1 Motivation and background

The challenge of modern traffic engineering lies in the design for sustainable mobility. Among several aspects, the concept emphasizes the suppression of congestions and also, the reduction of air pollution. Conventional traffic control designs focus on the former aspect, see e.g. ([1], [2], [3]). The involvement of the latter objective to the control design is possible thorough an appropriate analytic description of traffic originated pollution.

The solution of the above described complex control task can be addressed by three steps for motorway networks. Firstly, an analytic description is needed of the spatiotemporal distribution of emissions. To state the overall amount of pollution emitted by traffic, a macroscopic-level\(^1\) approach is needed, using the existing measurement framework of traffic networks. The problem can be further sophisticated by considering the emerging concentrations at the built-in areas near motorways. The second step can be executed by a dynamic emission dispersion model of low computational demand. In the third step, a model-based control can be designed for the aforementioned complex control task: stabilizing traffic and reducing pollutant concentrations. Here, an analysis is needed on the appropriate control objective statements for the handling of traffic-originated pollution.

The concept of sustainable mobility can also be applied for urban networks, however, the focus here is on the improvement of traffic performances. For the urban topology, the network fundamental diagram (NFD) based urban traffic model [4] offers a platform for a network-level demand control through manipulating the network gates. The urban gating problem can be however further improved by involving the performance of the exterior network to the control design, and a less ’greedy’ policy can be offered for network gating.

The thesis summarizes the research results addressing the above engineering problems. First, a solution is suggested for the complex motorway control problem following the outlined steps. In the sec-

\(^{1}\)i.e. describing traffic as a whole, using aggregated variables and neglecting the individual vehicles
ond part of the work, an improvement of the urban network gating problem is suggested and analyzed. The achieved research results serve as practical methods for the improvement of traffic control in both motorways and urban networks.

2 Tools and methods

2.1 Dynamic modeling of motorway traffic

For the macroscopic modeling of motorway traffic, the model META-NET [5] is used. The spatiotemporally discrete model is capable of representing various traffic phenomena (e.g. shockwaves and congested conditions in addition to free-flow traffic). Furthermore, METANET along with its extensions allows for taking into account control actions: the variable speed limits and ramp metering.

![Figure 1: Scheme of motorway networks](image)

The model provides a second order description of link dynamics with the dynamical equations regarding the traffic density $\rho_i$ and traffic mean speed $v_i$ of a section of arbitrary length $L_i$ (see Figure 1). For each segment, an additional equation is given for the time evolution of the ramp queues $l_i$. The manipulated control signals on segment $i$ are represented by the variable speed limit $VSL_i$ and the metered ramp flow $r_i$. The state dynamics of the motorway network of $N_s$ segments is given in the following set of dynamic state equations:
where $\tau$, $v_{\text{free}}$, $a$, $\rho_{\text{cr}}$, $\eta$, $\delta$, $\kappa$ are constant model parameters, and $T$ denotes the sample time.

### 2.2 NFD-based urban network modeling

Intersection-level modeling and control methods perform efficiently as traffic-responsive strategies. However, they are not able to deal with extreme traffic conditions when demands extremely overpass the network capacity for a long period of time. A plausible solution for this problem is to design a high-level control, by optimizing traffic conditions on a network level through the manipulation of the entering traffic flows. In this case, actually the demand of the network is controlled, however, on the expense of the outside network where the eliminated traffic may cause congestions [6]. The concept of the protected network (PN) has been highlighted recently as an efficient solution to prevent traffic jams in certain networks. PNs
are usually located in a city center or a dense urban area that needs protection against insatiable demands during rush hours.

![Network level modeling diagram](image)

Figure 2: Network level modeling

The topology of the network level model is demonstrated in Figure 2. The network is basically modeled through the overall number of vehicles in network, for which the law of conservation is applied. The flow conditions and network performance are characterized by an aggregated variable, that can be expressed as a function of the number of vehicles. Network dynamics are described through the conservation of vehicles in the protected network:

\[
N_{PN}(k+1) = N_{PN}(k) + T_C \left[ Q_{in}(k) + Q_d(k) - Q_{out}(k) \right]
\]

where \( N_{PN}(k) \) denotes the number of vehicles within the protected network, and \( T_C \) denotes the cycle time of the signal control.

Considering homogeneous conditions in the network, its performance and outflow can be stated as the total traffic flow within the network, and can be expressed as a nonlinear function of the number of vehicles. The so-called network fundamental diagram (NFD) [4] and [7] depicts the static relationship between the accumulation and the performance of the analyzed network. It is given in the following form:

\[
Q_{out}(k) = F (N_{PN}(k))
\]
2.3 Modeling of vehicular emissions

Vehicular emission models are basically established for the analysis of the effect of automotive and fuel engineering technologies and to present the national inventories of traffic-originated emissions.

The output of the emission models is called the emission factor (denoted by $ef$). It gives the intensity of the emission, expressing it by pollutant quantity per energy consumed, pollutant mass per fuel used, or pollutant mass per distance driven, in unit [g/kWh], [g/kg] or [g/km]. In a narrower sense, emission factors of vehicular emission models are the distance specific emissions of a vehicle, given in unit [g/km/veh].

According to the input variables of an emission model, several model levels are distinguished. In the thesis, models are used from the following two levels:

- **Cycle variable models** provide emission factors as functions of various driving and geographic variables (e.g. instantaneous speeds, idle times, acceleration, road slopes). These models require detailed information on vehicle movements, which can only be acquired from microscopic traffic models, or from GPS measurements. The thesis features the model Versit+ [8] for verification purposes.

- **Average speed models** provide emission factors as functions of average travelling speeds of vehicle driving cycles. This provides a lower level representation of traffic emissions than that of the cycle variable models.

The thesis features the model COPERT [9]. Its emission factor function is given as follows:

$$ef^p_c(v) = \frac{\alpha^p_c + \gamma^p_c v + \epsilon^p_c v^2}{1 + \beta^p_c v + \delta^p_c v^2} \quad (4)$$

with the parameters $\alpha^p_c$, $\beta^p_c$, $\gamma^p_c$, $\delta^p_c$, $\epsilon^p_c$ of pollutant $p$ and vehicle class $c$, determined by curve fitting to vehicle dynamometer measurements of prespecified driving cycles.
2.4 Modeling of emission dispersion

Emission dispersion models are primarily developed to describe the spreading of industrial pollution from point sources (e.g. [10]) and to examine the effect of buildings and rural settlements on the dispersion. The approach of Gaussian plume modeling is based on the observation of chimney smokes which are spreading in a plume shape. In the plume, the diffusion of gases are described perpendicular to the wind direction. The horizontal and vertical distribution of pollutant concentrations are characterized by Gaussian distributions which are parametrized by functions of atmospheric stability and wind speed. The distribution function of the concentration within the plume is given by the following equation:

\[
c_p(x,t) = \frac{Q_p(t)}{w(t)} \frac{1}{2\pi \sigma_y(x)} \int_{-\infty}^{\infty} \exp \left[ -\frac{y^2}{2\sigma_y^2(x)} \right] dy \\
\cdot \frac{1}{2\pi \sigma_z(x)} \int_{-\infty}^{\infty} \exp \left[ -\frac{z^2}{2\sigma_z^2(x)} \right] dz
\]

where the concentration \( c_p(x,t) \) (in unit \([g/m^3]\)) is obtained as a function of the pollutant emission rate \( Q_p(t) \) (measured in \([g/s]\)) and the wind speed \( w(t) \) (in \([m/s]\)). Parameters \( \sigma_y(x) \) and \( \sigma_z(x) \)
denote the crosswind- and vertical direction standard deviations of the concentration distribution at downwind distance $x$, respectively, and $H_{\text{plume}}$ denotes the height of the plume centerline.

2.5 Model predictive control

In the thesis the Nonlinear Model Predictive Control (NMPC) technique [12] is applied for controller design. Model Predictive Control calculates optimal input of a dynamic system throughout a certain control horizon $N_c$, using predictions on future system dynamics and future disturbances. Based on the predicted state-, disturbance- and input values, predefined objective functions are calculated, and optimized over the prediction horizon. Calculation of the optimal input is possible by using on-line optimization tools (e.g. \textit{fmincon} in the MatLab environment). The optimization problem of NMPC for a nonlinear traffic system model can be formalized as follows:

$$\begin{align*}
\min_{[u(k+1),\ldots,u(k+N_c)]} & \quad J(k) \\
\text{subject to} & \quad u(k + \ell) \in \mathbb{U} \quad \forall \ell = 1,\ldots,N_c \\
& \quad d(k + \ell) = d(k) \quad \forall \ell = 1,\ldots,N_c \\
& \quad x(k + \ell) \geq 0 \quad \forall \ell = 1,\ldots,N_c \\
& \quad x(k + 1) = f(x(k),u(k),d(k))
\end{align*}$$

where cost function $J(k)=V(x(k),u(k),d(k))$ is a functional describing the system performance; $\mathbb{U}$ denotes the convex set of applicable input values, and the equation $x(k+1)=f(x(k),u(k),d(k))$ describes the nonlinear dynamics of the controlled system.

In the predictive control framework, the manipulated inputs are updated in a rolling horizon manner: optimization is carried out and a control sequence is obtained in each sample step $k + \ell$, for $\ell = 1,\ldots,N_c$, but only the first element of the control sequence is applied on the system. The optimization is repeated for the same horizon length $N_c$ in each step.
3 Contributions summarized in thesis points

3.1 Macroscopic static description of traffic emissions

In the first thesis point, a static model function for traffic emissions is suggested. The aim here is twofold: first, to obtain the spatiotemporal distribution of traffic emission; and second, to describe the emitted pollution of traffic as a system performance. For this end, a macroscopic variable, called the emission field is derived as a function of traffic density and traffic mean speed (see Fig. 4). The modeling of vehicular emissions is incorporated to the model by using the average-speed emission modeling method. By itself the emission field $\varepsilon(x, t)$ describes the spatiotemporal distribution of pollution, and its finite integral gives an emission performance in the following form:

$$E_{[x_1, x_2] \times [t_1, t_2]} = \int_{t_1}^{t_2} \int_{x_1}^{x_2} \varepsilon(x, t) \, dx \, dt = \int_{t_1}^{t_2} \int_{x_1}^{x_2} ef(v(x, t)) v(x, t) \rho(x, t) \, dx \, dt$$  \hspace{1cm} (6)$$

where $E_{[x_1, x_2] \times [t_1, t_2]}$ denotes the total emission of traffic in the rectangle $[x_1, x_2] \times [t_1, t_2]$. The model function of the emission field is derived in the continuous space-time domain, and extended to the spatiotemporally discrete frameworks of motorways and urban networks for a real-time use. In the latter case, the model function is
extended to the scale of aggregated model variables of NFD modeling. For both network types, a simulation-based analysis is carried out to analyze the applicability of the suggested model framework. Also, the suggested model function is verified comparing the modeling results of the emission factors of COPERT [9] and VERSIT+ [8]. Finally, a model analysis is carried out, concluding in preliminary suggestions on the control objectives for different pollutant types.

**Thesis 1**  
A modeling approach is proposed for the macroscopic description of traffic emissions. The spatiotemporal distribution of emission is derived as a function of macroscopic traffic variables. The advantage of the proposed approach is that it requires only the existing measurement data of traffic networks. The modeling of vehicular emissions is incorporated into the derived model function via the average-speed modeling method. The obtained continuous space-time distribution variable is extended to the discrete frameworks of motorways and the NFD-based modeling of urban networks. The suggested macroscopic modeling framework is compared to microscopic level emission modeling in terms of consistency with acceptable simulation results. As a corollary of the analysis of the suggested model function, control objectives are postulated for the different pollution types.

**Corresponding publications:** [C1], [C4], [C7], [C12]

### 3.2 Dynamic model for the dispersion of motorway traffic emissions

In the second thesis point, a simple dynamic model is developed for the dispersion of motorway traffic emissions. The outputs of the model give the pollutant concentrations of built-in areas near motorways. Between the motorway and the protected area, balance volumes are defined, in which the law of mass conservation is modeled (see Fig. 5). In the balance volumes plug flow is considered to model the prevailing winds of changing speed.
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 both in space and time, given by the following equation:

\[ c_j^p(k+1) = c_j^p(k) + T \left( w(k) \frac{c_j^p,0(k) - c_j^p(k)}{X_j} - \lambda(X_j, w(k)) c_j^p(k) \right) \]  

(7)

where \( c_j^p \) denotes the concentration of pollutant \( p \) in balance volume \( j \), \( w \) denotes the wind speed and \( X_j \) denotes the downwind length of balance volume \( j \). The condition at the boundary, \( c_j^p,0 \) is obtained by using the macroscopic static emission model (suggested in Thesis point 1).

For the dynamic modeling of decay rate \( \lambda \), an analytical approximation is suggested based on a simplified version of the line source Gaussian plume model [11], given by the following equation:

\[ \lambda(k) = \frac{w(k)}{X_j a(w(k)) X_j^{b(w(k))}} 2\pi \int_{-\infty}^{-H_j/2} \exp \left( - \frac{z^2}{2a(w(k)) X_j^{2b(w(k))}} \right) dz \]  

(8)

where \( a \) and \( b \) are parameters of the Gaussian distribution function, obtained as a function of wind speed and \( H_j \) denotes the height of balance volume \( j \).

Following the verification of the model, it is analyzed in terms of computational stability according to the Courant-Friedrichs-Lewy
condition (see [13]). On the joint traffic-emission dispersion model a sensitivity analysis is performed which justifies the idea of considering the states of concentration dynamics to be kept under constraints in the controller design.

**Thesis 2** A dynamic model is developed for the description of emission dispersion of vehicular pollutants of motorway traffic. The process dynamics is formalized based on the law of mass conservation within the balance volumes defined between the motorway and the border of the built-in area. The excitation of the system is described by the static model function suggested in Thesis 1. Supposing a constant wind direction with changing wind speed, plug flow is considered within the balance volumes. The dissolution of pollution is stated as a linear function of the concentration, the decay rate coefficient is derived using a modified version of the Gaussian line source plume model. The mathematical formalization of the modeling assumptions leads to a hyperbolic PDE, the numeric solution of which is given based on process characteristics and topological considerations. The proposed model is analyzed in terms of computational stability and sensitivity to the control measures of motorway control systems, leading to preliminary considerations on control design.

**Corresponding publications:** [C13], [C14]

### 3.3 Hybrid control of traffic flow stabilization and pollution reduction of motorways

A control system is developed and analyzed for the prevention of motorway shockwaves and the reduction of pollutant concentrations of rural areas near motorways. The dynamic model of the controlled system is based on the second-order macroscopic model description of the freeway traffic, joined by an emission dispersion model, proposed in Thesis 2.

For the control tasks two different controllers are designed, both using the nonlinear model predictive control method, presented in [12]. The first mode of the controller is responsible for keeping pollu-
tant concentrations below prescribed limits under stable conditions. The optimization problem is ill-conditioned for the satisfaction of concentration limits, thus the constraints are reformalized for the primary state variable, the traffic density. The concentration limits are recast for a limitation in boundary conditions for steady-state excitation; and through the static emission model function, traffic control constraints are specified for the density values. The second mode of the controller works in case of a shockwave threat, and uses both VSL and ramp metering for traffic stabilization. To eliminate the oscillation in speed control, the optimization of the discrete set VSL values is carried out in two steps. The switching between the controllers is realized by a finite automata.

Figure 6: CO limitation and shockwave suppression - uncontrolled case

The behavior of the controller (switching stability, transient behaviour, and the performance in different modes) is analyzed in a complex case study (see Figs. 6-7). Simulation results indicate the stability of the switching controller, and an acceptable performance during different control tasks.

**Thesis 3** A controller is designed for the joint traffic - emission dispersion system, the model of which is presented in Thesis 2. For the controller two control aims are specified: the limitation of pollutant concentrations under stable traffic conditions, and the suppression of shockwaves in case of unstable traffic. A two-mode controller
Figure 7: CO limitation and shockwave suppression - controlled case

is proposed for the control tasks, applied for the distinguished control objectives. In both modes, the nonlinear model predictive control (NMPC) algorithm is used for input optimization. The first mode of the controller, responsible for concentration limitation uses ramp metering for control. The concentration limits of this mode are reformalized based on the steady-state analysis of the concentration dynamics, suggested in Thesis 2. The second mode of the controller, responsible for shockwave reduction features both the variable speed limit control and ramp metering. The switching between the modes is realized by a finite automata. The proposed control system is evaluated in different case studies which show acceptable results.

Corresponding publications: [C15], [C16]

3.4 Modeling and control of urban networks using aggregated traffic variables

A novel nonlinear system model is proposed for the urban gating problem. The aim is to involve the effect of gating control on the exterior network performance. For this end, additional state variables are allocated to describe the queue dynamics at the protected network gates. Using the extended model, a ‘non-greedy’ control
approach is suggested by reducing the queue lengths. The optimization is carried out by the nonlinear model predictive control algorithm.

![Network layout](image)

**Figure 8: Network layout**

The control strategy is analyzed through different case studies in a case study network model (see Fig. 8. Apart from the comparison of the greedy and non-greedy gating approach, the controller performances of the NMPC and the PID approach (suggested in [6]) are also compared. Controller performance results of the revised system show that significant improvements can be reached in exterior performance with only a minor loss in interior performance. The simulation results also show that the NMPC method provides better performance (due to the nonlinear characteristics of the process) than the PID design which is a simple linear control approach, see Fig. 9. Concerning the practical use, it has to be noted that modern traffic control centers are usually designed to perform network-wide control, which also indicates the construction of appropriate measurement system (e.g. detector measurements on each link), i.e. full information control. Therefore, the proposed method can be considered as efficient traffic control candidate for field implementation.
Figure 9: Congestion simulation

**Thesis 4**  An extension of the NFD-based urban traffic model framework and the gating problem is suggested. Additional state variables are allocated to describe the queue dynamics at the network gates, the minimization of which improves the traffic performance of the exterior network, leading to a less greedy control policy. The designed controller is analyzed in a test network built in VISSIM. The performance results justify the consideration of queue lengths in dynamic modeling and the use of NMPC approach for controller design.

**Corresponding publications:** [C17], [C18]

### 4 Further research

The most interesting future research is planned on the analysis of the motorway traffic, possibly formalizing it as a compartmental model.

Further research concerns thesis points 3 and 4:

- For the control systems, the concept of robust design is planned to be applied. In both cases, uncertainties can be defined
for the models through the variation of disturbances. In the emission dispersion model, the variation of wind speed can be handled as an uncertainty. The changes in main lane traffic loads on the motorway, or in the uncontrolled traffic entering the protected network in the urban case can be handled the similar way.

- The hysteresis in the urban fundamental model can be also involved in the control design (for an early result see [C19]).

- Another improvement regarding the NFD-based gating problem of urban traffic involves the consideration of traffic emissions into the control design, which is not considered in the present work. To handle traffic emissions as well, a multi-criteria control can be designed, based on a thorough analysis of the weighting of the emission aspect.

References


Publications of the author


