Emission modeling

2.1.1 Emission inventories

The original aim of macroscopic emission models is to provide a standardized method for estimation of national emissions of traffic related pollutants via emission inventories. Emission inventories list the amount of air pollutants discharged by a certain network, for a certain time period. Emission of pollutant p on network ν over time period τ is calculated as follows:

$$E^{p}_{\nu,\tau} = VKT_{\nu,\tau} ef^{\,p}(v_{\nu,\tau}) \tag{1}$$

where traffic activity value $VKT_{\nu,\tau}$ denotes vehicle kilometers travelled *[vehkm]* on network ν over time period τ, and is obtained from the average (daily, monthly, annual) mileage of vehicles or traffic stream level (see Smit et al. (2010) and Yao et al. (2011)). $ef^{p}(v_{\nu,\tau})$ is the average emission factor of pollutant *p* of the analyzed period obtained from the average-speed emission model (using average speed level $v_{\nu,\tau}$ of the network ν over time τ).

2.1.2 Average-speed emission modeling

In case of an average speed model, model outputs are the emission factors of the modeled pollutants *[g/km]* which are *m*-order convex polynomial functions of the average speed devised by certain driving profiles. Average speed in this particular case represents the average of standard driving patterns Smit:2008b, thus the sole model input variable is the average speed of the vehicle. Emission factor functions (2) are specific for different vehicle classes, fuel types, Euro norms and engine capacities. For a vehicle type *c* and pollutant *p*, emission factor function is usually (or can be approximated) as *m*-order polynomial functions of average speed:

$$ef^{p,c} = \alpha_m^{p,c} v^m + \alpha_{m-1}^{p,c} v^{m-1} + \ldots + \alpha_0^{p,c} = [g/km] \tag{2}$$

For heterogeneous traffic, an average emission factor can be formalized as:

$$ef^{p} = \sum_{c=1}^{N_c} \gamma_c ef^{p,c} = [g/km] \tag{3}$$

Emission can be analyzed by its temporal rate (emission rate function *e(v)*) or throughout a journey, by its spatial rate (emission factor function *ef(v)*). The relationship between emission rate e^{p} and emission factor functions ef^{p} for pollutant *p* is as follows (see Tiwary and Colls):

$$e_j^p = ef_j^p \cdot v_j \tag{4}$$

The formula can be generalized for temporal average emission factors and average emission rates for time intervals if instantaneous speed is substituted by average speeds over a time period.

In the macroscopic traffic control problem, the available driving pattern information is quite small: only average traffic speed data are available from loop detector measurements. In Csikós et al. (2010), Ding et al.) it is also shown that macroscopic approximation of vehicle accelerations at high speeds are of low fidelity, thus the use of an average speed model is reasonable. Thus, an average-speed model is embedded into the macroscopic modeling framework. Average speed emission models can be interpreted on both macroscopic and microscopic level – on macroscopic level, the input variable average speed is the time mean speed of traffic, on microscopic level the input variable is the trip-based average speed of the vehicle. In section 3, the suggested real-time model function is derived from aggregate microscopic variables.

2.2 Macroscopic traffic modeling

Freeway traffic is most commonly described by macroscopic traffic models. This approach considers 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)=[veh/h]*), traffic density (denoted by *ρ(x,t)=[veh/km]*) and space mean speed of traffic (denoted by *v(x,t)=[km/h]*). These continuous variables are approximated by discrete variables in time and space by loop detector measurements (for measurement resolutions see Cremer et al. (1981)). In the following, different definitions of traffic variables are stated, review of the derivation of definitions is detailed in Section 7.

Consider a homogeneous traffic moving along a motorway and analyze the traffic variables in the short motorway segment $[l_0;l_0+L]$ and a short period of time $[t_0; t_0+T]$ (analysis in a spatiotemporal window of size *LxT*).

Average traffic density in a spatiotemporal window *LxT* is equal to the Total Time Spent (*TTS*) in that window:

$$\rho_{[l_0;l_0+L]\times[t_0;t_0+T]} = \rho_{L\times T} = \frac{TTS_{L\times T}}{L \cdot T} \tag{5}$$

where $\rho_{L\times T}$ denotes the average traffic density in *LxT*.

Average traffic flow in the spatiotemporal window is equal to the Total Travel Distance (*TTD*) in window *LxT*:

$$q_{[l_0;l_0+L]\times[t_0;t_0+T]} = q_{L\times T} = \frac{TTD_{L\times T}}{L \cdot T} \tag{6}$$

where $q_{L\times T}$ denotes the average traffic flow in *LxT*. For the derivation of (5) and (6) see Ashton.

The relationship among the three traffic variables is called the fundamental equation:

$$q_{L\times T} = q_{L\times T} \cdot \rho_{L\times T} \tag{7}$$

Using (5) and (6) traffic performance in a spatiotemporal window can be expressed by the size of the window and the average traffic variables within. In small windows, from loop detector measurements using relationships (5) and (6), real-time traffic performance can be expressed. These traffic performance functions are widely used in traffic control designs (e.g. Hegyi et al. (2005)). In section 3.2 'emission performance' is formalized for small rectangles and equality is shown to the aggregated microscopic approach, detailed in section 3.1.

3 Modeling framework for real-time macroscopic emissions

In case of process control (in this case the control of traffic on a motorway network) decision is made in each sample step based on the real-time information of some performance criterion (in this case traffic stability, travel times, etc). This framework is now extended to the consideration of local and global pollution, thus information is needed of the emission conditions of the controlled network in each sample step. For this reason a macroscopic emission model function is introduced that uses macroscopic variables to provide information of emission emerging in each discrete spatiotemporal window. The model is derived and validated using the aggregation of microscopic emissions in Csikós et al. (2011), here the formula is obtained using macroscopic performance functions (*TTS* and *TTD)* (mentioned in Section 2.2) of small spatiotemporal windows *LxT*. Formalize emission of pollutant *p* in the rectangle *LxT*. (Assume that traffic is homogeneous and each vehicle travels with the same speed). Based on the macroscopic meaning of (3) and using (5) Applying the method of emission inventories on small spatiotemporal rectangles, real-time modeling of traffic emissions can be formalized with the following contexture:

- Calculate emission factors using traffic mean speed obtained from real-time measurements of the spatiotemporal window *LxT*:

$$ef^{\,p}(v_{v,\tau}) = ef^{\,p}(v_{L\times T}) \tag{8}$$

- Substitute *TTD* to *VKT*, using (6). Thus, emission inventory in a small spatiotemporal segment *TxL* using real-time macroscopic variables:

$$E^p_{L\times T} = ef^{\,p}(v_{L\times T}) \cdot TTD_{L\times T} = ef^{\,p}(v_{L\times T}) \cdot q_{L\times T} \cdot L \cdot T \tag{9}$$

- Substitute the fundamental relationship (7):

$$E^{p}_{L\times T} = ef^{\,p}(v_{L\times T})\cdot v_{L\times T}\cdot \rho_{L\times T}\cdot L\cdot T \qquad (10)$$

- Use the macroscopic meaning of (4):

$$E^{p}_{L\times T} = e^{p}(v_{L\times T})\cdot TTS_{L\times T} = e^{p}(v_{L\times T})\cdot \rho_{L\times T}\cdot L\cdot T \qquad (14)$$

By using the notations introduced in Section 2, real-time macroscopic emission of pollutant p in the spatiotemporal window $L_i x T_s$ – in section i, during time step k:

$$E_i^p(k) = \frac{T_S}{3600} L_i \rho_i(k)\left(\alpha_m^p v_i^{m+1}(k) + \alpha_m^p v_i^m(k) + \ldots + \alpha_0^p v_i(k)\right) = [\text{vehg/samplestep}\cdot\text{segment}] \qquad (12)$$

This notation is according to the formula derived and validated in Csikós et al. (2011). In case of inhomogeneous traffic composition, the formula is as in (13). As single-variable polynomials of order m (in this case the emission factors) constitute an m-dimensional linear space, the overall emission function turns out as a linear combination of the functions of traffic fractions containing different vehicle types:

$$E_i^p(k) = \sum_{c=1}^{N_c} \gamma_c(k) E_i^{p,c}(k) = [\text{vehg/samplestep}\cdot\text{segment}] \qquad (13)$$

where c denotes vehicle type, N_c denotes the number of vehicle types, γ_c denotes the proportion of vehicle class c of whole traffic. The surface of real-time macroscopic emission function of pollutant CO is illustrated on Fig. 1. for a 1 km long motorway stretch for the static fleet composition of Hungary of year 2010. (emission factor functions were obtained from the model COPERT IV) Csikós:2011. To highlight the range of the function, emissions of measured traffic states of motorway M5, year 2010 are plotted as dots.

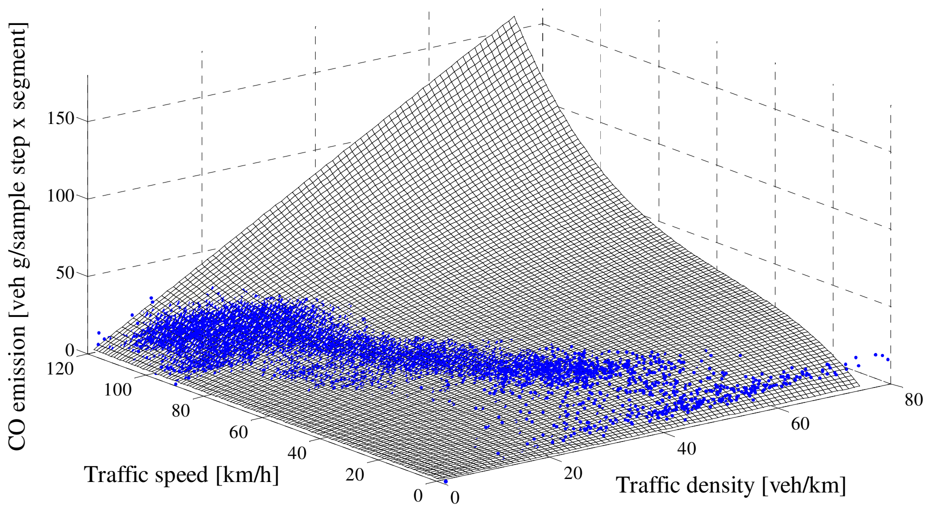

Figure 1: Real-time macroscopic emission of CO for a vehicle composition. Segment length: 1 km, sample time: 10 s.

4 Model validation

In this section a model comparison is shown of the suggested macroscopic model function (using the average model COPERT IV) to the emission model Versit+*Micro* (shown in Smit et al. (2007)) which is considered as reference.

Simulations are carried out in VISSIM which is a microscopic traffic simulation tool and is suitable for macroscopic traffic measurements. In VISSIM, an existing motorway stretch at the border of Budapest is modeled: the motorway M5 from waymark 18 km to 24 km, in nort-south direction. A 30 minute-long period is simulated and the macroscopic emission of the proposed model function (15) (using the emission factor functions of COPERT IV) is calculated using MatLab and compared to the microscopic emissions (modeled by Versit+*Micro*) obtained from the add-on emission module of VISSIM called EnViVer. For the simulation, the standard vehicle composition of EnViVer for the year 2009, and the emission factor functions of the corresponding vehicle classes of COPERT IV are used.

During the simulation, different traffic states are generated: free flow conditions (low traffic flow volumes, high traffic speeds), saturated flow (high traffic flow volumes, near the critical density), and congested situations (above critical density, and high density situations). These three rather differing situations are the most characteristic and significant states of traffic. Congestion is triggered by an accident and since motorway accidents usually lead to bottlenecks, significant changes in traffic density, speed and also in emissions can be observed.

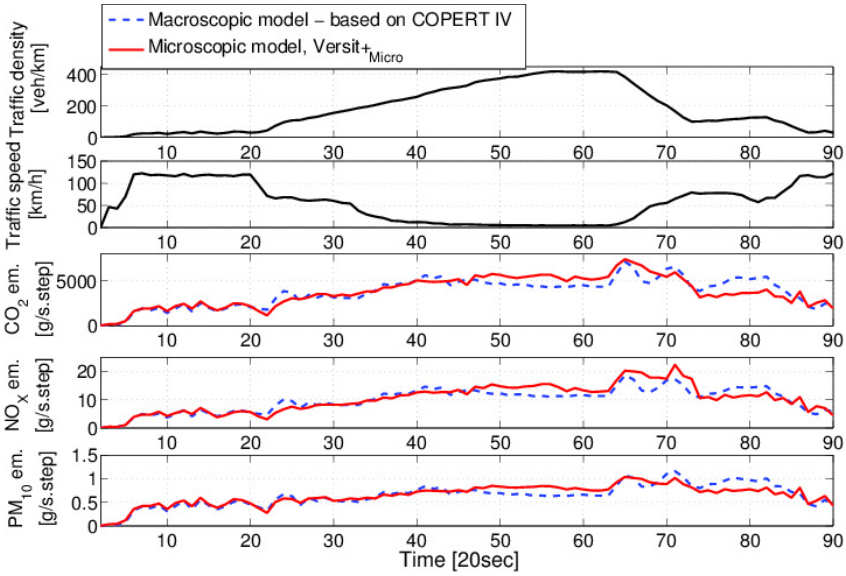

Figure 2: Traffic variables and emissions on the analyzed segment.

For the first 7 minutes (20 steps) free flow and saturating traffic conditions are simulated. Until the 20th simulation step (400 s) free flow traffic is present with no congestion. An accident occurs at 400 s, and leads to a solid increase in traffic density until 1200 sec, when the congestion is formed. The congestion starts to dissolve at the 65th step (1300 s), and the density on segment no. 33-34 starts decreasing.

The simulation results are detailed on the segment that is most afflicted by the congestion - emission of a 1 km long section was analyzed in 20 sec time steps. Simulation results (see figure 2) show that the suggested macroscopic model is a good approximation of the reference emission values produced by the model Versit+*Micro* especially on high speeds. As Versit+*Micro* uses instantaneous service data of the vehicles as input parameters, model error of the proposed macroscopic function is high at low speeds and changing traffic conditions because of the neglected effect of accelerations. To quantify the accuracy of the model, three main traffic states are distinguished: free flow conditions (0-50 veh/km) (sample steps 0 to 20 and 85 to 90), saturating flow (50-100 veh/km) (sample steps 20 to 35 and 70 to 85) and congested traffic ($>$100 veh/km) (sample steps 35 to 70).

Table 1: Highest relative errors in different traffic conditions.

Pollutant	Free-flow 0-50 [veh/km]	Saturating 50-100 [veh/km]	Congested >100 [veh/km]
CO_2	0.0908	0.3239	0.1958
NO_X	0.1321	0.2876	0.1596
PM_{10}	0.1153	0.3142	0.1783

Model accuracy is best at free-flow conditions. Relatively high model errors in saturating (desaturating) traffic conditions are due to the neglect of vehicle accelerations in average-speed emission modeling.

5 Cost function analysis of emission functions for a multi-criteria control

5.1 Pollutants causing global effects

When considering global effects caused by traffic, two main points arise: the exhaustion of fossil energy reserves because of high fuel consumption[†] and the greenhouse effect. The most important exhaust gases responsible for global warming are CO_2 and NO_X, but using *GWP* (Global Warming Potential index, see Elrod et al.) factors the effect of each exhaust gas can be characterized, thus all of them can be considered and put into the overall weighting function of emission optimization.

Consider a certain traffic demand, which can be formalized as: vehicles of a number *N* travel from *A* to *B*; minimize $TE_{A,B}$ (total emission emerging on section *A,B* of length *L* during this traffic task). For notation simplicity, the problem is shown for one pollutant only:

$$TE_{A,B} = \sum_{k=1}^{K} E_{A,B}(k)L = \sum_{k=1}^{K} q_{A,B}(k)\cdot ef\left(v_{A,B}(k)\right)\cdot L\cdot T_S = \sum_{k=1}^{K} \frac{N_{A,B}(k)}{T_S} ef\left(v_{A,B}(k)\right)\cdot L\cdot T_S \tag{14}$$

where T_S denotes sample time.

Using that $\sum_{k=1}^{K} q_{A,B}(k) = \dfrac{N}{K\cdot T_S}$, and assuming that each vehicle would travel with the same speed, the total emission of the vehicles running from *A* to *B*:

$$TE = \frac{N}{K\cdot T_S} ef(v_{A,B})L\cdot T_S = N\cdot ef(v_{A,B})\cdot L \tag{15}$$

Expression (14) is minimal if $ef(v(k))$ is minimal, thus average speed of traffic (and in case of equilibrium flow, each vehicle) is at its optimum regarding the emission factor function. (Notice: effect of traffic flow in (13) drops out: in fact traffic flow is only responsible for the overall time period (thus horizon *K*) in which the traffic task is completed which is not relevant when analyzing distant specific emission. Low traffic flow means low

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[†]Elaborating the reaction stochiometrics of internal combustion engines a linear connection between fuel consumption and CO_2 emission of a vehicle can be stated, see Tiwary and Colls.

$$ef^{CO_2,c} = K\cdot fc^c$$

where fc^c=*[l/100km]* is the fuel consumption of vehicle type *c*. *K* is a constant factor, in case of Diesel fuel *K*=26.29, gasoline *K*=23.18. Thus the criterion of fuel consumption is equal to the criterion of CO_2 minimization.

total emission rate function, but because of the fundamental relationship (7) traffic runs with low density, thus high spacing values. This leads to a long time period for completing the transportation task, thus emission in a spatiotemporal rectangle remains low, but overall emission is not minimized.

Emission leading to global effects is optimal if each vehicle is travelling at its optimal emission speed, i.e. the global optimum of (3).

Thus, the cost function of the emission of global pollutant p can be formalized as:

$$J^{p}_{global} = \sum_{i=1}^{n}\sum_{k=1}^{K}\sum_{c=1}^{N_c}\gamma_c GWP_p \frac{ef^{\,p,c}\left(v_i(k)\right)}{ef^{\,p,c}_{max}} \rightarrow min \qquad (16)$$

where n denotes the number of controlled freeway segments; K denotes control horizon; $ef^{\,p,c}_{max}$ is defined by: $ef^{\,p,c}_{max} = ef^{\,p,c}(v_w)$ where $v_w = arg\max ef(v)$; GWP_p denotes the global warming potential factor of pollutant p.

This cost function is minimized, if $ef^{\,p,c}(k)$ is minimized for all k, thus traffic mean speeds for segments $i=1,...,n$ equal $v_{opt} = arg\min ef(v)$.

5.2 Pollutants causing local effects

Apart from CO_2, all of the exhaust pollutants cause local harms (health problems, acid rain, etc). To ease these effects of pollution, local concentration of polluting gases needs to be kept low. This is aimed by keeping the macroscopic emission function (13) of local pollutants low in each spatiotemporal window over the control horizon. Concentration of pollutants is a matter of immission modeling which is not in the scope of this paper; however, the model function total emission rate can be utilized also for immission modeling as it provides exact data of emission distribution in space and time.

Thus, cost function of the emission of global pollutant p is as follows:

$$J^{p}_{local} = \sum_{i=1}^{n}\sum_{k=1}^{K}\sum_{c=1}^{N_c}\gamma_c \frac{E^{\,p,c}(v(k),\rho(k))}{E^{\,p,c}_{max}} \rightarrow min \qquad (17)$$

Notice: cost function J_{local} is minimized if the bivariate macroscopic emission function (13) is minimal in each control time step. The global minimum of J_{local} is at $[v;\rho] = [v_{free};0]$ regardless of pollutants and traffic composition - thus the control task is to minimize traffic density for the controlled network. Cost function (17) provides the weighting function for the control design.

Now examine the function total emission rate in case of equilibrium flow conditions. Consider the following equilibrium speed equation:

$$V(\rho_i) = v_{free}\cdot \exp\left(-\frac{1}{a}\left(\frac{\rho_i}{\rho_{crit}}\right)^{a}\right) \qquad (18)$$

where ρ_{crit} denotes the critical density, v_{free} denotes free flow speed and a is a constant parameter. In the following, for illustration purposes the parameter values are set to $v_{free}=114.6$ *km/h*; $\rho_{crit}=24.83$ *veh/km* and $a=2.76$.

Assuming equilibrium flow conditions, by substituting (18) to (12), emission can be expressed as a single variable function of traffic density. Fig. 3 shows the emission factor function of pollutant CO in case of equilibrium flow conditions.for the static fleet composition of Hungary of year 2010. Emission values, obtained by substituting real traffic measurements to the model are also plotted as dots.

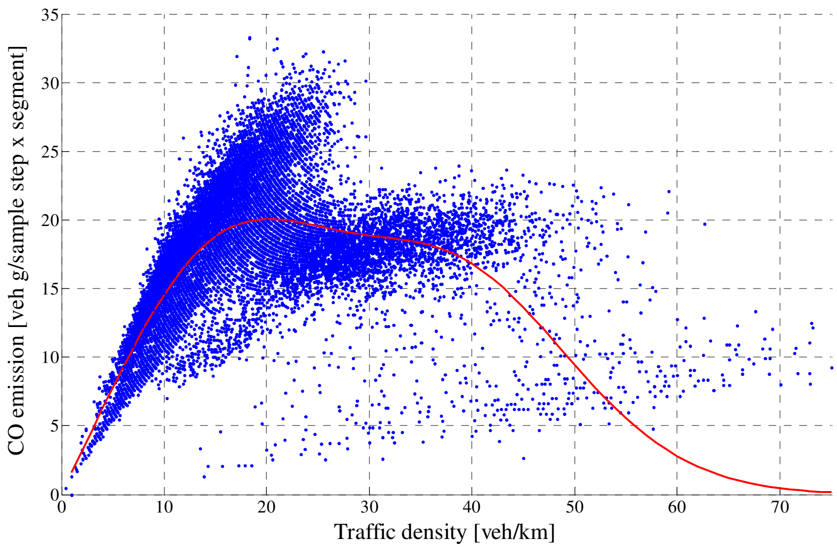

Figure 4: Total emission rate of CO for a vehicle composition

Figure 4 shows that total emission rate in a spatiotemporal rectangle is minimal, if traffic density is minimal. Thus control objective of optimizing the emerging of local pollutants is to minimize traffic density for the controlled network. Cost function (17) provides the weighting function for the control design.

6 Summary

In this paper a real-time modeling framework is suggested for freeway traffic emission analysis. A real-time model function is derived that uses an average-speed traffic emission model. The bivariate trait of traffic process is highlighted: all traffic variables are bivariate functions of time and space. Traffic variables are also formalized as traffic performance functions in certain space-time windows. The bivariate space-time dependency is characteristic of emission as well. Emission of traffic in a certain space-time window is first derived from macroscopic performance functions and thus real-time emission is formalized as a function of real-time macroscopic traffic variables. The accuracy of the introduced model function is then examined by a simulation. A bottleneck situation is modeled on a motorway, and real-time emission values of the proposed function were compared to the figures of a validated and accepted traffic emission calculation tool called EnViVer which is uses the model Versit+*Micro*. The simulation is realized in VISSIM environment. The suggested model function is then used to create cost functions, for control tasks. A diverse approach is carried out for local and global effects of emissions. The suggested cost functions will be used in a model-based multicriteria control in the future.

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