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An Integrated Dynamic Traffic Simulation and Air Pollution Decision Support System

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solutions for traffic.

An integrated dynamic traffic simulation and air pollution decision support system

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1 INTRODUCTION

The link between vehicular traffic and air pollution is well established. For example, it is estimated that road transport contributes more than 50% of VOC, more than 75% of NOx and over 90% of CO in London (source: DOT, 1997). In the Netherlands as a whole, transport contributes 40-45% of VOC, more than 60% of NOx and some 70% of CO (source: Van Wee, 1996). Authorities in metropolitan areas throughout the world require support in managing and controlling road traffic so as to avoid exceeding pollution limits by national and international governing bodies.

The time dimension for traffic management and control to reduce air pollution can range

- from short to medium to long,
- from minutes, to days, to years,
- from immediate reactions to incidents, to pre-emptive measures during periods of adverse weather conditions, to long term strategies to reduce greenhouse gas emissions.

Much of the current and past modelling work on to transport and air pollution has concentrated on long term strategies, related to decisions on car ownership (affected by e.g. stratified taxation), vehicle choice (e.g. towards smaller, fuel-efficient or electric vehicles) and decisions related to land use (e.g. reducing urban sprawl). For these long term strategies, their effects on air quality may be expressed efficiently through energy use and emissions, with air pollution being modelled separately, at a regional, national or perhaps even global scale.

Figure 1: Transport and environment modelling in the short, medium and long term

	short term (minutes)	**medium term (days/months)**	**long term (years)**
transport management and control	- incident management	- demand management - signing - guidance - road closures - medium term planning	- land use - location choice - car ownership - vehicle choice - technology
traffic model	short term forecasting	dynamic assignment	(equilibrium) demand model
environmental model	not relevant	dynamic air pollution model	emissions modelling
need for integration	not feasible	**SIMTRAP**	low

At the other end of the spectrum is short term control in response to unexpected incidents. Then, the ability to reduce adverse environmental conditions through traffic management and control is limited, for example because of the difference in time scale of the reactions in the two systems (transport system within minutes, environmental system only after several hours). Therefore, for these control strategies, the environmentally sound choice may best be guided by optimising the resulting traffic conditions, assuming that emissions and therefore air quality will also benefit. Again, integrated and detailed simulation of traffic and air quality is less important.

For developing medium term strategies, the demands on integration between the traffic model and the air quality model are highest, whilst then, also, the time scale allows for more detail and dynamics in each of the components. Examples of such strategies at the urban level are demand control during adverse meteorological conditions (e.g. the odd/even numberplate mechanism used in Paris in Summer 1997), the planning of signing and guidance during special events (City centre closures, sports events, but also medium term bridge or sewer repairs). Integrated dynamic tools are required to quantify the effects of alternative strategies, and to aid in choosing the most appropriate one.

1.1 Current international approaches

Because of the many dimensions of the link between traffic flows and air pollution, modelling tools are essential when identifying management or control strategies to cope with increasing demands on the travel system and tightening environmental standards. Different countries have different tools available to quantify the transport-environment link in the medium to long term, and different levels of enforcement.

In the United States, since the publication of the Transport Conformity Rule in 1993, metropolitan planning organisations have had to extend their analyses regarding the environmental consequences of their transport plans. The required analyses are geared towards medium to long term planning (of the order of years) and must take place at two levels:

- regional analyses, estimating emissions from road traffic and other sources, using large scale traditional transport models;
- local analyses, concentrating on air quality impacts at emission hot-spots.

The regional analyses employ standard emissions models (EMFAC and MOBILE), which are driven by total traffic volumes and average speed, with generally a standard fleet composition. Their input is provided by static travel demand models, distinguishing the demand for travel, its spatial distribution, and the resulting road traffic conditions in the network, now and in alternative future scenarios. Emissions rather than immissions are at the centre of the American approach.

In the UK, also, the emphasis in modelling air quality impacts of transport is on emissions. The Design Manual for Roads and Bridges (Vol 11) prescribes an air quality screening method based on traffic flows, vehicle mix and fixed emission parameters. Simple empirical relations are used to convert these into air quality values, based on Gaussian dispersion techniques. The analyses are limited to the immediate vicinity of the roads, generally no further than 10m from the central axis.

In The Netherlands, for the long term National Environmental Policy Plans, traffic emission scenarios are calculated using the FACTS and ATTACK models (see Van Wee, 1996). The

FACTS model forecasts car ownership, use and emissions, based on demographic scenarios, macro-economic scenarios, price scenarios and technical scenarios. The ATTACK model calculates the number of freight vehicles, their use, energy consumption and emissions. Because of their non-spatial nature, only aggregate estimates of emissions can be made, based on total vehicle kilometres. The National Model System (e.g. Gunn, 1994) enables network analyses, but has less detail in, for example, vehicle fleet composition and emissions calculations.

At the other end of the spectrum, detailed emissions and air pollution modelling at street level takes place in The Netherlands using the CAR Model (e.g. Eerens et al, 1993). The model is a simple parametrised model calibrated using data from the Dutch National Air Quality Monitoring Network (NAQMN), estimating pollutant concentrations accounting for:

- regional background concentration (from the NAQMN);
- city specific contributions (proportional to the city's radius);
- street-specific contributions (as calculated below).

Local street emissions are calculated from the traffic intensity, the average traffic speed, congestion and speed-class dependent emission factors, distinguishing four speed classes. Emission factors are defined for two traffic categories: cars, vans and LGVs on the one hand, and HGVs on the other. The emission factors are the weighted average for the Dutch vehicle fleet. A further element in the calculation is the street type, depending on building height and the distance of buildings from the road axis, distinguishing 5 types. Finally, the result is corrected for the difference between the national and regional average wind speed, and for the effect of trees. From a sample of 22 cities national totals of kilometres of road per pollutant class can be obtained by factoring the above calculations to the appropriate national level.

Thus, despite advanced modelling tools for long-term forecasting, the transport-environment toolkit in The Netherlands lacks a medium term planning tool at the urban level, with which the impacts of different management strategies in the next few days, weeks or months can be estimated.

In summary, most of the current approaches used to quantify the link between transport and the environment are geared towards the long-term, are based on static models, using aggregate outputs from large scale demand modelling systems, or generalisations of relationships established elsewhere, and concentrate on emissions rather than resulting air quality. Although each of the individual components used in these approaches addresses a small number of all the interrelations that play in detail, the overall results cannot reflect all relevant dimensions in an integrated manner. And the dimensions of the transport-environment link are many (with different suitability for control in the short, medium and long term):

- traffic volumes, in terms of total number of trips or kilometres, driven by economic growth

- demand profile, in terms of its spatial distribution over alternative destinations (in or outside city centres), nearer or further away, and its temporal distribution over peak and off-peak periods
- fleet composition, affecting the emissions characteristics of the vehicles on the road, and their fuel consumption
- traffic conditions resulting on-street, in terms of congestion and its impact on emission characteristics, the number of cold starts (reflected in a trip length distribution), and the level of flow in individual streets in the network
- future technological changes affecting energy consumption and emission characteristics
- other sources of pollutants, adding to but also reacting with the pollutants from transport
- orography of the study area, affecting the dissipation of emissions and the location and severity of resulting air quality impacts
- land use patterns, both of relevance to the emissions from non-transport sources and to the estimation of impacts of air pollution on the population
- meteorological circumstances, in terms of wind speed and direction, temperature and amount of sunshine, affecting the creation and dissipation of secondary pollutants, such as ozone
- dynamics, in the traffic simulation model and in the air quality model, representing the subtle interactions over time of travel decisions and environmental impacts.

Current approaches are in general still limited by the use of existing methods for traffic and air quality modelling separately, which in many cases were developed decades ago, and the limited computer power available to the average transport or environment analyst in practice. There is a need, clearly, for a system that will be able to address all dimensions of the transport-environment link in an integrated manner, particularly in the medium term. Any dimension added to a modelling system increases the burden on the analyst, and such a system should be well supported by appropriate decision support tools, e.g. through visualisation.

1.2 SIMTRAP Objectives

From the above it emerges that, particularly for medium term planning, detailed and integrated modelling of both the transport system and the complex air quality system is required. Various independent developments have taken place that have improved the building blocks available to the decision maker in this context:

- the development of dynamic traffic simulation software which, more than steady state tools, can produce detailed emissions calculations related to operating conditions in the network and vehicle fleet composition;
- a continuous improvement in emissions modelling, taking into account speed, acceleration, deceleration, engine size, temperature, etc.;
- the progress in dynamic 3D air pollution modelling, accounting for the complex interactions between emissions, landscape and meteorological conditions;
- the evolution of high quality visualisation tools in 3D GIS, which can also support the enormous data bases related to the envisaged application;
- the availability of accessible and affordable parallel computing technology;
- the natural emergence of cheap and general access communications between remote computers through ISDN and the Internet.

All the above developments are recognised in the EC ESPRIT funded SIMTRAP project in which an integrated system for traffic flow simulation, air pollution modelling and decision support is being developed in a distributed HPC network. SIMTRAP (SIMulation of TRaffic and Air Pollution) centres around two well-established core components: the mesoscopic dynamic traffic simulation tool DYNEMO (Schwerdtfeger, 1984) and the 3D air quality model DYMOS (Sydow, 1994). The project aims to integrate both modules in a remote HPCN (High Performance Computing and Networking) environment - a parallel computer will enable the detailed simulation of an area of sufficient geographical extent (approx. 100x100km). Interpretation and visualisation of results will take place in a local 3D GIS system. Communication will take place using existing computer networks and protocols. The system will be tested through applications in three European cities: Maastricht (NL), Vienna (AU) and Milan (I).

The remainder of the paper is set out as follows:

- in chapter 2 a concise description is given of the individual SIMTRAP components (DYNEMO and DYMOS);
- chapter 3 provides a more detailed specification for the SIMTRAP system architecture;
- in chapter 4 example application results are presented for the Berlin;
- in chapter 5 we conclude and summarise with future directions, related to real-time monitoring and control.

2. SIMTRAP COMPONENTS

The SIMTRAP system effectively integrates two previously existing simulation packages and adds a GIS toolkit with built-in functionality for decision support to facilitate user interaction and analysis of the results.

Two considerations guided the choice of the transport model:

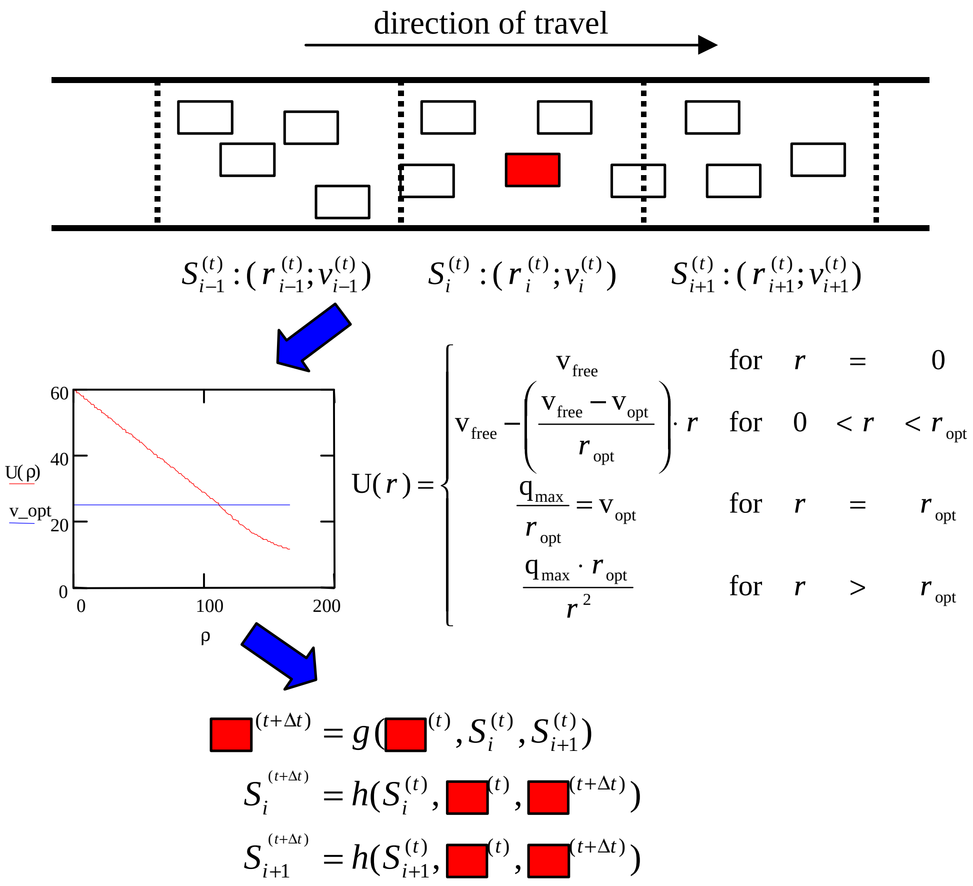
- To reflect the diurnal profile of traffic-related emissions, the model must be dynamic. This requirement becomes evident when transient traffic control measures (e.g. peak-hour driving restrictions or diversions) are studied.
- Since ozone develops in a relatively slow photochemical process and intermediate products drift with the wind during its generation, the study area must be large enough so that boundary effects do not dominate. An area of 100 by 100 km is absolutely necessary, 200 by 200 km is desirable.

These two requirements are hard to satisfy simultaneously, because the first one rules out static assignment models, whereas a study area of the size needed is beyond the capabilities of today’s microsimulation models. Instead in SIMTRAP we use the mesoscopic simulation model DYNEMO.

DYNEMO is a simulation tool for both urban and rural road networks. It is able to deal with networks with about 100,000 vehicles moving simultaneously, and has been used to simulate a large part of the German motorway network. Regarding movement of vehicles, DYNEMO is a mesoscopic model in the sense that the unit of traffic flow is the individual vehicle rather than the temporal and spatial aggregates used in static assignment models. Their movement, however, is governed by the average traffic density on the link they traverse rather than the behaviour of other driver-vehicle units in the immediate neighbourhood as in microscale models.

More precisely, each link is subdivided into sections of typically 100-200 meters length for which constant traffic density is assumed. The traffic condition on a section S_i is characterised by traffic density ρ_i. As input to the model, depending on the type j of the section (inner-urban, rural, motorway, ...) the relation between density and mean speed is given by a function U_j: Density → Speed, and V_j denotes the distribution of speeds at free flow ($\rho \to 0$).

<u>Figure 2: Graphical representation of the concepts behind the DYNEMO transport model</u>



$$S_{i-1}^{(t)}:(r_{i-1}^{(t)};v_{i-1}^{(t)}) \qquad S_{i}^{(t)}:(r_{i}^{(t)};v_{i}^{(t)}) \qquad S_{i+1}^{(t)}:(r_{i+1}^{(t)};v_{i+1}^{(t)})$$

$$U(r)=\begin{cases} v_{\text{free}} & \text{for } r = 0 \\ v_{\text{free}}-\left(\dfrac{v_{\text{free}}-v_{\text{opt}}}{r_{\text{opt}}}\right)\cdot r & \text{for } 0 < r < r_{\text{opt}} \\ \dfrac{q_{\max}}{r_{\text{opt}}}=v_{\text{opt}} & \text{for } r = r_{\text{opt}} \\ \dfrac{q_{\max}\cdot r_{\text{opt}}}{r^{2}} & \text{for } r > r_{\text{opt}} \end{cases}$$

$$\blacksquare^{(t+\Delta t)} = g(\blacksquare^{(t)}, S_i^{(t)}, S_{i+1}^{(t)})$$

$$S_i^{(t+\Delta t)} = h(S_i^{(t)}, \blacksquare^{(t)}, \blacksquare^{(t+\Delta t)})$$

$$S_{i+1}^{(t+\Delta t)} = h(S_{i+1}^{(t)}, \blacksquare^{(t)}, \blacksquare^{(t+\Delta t)})$$

At each time step ρ_i is updated from a count of the vehicles on the section and according to the relation U_j the mean speed $u_i = U_j(\rho_i)$ is computed. A vehicle which is at time t at position $x^{(t)}$ in segment S_i and drives with speed $v^{(t)}$ is moved in accordance with the speeds u_i and u_{i+1} (the speed in the next section downstream) and with its own state:

$$v^{(t+\Delta t)} = f\left(\left(1-\frac{x^{(t)}}{\text{length}(S_i)}\right)u_i + \frac{x^{(t)}}{\text{length}(S_i)}u_{i+1}\right)$$

The function *f* chooses a speed based on the computed mean speed and on the distribution V_j.

The new position of the vehicle becomes:

$$x^{(t+\Delta t)} = x^{(t)} + \frac{1}{2}(v^{(t)} + v^{(t+\Delta t)}) \cdot \Delta t$$

If $x^{(t+\Delta t)} > \text{length}(S_i)$, the vehicle is placed in segment S_{i+1}, the successor downstream, and the vehicle counts of S_i and S_{i+1} are adjusted. Then the traffic densities are updated and the next time step is computed.

Figure 2 shows a graphical representation of the model (the shaded box represents an arbitrary vehicle travelling down the link from left to right). Here r_{opt} and v_{opt} denote the density and mean speed at maximum capacity of the section, respectively. v_{free} is the free-flow speed.

For each junction within a network signal control or priority rules can be specified separately. Furthermore, so-called decision points can be placed anywhere within the road network, where vehicles can alter their calculated routes. e.g. in response to dynamic information or guidance. The cost function used for route choice is a weighted sum of various criteria, e.g. travel time, distance, cost. It is evaluated once at the beginning of the simulation, and if it depends on the current traffic situation (e.g. travel time), optimum routes are optionally updated by DYNEMO at regular intervals, based on the current traffic volumes. Furthermore, fixed routes can be specified, e.g. the sequence of links and junctions as specified by guide signs or for temporary diversion. Vehicles are classified into up to 100 types and route-choice behaviour can be specified for each type separately.

For the purpose of evaluation observation points can be specified anywhere within the road network. At these observation points the patterns of traffic volume, traffic density and mean speed are recorded. Additionally total travel time, total performance (in veh km) and pollutant emissions can be recorded for each link within the network. This functionality is used in SIMTRAP to provide the spatial distribution of traffic-induced primary pollutants (CO and NO_x); it is aggregated to a regular grid for use in the ozone model.

During the traffic flow simulation in each simulation time step state information about each vehicle is recorded including current speed and distance travelled since the origin of the trip. This state information, together with the vehicle type and the type of the link on which the vehicle is currently travelling, is used to determine the current emission of the vehicle.
The emission of a pollutant *p* by a vehicle of type *i* travelling a distance *s* with speed *v* at ambient temperature t_a on a link of type *j* where the total distance travelled so far is *s'* is given by:

$$E_{p,i,j}(s,v,s',t_a) = \begin{cases} s \cdot e_{p,i,j}(v) & \text{if } s' > csd_{i,j}(t_a) \\ s \cdot e_{p,i,j}(v) \cdot ccf_{p,i,j}(t_a, s') & \text{else} \end{cases}$$

where

- $csd_{i,j}(t_a)$ = the distance travelled with cold engine or below the operating temperature of the catalyser (if present), at ambient temperature t_a,
- $ccf_{p,i,j}(t_a,s')$ = the cold start correction factor for pollutant p, i.e. the ratio E_{cold} / E_{hot} at ambient temperature t_a after total travelled distance s',
- $e_{p,i,j}(v)$ = the emission factor for pollutant p, vehicle type i and link type j as a function of speed v, under the assumption of a warm engine.

Published emission factors are typically either speed-dependent and link type-independent or vice versa. Link type-dependent emission factors are aggregations of speed-dependent factors with respect to predefined driving patterns. Additional dependencies on gradient and/or degree of congestion can be coded into the link type. Where available preference is given to speed-dependent emission factors, because their level of detail matches the mesoscopic traffic model of DYNEMO better.

In the SIMTRAP project, emission factors, cold start correction factors and cold start distances are taken primarily from (CORINAIR, 1994) and (UBA, 1995).The model equation is designed to accommodate both. The following table sums up significant differences between the two sources:

Table 1: Comparison of UBA and CORINAIR emission models

	UBA	**CORINAIR**
speed dependent	only fixed driving patterns → link type	yes for some vehicle types, driving patterns for others
acceleration dependent	only implicit in driving patterns, patterns not published	no
vehicle types	extremely detailed	only most important types, diesel-powered cars missing!
cold start correction factor	given as additive factor, depends on same parameters as emission factor, and in addition on total distance travelled (separate ccf for km 1 .. 5)	given as multiplicative factor independent of distance travelled
cold start distance	always 5 km	given as function of ambient temperature

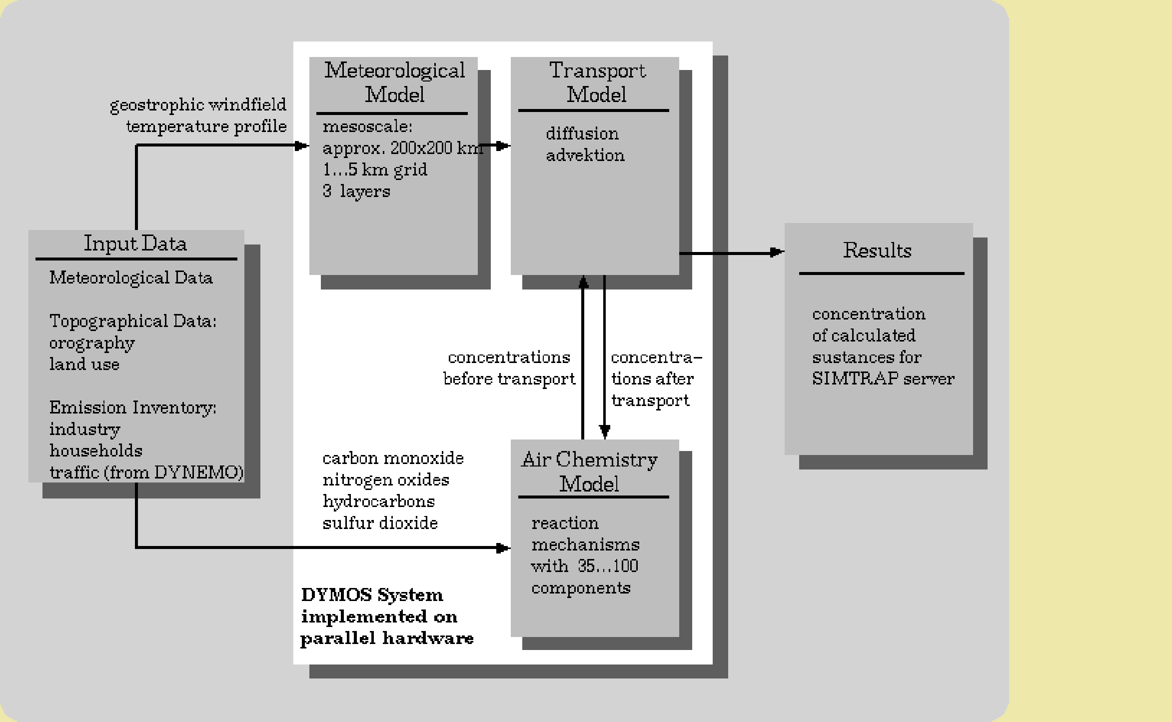
At GMD FIRST, the DYMOS system (Sydow, 1994) has been developed implemented and extensively tested during the last 5 years. DYMOS is a parallel implemented simulation system to analyse the generation, dispersion and chemical transformation of gaseous air pollutants and different aerosols. The model is well suited to reproduce most frequent occurring kinds of smog situations:

- winter smog: high concentration of inert (regarding the model domain) pollutants (e.g. SO2, NOx, 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 insulation 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). The major system components are given in Figure 3.

Figure 3: Graphical representation of the concepts behind the DYMOS pollution model



REWIMET is a mesoscale atmospheric model which is officially distributed by the German Engineers 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. One 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 the turbulent flux of impulse, heat and air pollutants are determined at the boundaries between the layers. The vertical division of the atmosphere follows certain criteria:

- The model atmosphere (all 3 layers) extends from the earth's surface to the height of the suprascale inversion. The upper level is described by a freely movable and impervious model boundary.
- The atmospheric boundary layer (ABL) characterised by turbulent mixing processes is represented by 2 model layers. The first layer (surface layer) reaches from the surface to

a height of 50 m above ground. It follows the ground level and its thickness is constant in time and space.
- The second layer (mixed layer) reaches from the upper level of the surface layer to the upper level of the ABL. As the height of the ABL depends on the stability of the atmosphere the mixed layer has a variable thickness. The thickness can be changed on the one hand by mesoscale vertical motions, on the other hand it can grow up by increasing lability, and fall down by increasing stability, respectively. In this cases air with its properties is either included from the third model layer into the mixed layer or is transferred from the mixed to the third layer.
- The third model layer (temporary layer) is always situated above the mixed layer and therefore it is assumed to be free of turbulence. As the ABL can grow up to the suprascale inversion it is possible that the temporary layer locally disappears. It is created again when the ABL sinks.

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 utilisation 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, due to 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 lapse time or to actually allow smog prediction (i.e. computation time less than simulation period) the DYMOS system is already parallelised 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 parallelisation is performed by grid partitioning.

The data entry and visualisation facilities of the models, DYNEMO and DYMOS, are limited to their respective application areas, traffic and air pollution. Since SIMTRAP aims at an integrated planning tool, it is essential that also from the users‘ point of view the integration must be as seamless as possible. For this purpose, the ACA Toolkit (Zhao et al. 1985), developed and marketed by ESS GmbH, is used as the graphical interface. This toolkit supports state-of-the-art window-based and menu-driven user interaction, but in addition offers a built-in geographical information system (GIS). The GIS functionality is not only used to view and analyse simulation results, but also to define the simulation scenarios themselves, e.g. by clicking on a link in the map of the traffic network and marking it closed for a simulation run. Powerful analysis functions compare at a glance the environmental effects across a complete set of scenarios.

3. SYSTEM ARCHITECTURE

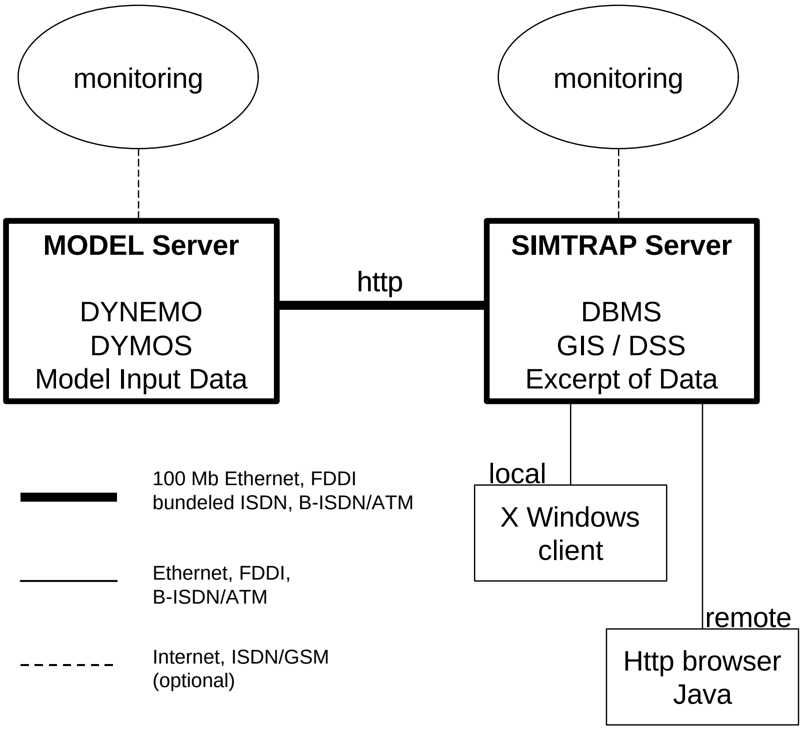
One of the objectives in the SIMTRAP project is to design a system architecture in such a way that the hardware and software resources match the computational load in the various modules. Clearly, application of the simulation models DYMOS and DYNEMO to an area of up to 200 by 200 km requires considerable computational resources. On the other hand typical end users (e.g. transportation planners) will not have access to high-performance computing equipment at their site, nor is use of such a system for the user front end justifiable.

The basic architectural decision in SIMTRAP is therefore to separate user interface and visualisation from simulation and specify a flexible communication structure that can be implemented using a variety of protocols. The separation into a SIMTRAP server (graphical user interface, decision support system) and a MODEL server (simulation) is depicted in Figure 4 below.

The **SIMTRAP Server** provides:

- overall integration including:
  - communication with the model server(s)
  - communication with the monitoring system (optional)
- the interactive user interface, including:
  - GIS and visualisation functions
  - model scenario editing and management
  - DSS functionality

Figure 4: Basic SIMTRAP architecture



The SIMTRAP Server can be any of a wide variety of machines, as long as they support LAN / WAN connections and are capable of running a GIS system. For the demonstrator applications within the SIMTRAP project the prototype SIMTRAP Server will be implemented on a SUN Sparc workstation under UNIX (Solaris 2.5 or higher).

The **MODEL Server** provides:

- implementation of the simulation models DYNEMO and DYMOS
- local data management for the models
- direct connection to weather forecast and monitoring data (optional)

The simulation of large traffic networks with substantial numbers of cars requires considerable run times. The traffic flow model DYNEMO has been parallelised in order to speed up this simulation process. One of the major problems is to develop a suitable communication structure of the parallel processes. First results have shown that an ordinary master slave topology appears to be well suited.

The master process is responsible for supervising the slaves, the initialisation and decomposition of the traffic network as well as for such tasks requiring information of the state of the complete network, e.g. the dynamic route choice. During one time step, each slave calculates the spatial motion of the vehicles situated on their subnetworks. The slaves are arranged on a nonregular 2D-grid, whereas the shape of this 2D-grid depends on the decomposition of the network. In fact, the decomposition has to satisfy partly contradictory aims. On the one hand, the decomposition should provide possibly large coherent regions of the subnetworks with minimal interconnections (stretches) between the subnetworks. The number of stretches influence the number of cars moving to a neighbouring subnetwork.

Since car exchange between subnetworks requires time for interprocessor communication, this approach guarantees a minimal communication effort.

On the other hand, the decomposition has to ensure a nearly equal-distributed workload on all physical processors. This workload depends not only on the number of stretches or lanes but also on the number of vehicles driving on the subnetwork. Unfortunately, the traffic on the roads is apriori unknown and may change rapidly. Consequently, a dynamic load balancing may be required. In the case of dynamic load balancing a rearrangement of the topology of the communication structure has to be performed from time to time. Since this procedure is very time consuming, we have not included this option at the moment. At a later time it will be decided whether to implement the dynamic load balancing depending on the run-time results or not.

The traffic flow model has been implemented by means of the PVM (Geist et al., 1994) message passing model.

The model server can be implemented on a dedicated parallel machine (within this project at GMD, but ultimately at any convenient site), or on a UNIX workstation cluster or multi-processor system (taking into consideration the description of hardware requirements).

Straightforward protocols are defined for passing a simulation request from the SIMTRAP Server to the Model Server, and for passing the results back.

4. WORKING WITH SIMTRAP – AN APPLICATION EXAMPLE

Working through a typical SIMTRAP project in a strategic planning setting takes four steps:

- capturing the model base data (transport network, topography, emission inventory),
- defining simulation scenarios,
- running the simulation,
- visualising and analysing the simulation results.

The initial model data preparation is a one-time effort at the beginning of the application of SIMTRAP to a new study area. These data change only infrequently, if ever, during the duration of the project. DYNEMO and the ESS-ACA toolkit provide powerful editing tools which ease data entry, but there is also a well-defined file interface for all model data, since often existing model data will be available for conversion. In fact, for all four SIMTRAP demonstrator applications, at least part of the data could be reused from earlier studies.

SIMTRAP, like all simulation packages, lends itself to ‘what-if’ scenario analyses. Prior to running a simulation the user selects the scenario to study in terms of the following parameters:

- weather situation (either one day from a database of historical data for the study area or a fictitious, extreme situation),
- changes to the emission inventory (households, industry, background),
- changes to traffic demand (both long-term trends and short-term fluctuations, e.g. due to events),

- changes to the transport network (e.g. additional or removed links),
- changes to the attributes of network links (e.g. blocked links / lanes, lower permitted speed, new traffic light phasing scheme),
- changes to the fleet composition (e.g. more environmentally-friendly vehicles).

The graphical capabilities of the ESS-ACA toolkit provide a very intuitive interface for setting these parameters and give immediate visual feedback on the selected scenario (fig. 5).

Once the scenario parameters have been set locally, the user starts the simulation, effectively sending the parameter settings to the Model Server and requesting the model to be run on these data. When the simulation results are received by the SIMTRAP server they are automatically loaded into the ESS-ACA toolkit. The GIS functionality of the toolkit provides a wide range of display facilities for spatial (e.g. immissions or emissions) and linear (e.g. traffic density) data. In particular traffic and immision data can be overlaid and difference plots allow data from several runs (corresponding to different traffic control options) to be compared graphically.

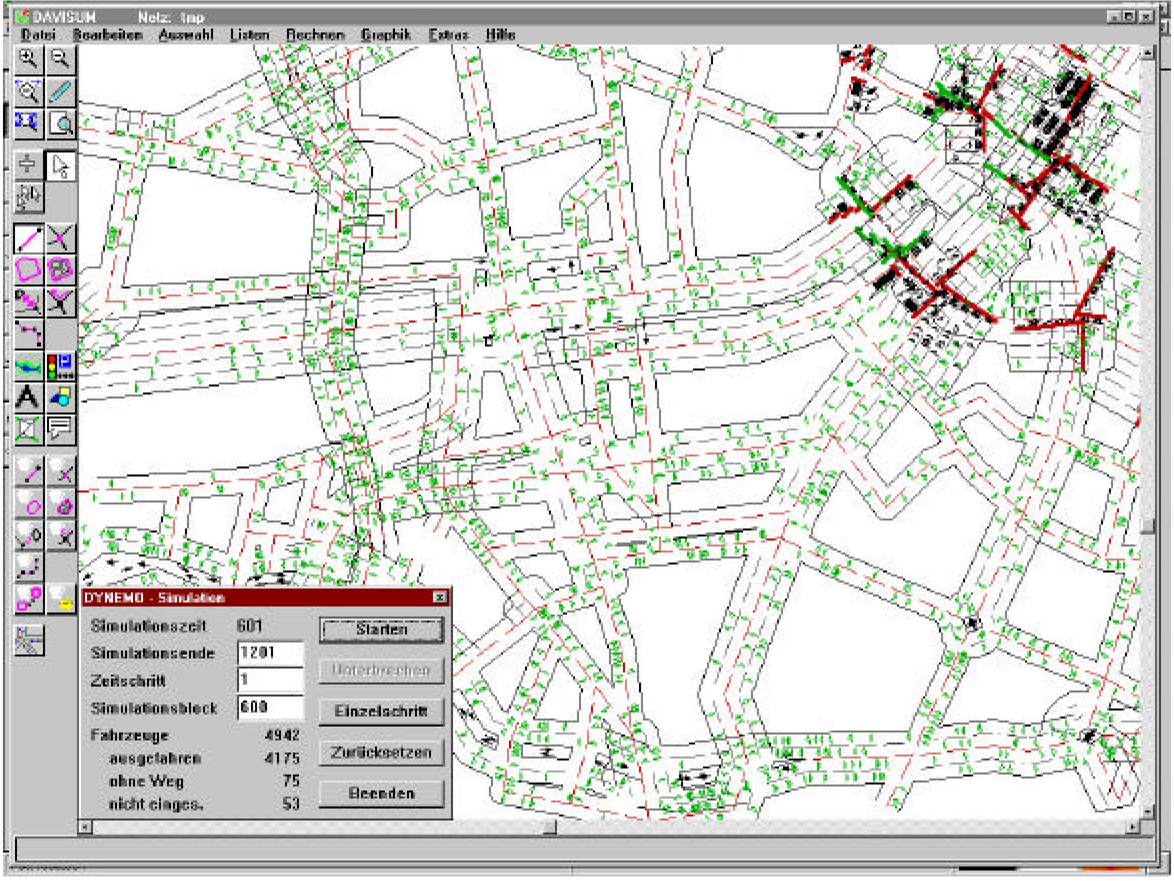
The following example is taken from the first SIMTRAP demonstrator which covers the Berlin-Brandenburg area. The transport network comprises all main roads within Berlin (i.e. all except residential streets) and the major roads in Brandenburg. The network consists of 1020 zones, 5282 nodes and 13738 links. This network and the corresponding O/D matrix have been built by the Senate of Berlin over the past years and is the most detailed traffic model available for the area. For use in SIMTRAP the model of the central part of Berlin was greatly refined, including priority rules and traffic light phasing schemes for numerous intersections. Environmental and geographical data, including a history of meteorological measurements, were reused from an earlier project of GMD First aimed at ozone forecasts using static traffic assignment.

Figure 5: Screenshot of ESS-ACA toolkit

On top of these model base data traffic control options and anticipated trends in traffic demand and technology can be evaluated regarding their environmental impact. Suppose we wish to assess the impact of a large sporting event like the Berlin Marathon which not only results in increased traffic demand with a particular pattern, but also requires many streets to be closed temporarily. Given a critical weather situation to start with, could this lead to ozone concentration thresholds being exceeded in places, and are there traffic regulation measures which could lessen this effect?

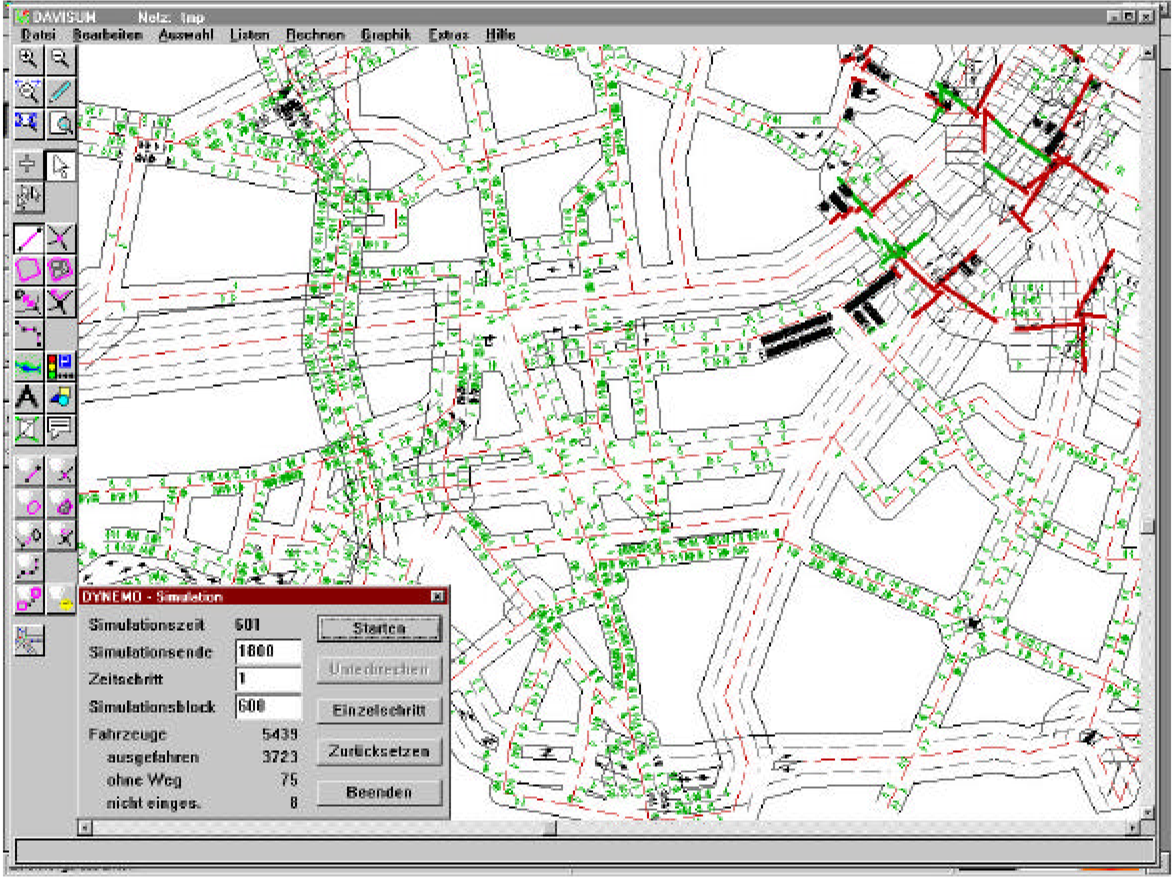
SIMTRAP can help answering this question in the following manner. First, the Berlin Marathon scenario is set up by modifying the O/D matrix (to account for the spectators) and the links over which the marathon will take place are marked closed in the traffic model. Data from the weather forecast for the day of the marathon (or a worst case day from the meteorological history) are added, and the scenario is run. The results are analysed for concentration hot spots exceeding environmental standards, or compared to the base case without the marathon.

Figure 6: Screenshot of DYNEMO simulation without marathon event



Simulationszeit 601
Simulationsende 1201
Zeitschritt 1
Simulationsblock 600
Fahrzeuge 4942
ausgefahren 4175
ohne Weg 75
nicht eingès. 53

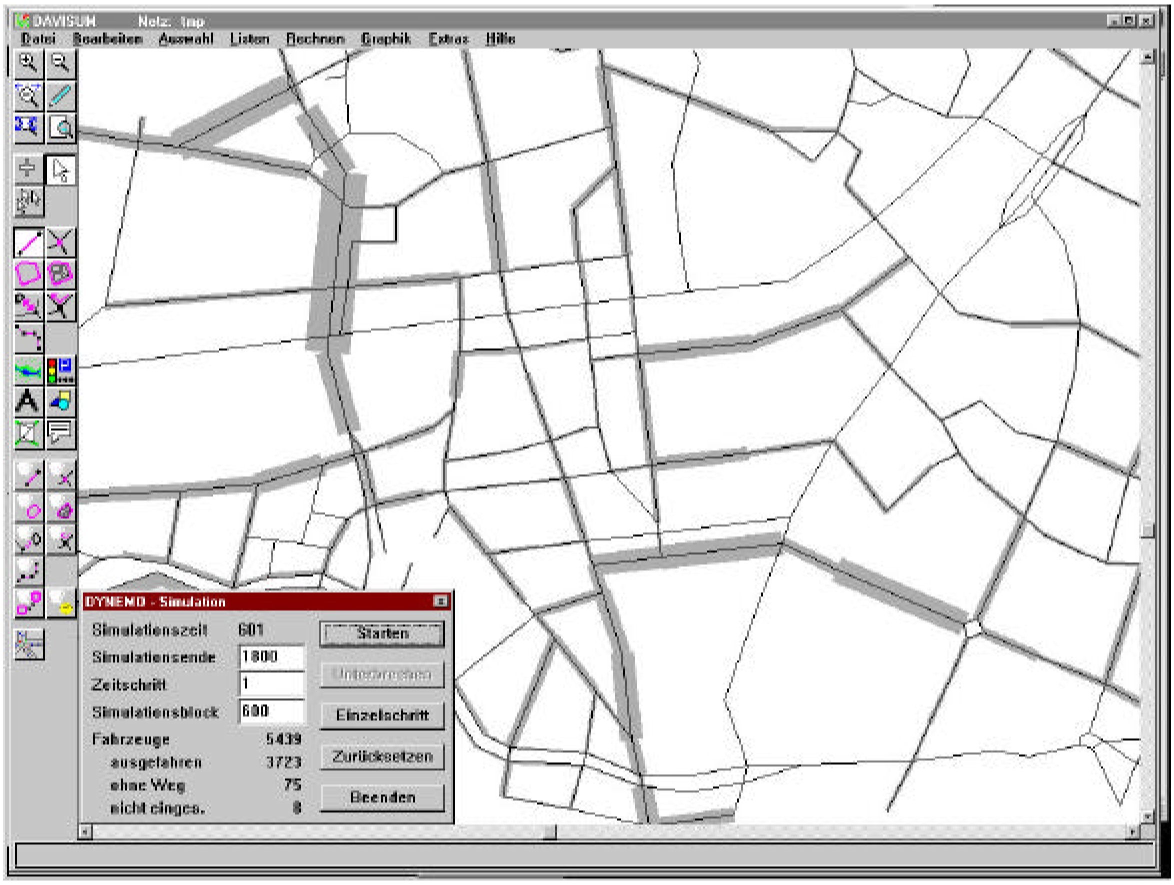
Figure 7: Screenshot of DYNEMO simulation with marathon event



Simulationszeit 601
Simulationsende 1800
Zeitschritt 1
Simulationsblock 600
Fahrzeuge 5439
ausgefahren 3723
ohne Weg 75
nicht eingès. 8

The pair of diagrams above shows a screenshot from the traffic simulation without (Figure 6) and with (Figure 7) the marathon, as seen in the existing user interface of DYNEMO. The course of the marathon clearly stands out as the Z-shaped traffic-free route starting middle-left and ending in the lower right corner. Traffic is re-routed via the remaining links many of which are congested, which is mirrored in a diagram of the traffic-related CO emissions (fig. 8).

Figure 8: Screenshot of DYNEMO emission estimates with marathon event



DYNEMO - Simulation

Simulationszeit 601
Simulationsende 1800
Zeitschritt 1
Simulationsblock 600
Fahrzeuge 5439
ausgefahren 3723
ohne Weg 75
nicht einges. 8

When the SIMTRAP prototype is completed, the aggregated CO and NOx emissions will be passed to DYMOS which forecasts the ozone concentrations in half-hourly steps. An example map corresponding to one timestep is shown in Figure 9.

The ozone concentration shown above is obtained by assuming a typical hot summer day with maximal temperatures about 32 degrees Celsius and low wind from the east. The values of the ozone concentration, given in µg/m³, are calculated on a 2 by 2 km grid for the extended region of the Berlin/Brandenburg area. The emissions from industry, households and traffic[1] were taken into account. The picture indicates that the highest ozone levels usually occur in the wind plume outside the inner city.

Eventually, all the simulation results are loaded into the GIS data base of the ACA toolkit and are available for difference plots, exception reporting, etc. Assuming that the emission

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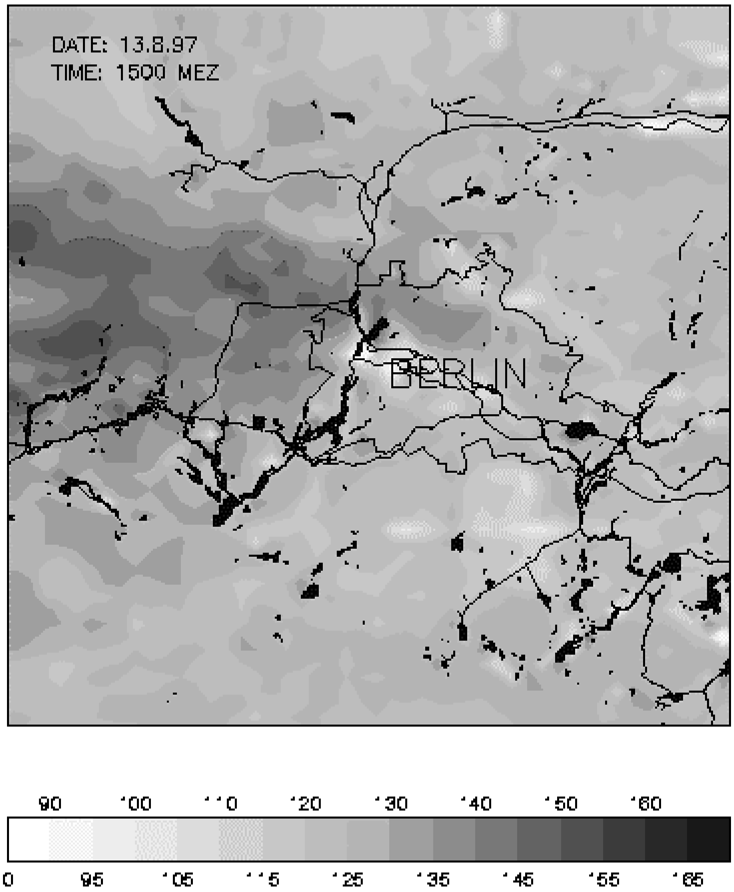
[1] In this example, because of the incomplete status of development of the SIMTRAP integrated model, a static traffic model was used. This will clearly not be the typical case for the finished system.

effects of the marathon scenario are not acceptable, the user can now experimentally invoke traffic regulation measures (e.g. restricting spectators to park & ride facilities further out, or admitting only environmentally-friendly vehicles to the city centre) and assess their effectiveness.

Figure 9: Screenshot of typical DYMOS ozone estimate for single time step



5. BENEFITS AND FUTURE DIRECTIONS

The integrated approach of the SIMTRAP project results in a more realistic picture of traffic-related air pollution than can be achieved by separate traffic and air pollution models. While pollutant formation is a slow process (of the order of hours), diurnal variations in the traffic pattern still have a profound effect on it. Static assignment does not provide primary emission data at the temporal resolution needed for an ozone concentration forecast of satisfactory spatial[2] or temporal resolution. But this is a prerequisite for the evaluation of many traffic regulation measures which, for example,. impose restrictions at peak hours (such as toll systems depending on time of day). DYNEMO and DYMOS are not only well-matched in terms of temporal and spatial resolution, recent advances in computing power and the parallelisation of the simulator cores now permit sufficiently large areas to be studies. For studies of ozone concentrations this is a key capability, since in the past various proposed countermeasures have been plagued by ambivalent results (lowered

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[2] The forecast is also blurred in the spatial dimension, because size and shape of a plume formed by wind drift depend on the pattern of wind speed/direction and primary emissions over space *and time*.

concentrations in one area being offset by higher concentrations elsewhere), which has not improved acceptance by the public.

In the initial development of SIMTRAP efforts are concentrated on the integration of the transport and air pollution model, their implementation on a parallel platform, their interface with the decision support system, the establishment of communication links and the demonstration of the system's capabilities at test sites. Possible future directions for enhancement are numerous, although three strands appear particularly promising:

- on-line monitoring of air quality monitoring sites, also using the detailed information obtained in modelling and decision support;
- linking the decision support system to traffic control centres, to enable the automatic implementation of control measures on-street;
- optimisation in the design of ameliorative measures, rather than pure decision support.

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