Simulation of Traffic Induced Air Pollution

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Abstract In recent years the growing traffic demand combined with an increase in exhaust gas emissions is the main reason for a permanent decrease in air quality in urban areas. Especially during hot summer days, mainly traffic emissions are responsible for providing precursor substances for the ozone reaction. They account for approximately 70% of all emissions. In order to facilitate investigations analyzing this situation, local authorities in environmental protection and urban planning agencies are interested in performing emission and air pollution simulation as well as scenario analysis by means of model based simulation systems. Therefore a realistic modeling of the physical behavior of the atmosphere as well as the exact description of the emissions is necessary. Up to now mainly traffic countings combined with different statistical methods have been used to calculate these emissions. The obtained results are often incorrect and do not reflect the dynamic behavior of the traffic flow. Traffic flow models provide a more promising approach. Currently, in the European Community funded SIMTRAP project, an integrated system for traffic flow information, air pollution modeling and decision support will be developed in a distributed HPC network, and subsequently tested in a number of European sites. SIMTRAP centers around two well-established core components: the air pollution model DYMOS and the meso-scopic dynamic traffic simulation tool DYNEMO. The project aims to integrate both modules in a remote HPCN environment in order to enable the detailed simulation of an area of sufficient geographical extent. Interpretation and visualization of results will take place in a local 3D GIS system. Communication will take place using existing computer networks and protocols.

1. INTRODUCTION

In nearly all regions of the world, where industrialization is causing large urban areas supplemented with high traffic density, higher concentrations of photochemical oxidants can be observed periodically during the summer months. Especially critical examples are Mexico City, Sao Paulo, Los Angeles, Athens, Berlin and most of the other major European cities. Experts and public authorities are seriously involved in investigations searching for appropriate measures to improve air quality in these areas. One of the main sources of atmospheric pollution in urban areas are motor vehicle emissions. It is estimated that road transport contributes in most European cities more than 40% of emissions of volatile organic compounds (VOC), more than 70% of nitrogen oxides (NO_X) and over 90% of the emissions of carbon monoxide (CO). Many of these pollutants have injurious effects on human health, vegetation and material, besides contributing to altering the atmospheric characteristics. Urban traffic is actually the main cause for the health-critical concentration of surface-near ozone typically for hot mid-summer periods in urban areas. Due to the nonlinearity of the chemical reactions contributing to the ozone production it is impossible to derive simple emitter-receptor relationships between the emitted primary species and the ozone concentration.

The growing traffic demand together with an increase of exhaust gas emissions and travel times on one side, and the likewise growing need for mobility on the other side, requires the realization of measures for a better traffic control and planning. Aiming at shorter travel times and a reduction of air pollution, these measures include for example traffic control strategies (rerouting) and the shifting from car traffic to public transportation. Currently, the decision which measure serves the purpose best can not be simulated in advance. Therefore a simulation system for traffic flow, traffic emissions and air pollution dispersion is under development at GMD FIRST (Sydow et al.[1995]) consisting of the following modules (see Figure 1):

- a traffic flow model considering single vehicles,
- a traffic emission model processing a variety of parameters and vehicle characteristics,
- air pollutants dispersion models calculating transport and chemical transformation,
- a database storing and managing all input and output data,
- a decision support system visualizing data in spatial relations and deriving decision proposals.

2. THE AIR POLLUTION TRANSPORT MODEL DYMOS

At GMD FIRST the DYMOS system (Sydow [1994]) has been developed, a parallelly implemented simulation system to analyze the generation, dispersion, and chemical transformation of gaseous air pollutants and different aerosols. The model is well suited to reproduce most frequent occurring kinds of smog situations:

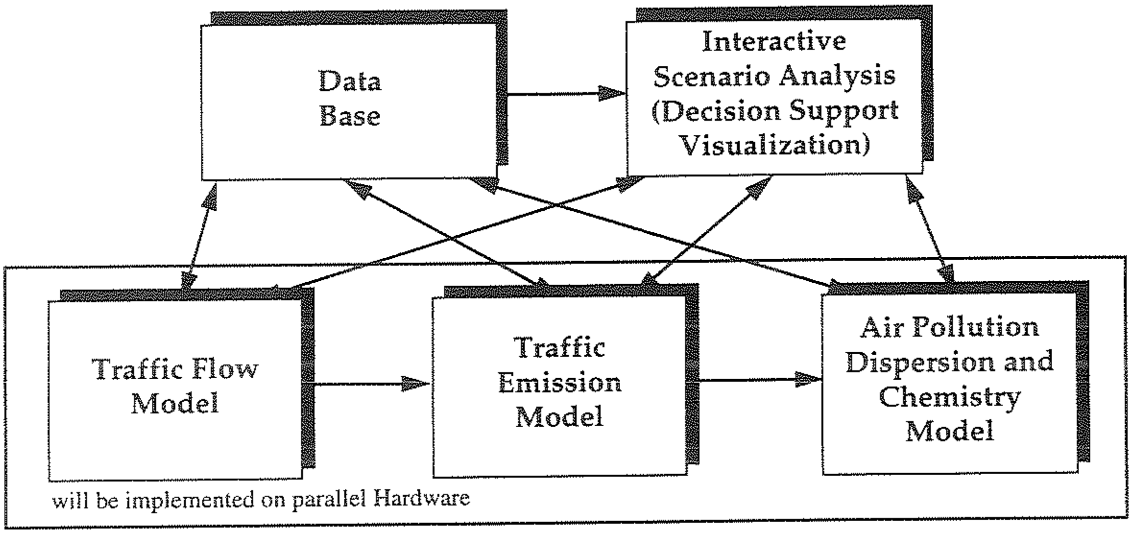

Figure 1: System architecture and communication links of SIMTRAP

- winter smog: high concentration of inert (regarding the model domain) pollutants (e.g. SO_2, NO_x, dust, etc.) caused by high pressure weather situations in the winter months.
- summer smog: high concentration of ozone and other photochemical oxidants caused by strong insolation during high pressure weather situations in the summer months.

DYMOS consists of the air pollutants transport model REWIMET (Heimann [1985]) and the air-chemistry model CBM-IV (Gery et al. [1988]).

REWIMET is a mesoscale atmospheric model which is officially distributed by the German Engineer Association VDI. Mesoscale models describe processes (e.g. thunderstorms, cloud clusters, low-level jets) occurring over a horizontal extension of about 20 to 200 km and therefore provide the foundation for simulations covering urban areas. REWIMET is based on a hydrostatic, divergenceless and dry atmosphere. In contrast to true three-dimensional models calculating the variables at the nodes of a locally fixed spatial grid, REWIMET uses the fixed grid structure only horizontally. Vertically, the model is subdivided into 3 layers lying on top of each other. A part of the model variables, namely the horizontal wind components, the potential temperature, and the air pollutant concentrations, is calculated for each horizontal grid point as box average in all 3 layers. The vertical wind component, the pressure, and

Driving cycle	Mean speed [km/h]	Speed v_{min} - v_{max} [km/h]	Percentage of stops
New European Driving Cycle (NEFZ) inside of cities	19	0 - 50	31
NEFZ outside of cities	63	0 - 120	10
NEFZ	34	0 - 120	24
US-Test-75, Phase1/3	41	0 - 91	20
US-Test-75, Phase 2	26	0 - 55	19
US-Test-75	34	0 - 91	19
Highway	78	0 - 96	<1
Motorway, $v_{max} > 150$ km/h	118	86 - 162	0
Motorway, 130 km/h < v_{max} <= 150 km/h	110	86 - 139	0
Motorway, v_{max} <= 130 km/h	107	90 - 124	0

Table 1: Parameter of the driving cycles

the turbulent flux of impulse, heat and air pollutants are determined at the boundaries between the layers.

The model REWIMET is driven by the suprascale stratification, the suprascale horizontal pressure gradient (geostrophic wind), and the surface temperature. The input of the geostrophic wind and surface temperature can be time-dependent. REWIMET considers the orography and the land utilization in the model domain. The transport of several air pollutants can be calculated simultaneously.

CBM-IV is a popular and sufficiently tested reaction scheme describing the most important chemical processes in the gas phase chemistry for the production of ozone and other photooxidants. It is officially distributed by the Environmental Protection Agency of the United States. CBM-IV is a condensed version of the original CBM. Carbon atoms with similar bonding are treated similarly. There is no need for the definition of an average molar weight so that this mechanism is mass balanced. Some species are handled explicitly, because of their special character in the chemical system (for example isoprene which is the most emitted biogenic species). The mechanism involves 34 species and 82 reactions, and contains 9 primary organic compounds. To profit from the features of the CBM-VI detailed information of the hydrocarbon mixture is necessary.

Simulation runs with these complex models REWIMET and CBM-IV have an extensive need for computation time. In order to supply users with results of case studies in acceptable time or to actually allow smog prediction (computation time less than simulation period) the DYMOS system is already parallelized and implemented as message-passing version on parallel computers with Intel i860 and PowerPC processors using tools like PVM. As the model domain of REWIMET and CBM-IV is represented by a 3D grid the model parallelization is performed by grid partitioning.

3. TRAFFIC EMISSION MODELING

3.1 Vehicle Type Analysis

In view of their different emission characteristics vehicles are classified by engine type. Vehicles with similar parameters e.g. age, mileage and engine type are grouped in one vehicle layer. It is advisable to classify vehicles according to the following features:

- vehicle type (car, van, truck, bus etc.)
- engine type (gasoline 4-stroke, 2-stroke, diesel)
- engine size
- the concept of emission reduction

Driving pattern	Characteristics	Percentage of constant speed	Percentage of stops	Mean speed [km/h]
1	Area sources (side streets)	31,8	5,3 %	18,6
2	Line sources with non controlled traffic lights, high density of buildings	23,3	32,5 %	19,9
3	Line sources with non controlled traffic lights, low density of buildings	36,6	13,5	32
4	Highway (lower category), driving in towns	26,2	15,3	37,5
5	Line sources (main streets), low density of buildings, controlled traffic lights	52,2	0,6	46,2
6	Highway (unsteady)	27,9	1,1	60,6
7	-Highway (lower category) -Line sources (controlled traffic lights, speed>50 km/h)	46,2	0,7	58,4
8	Highway with acceleration shares (e.g. leaving towns)	35,3	0,2	78,3
9	Highway (steady) with braking shares (e.g. driving into towns) Highway (lower category)	39,5	0,7	72
10	Highway (steady)	59,6	0,7	76,7
11	Stop and Go inside cities	48	52	5,3
12	Stop and Go on motorways	16,3	23	9,4

Table 2: Classes of driving pattern on urban roads

- the engine mileage and catalyst

The percentage of each vehicle layer compared to all vehicles could be extracted from statistical collections of governmental institutions. As yearly mileage reduces with increasing vehicle age, it is recommendable to weight the percentage of every vehicle layer according to its yearly mileage.

3.2 Driving Behavior and Exhaust Gas Emissions Factors of the Vehicles

Recent studies have shown that fuel consumption and emission depend to a large extent on the vehicle speed and its acceleration. Most serious approaches to calculate traffic emissions are connected with investigations of the exhaust gas of vehicles. Recently, comprehensive measurements were carried out by the TÜV Rheinland [1987, 1994, 1995] to obtain the exhaust gas emission factors of different vehicle types depending on their driving parameters. The measured emission factors provide the basis for the calculation of more realistic emission models.

Existing traffic emission models are based on statistical approaches to estimate the driving parameters of the vehicles. Two of the most common approaches use driving cycles or driving pattern for the determination of the emission of a single vehicle. The basis of driving cycles are standardized driving modes with fixed periods of acceleration, continuous speed and stops. Such driving cycles reflect the mean heuristic driving behavior of vehicles on different kinds of roads.

By driving under the fixed conditions of each cycle the exhaust gas emissions and fuel consumption of different vehicles could be measured in a uniform way. The most common cycles are the "New European Driving Cycle" (NEFZ), the "US Test", the "Motorway Cycle", and the "Highway Cycle". Table 1 shows the most important parameters of these cycles. Approximate classifications of road types, local road conditions, and traffic density limit the quality of the calculated emissions, especially in urban areas.

A more advanced statistical approach, that is the approach of driving patterns, is based on statistical investigations of the driving behavior of vehicles on different kinds of city roads and highways. In several cities in Germany measurements of speed, acceleration and exhaust gas of vehicles as well as the registration of the geometry and the traffic conditions on the road were carried out to find significant classes of driving pattern with its specific emission factors for each vehicle layer. In Table 2 the observed pattern with similar features is described (TÜV Reinland [1994]). The application of this approach involves a considerable effort to classify the road network.

A disadvantage of all statistical emission models is the limited accuracy of the dynamic behavior of a single vehicle and the determination of the traffic density. An exact analysis of speed and acceleration in certain situations (e.g. stop and go at traffic lights, stop and go scenarios in overcrowded roads) can only be performed by means of traffic flow models. Currently, simulation systems for traffic emission coupled with a traffic flow model do not exist. They would greatly improve the dynamic description of the emissions.

4. TRAFFIC FLOW MODELS

4.1 Overview

Traffic flow models are an approximated description of specific phenomena within the traffic flow operations, normally based on a set of mathematical equations or on an analogy to other physical systems.

There are two basic concepts in traffic flow simulation: the microscopic concept based on the driver behavior and the interaction of individual vehicles, and the macroscopic concept based on the hydrodynamic theory. Apart from this classification, some modifications and derivations exist such as the follow-the-leader concept, gas kinetic (Boltzmann-like) models, fluid dynamic models and cellular automaton models (Prigogine et al. [1971]; Kerner and Konhäuser [1993]; Helbing [1995]). However, the scientific world is still searching for the most suitable approach for an effective and environmentally tolerable traffic control.

Microscopic traffic flow models describe the interaction of individual vehicles which in turn depend on the vehicle drivers. Depending on the sophistication of the model, each vehicle in a road network may be described by its position $x(t)$, its actual velocity $v(t)$, its desired velocity $v_{wu}(t)$, its route from an origin to a destination, its tendency to pass other vehicles, characteristics of the drivers behavior, and the vehicle type. Clearly, the computational effort for these models is increasing rapidly with the number of vehicles within the system. The advantage of microscopic simulation of the traffic flow is that the user has complete information about the state of the vehicles in the system over time and space.

The second model class, the macroscopic models, use aggregate variables such as traffic density ρ, mean speed $\bar{v}$, and volume q to describe the traffic flow. This model class is based on the hydrodynamic theory. Under the assumption that the traffic flow can be considered as a compressible medium, the following equation of continuity for a one-dimensional flow reads as

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x}(\rho\bar{v}) = 0.$$

Due to the representation of the state by aggregate variables, the computational requirements here is much smaller than with microscopic variables. On the other hand, macroscopic models are not able to provide information about travel time, fuel consumption or route choice.

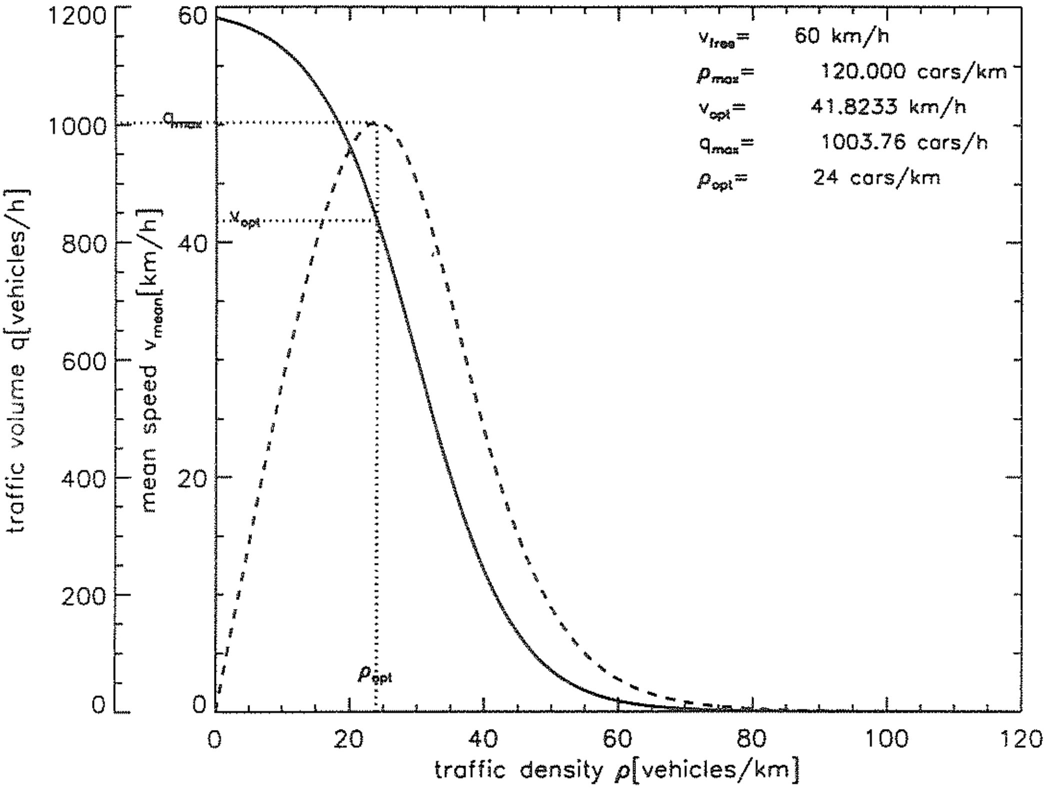

Fig. 1: Fundamental diagram of the street: Relation between the mean speed respectively traffic volume and traffic density

4.2 The Traffic Flow Model DYNEMO

The mesoscopic traffic flow model DYNEMO (Schwerdtfeger [1984]), as shown below, combines the advantages of microscopic and macroscopic models. For each stretch in the network the model needs as input the relationship between traffic density and mean speed. Figure 2 shows this fundamental relationship.

The relationship reflects the fact that the behavior of a driver strongly depends on how many vehicles he/she notices on the road and particularly on the distance to the vehicle immediately in front. Actually, this relation is only valid in the stationary and spatially homogeneous case. The maximum value of traffic density ρ_{max} depends upon the vehicle length, and on the distance bumper to bumper (spacing when they come to a stop). The value v_{free} characterizes the free flow state where the mean speed is nearly independent of the traffic volume.

A basic assumption of the model is that each individual vehicle-speed at a given traffic condition characterized by its density varies within the interval $[\underset{\sim}{v}(\rho), \tilde{v}(\rho)]$. The actual speed v of a vehicle depends on its desired speed v_{wu} and is restricted by the given interval. Therefore, for vehicles with the maximum desired speed (that is $v_{wu} = \tilde{v}_{wu}$) we have $v = \tilde{v}$, whereas for vehicles with the minimum desired speed (that is $v_{wu} = \underset{\sim}{v}_{wu}$) we have $v = \underset{\sim}{v}$. Furthermore the transition from partly constrained to constrained traffic is assumed to occur in the neighborhood of the maximum of the curve shown in Figure 2. Here, the mean speed of this point is denoted as v_{opt} , although it is an open question whether the traffic flow at the maximum volume is in every respect optimal. Under these assumptions the speed of an individual car is

$$v(\rho) = \begin{cases} \underset{\sim}{v}(\rho) + \dfrac{v_{wu} - \underset{\sim}{v}_{wu}}{\tilde{v}_{wu} - \underset{\sim}{v}_{wu}}(\tilde{v}(\rho) - \underset{\sim}{v}(\rho)) & \\ & , \rho > \rho_{opt} \\ \tilde{v} & , \rho \le \rho_{opt} \end{cases}$$

The limiting values $\tilde{v}(\rho)$ and $\underset{\sim}{v}(\rho)$ have to be chosen so that the expected value of the individual speeds is equal to the mean speed of the fundamental diagram, that is

$$E(v(v_{wu})) = \int_{\underset{\sim}{v}_{wu}}^{\tilde{v}_{wu}} v(v_{wu}) f(v_{wu}) dv_{wu} = \bar{v} \quad ,$$

were $f(v_{wu})$ denotes the probability function of the desired speed. When v_{wu} belongs to a symmetric distribution and

$$\tilde{v}(\rho) = 2\bar{v} - \tilde{v}(\rho) \quad ,$$

the equation above is always satisfied. Finally, the actual speed of the vehicle is obtained from

$$v = \left(1 - \frac{x}{l}\right) v_i + \frac{x}{l} v_{i+1} \quad ,$$

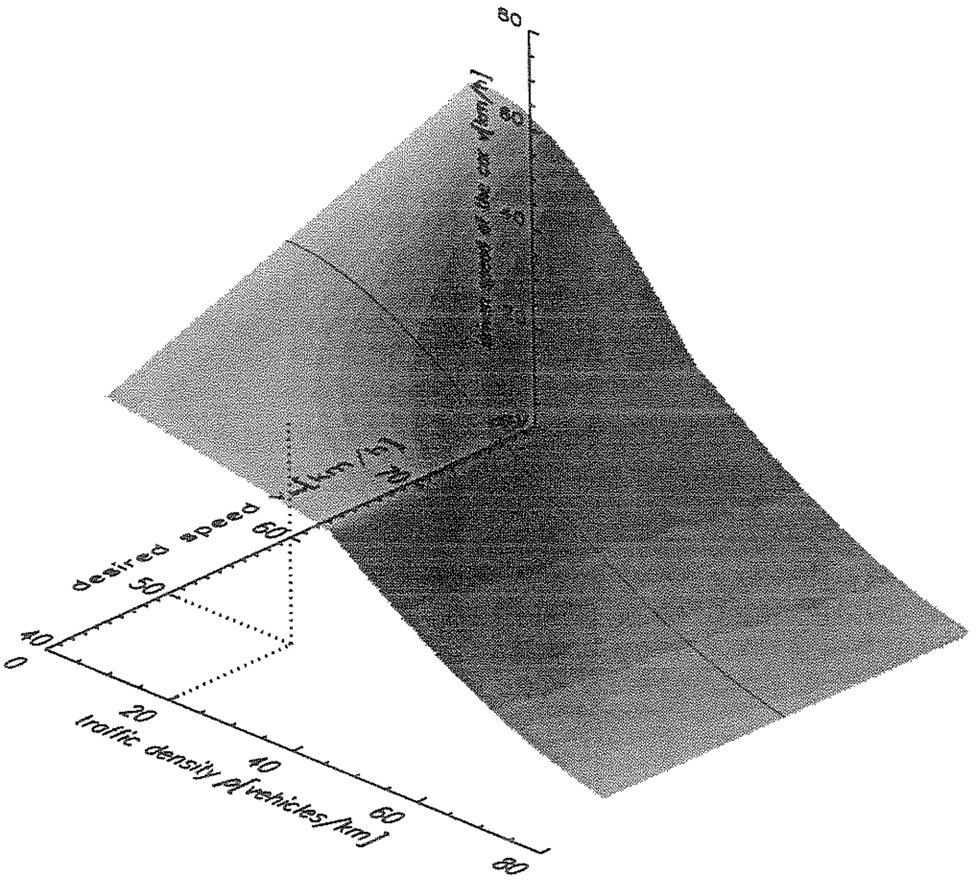

Figure 3: Behavior of the speed of an individual vehicle depending on the traffic density and the desired speed of the driver

where x denotes the actual position, i the number of the stretch, and l the length of the stretch. This reflects the anticipation of changing traffic conditions. The resulting speed of an individual vehicle depending on the traffic density and the desired speed of the driver is shown in Figure 3.

The model described above is implemented on a parallel computer to speed up the calculations. The inherent structure of this traffic model favors a domain decomposition as a general approach to parallelization. Nevertheless, traffic modeling partly generates irregular problems. We will discuss our implementation on a MIMD platform at the conference.

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