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TEMMS: an Integrated Package for Modelling and Mapping Urban Traffic Emissions and Air Quality

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Abstract

The Traffic Emission Modelling and Mapping Suite (TEMMS) is a program designed to provide detailed estimates of vehicle emissions on urban road networks, and so act as a precursor to urban air quality modelling. TEMMS is a module of the "Quantifiable City", a more extensive model designed to address questions relevant to urban sustainability. Within the Quantifiable City model, TEMMS interfaces with SATURN, a traffic assignment model, and the Airviro or ADMS-Urban pollutant dispersion models, to calculate spatially defined pollutant concentrations for given traffic, meteorological and stationary source emission inputs. TEMMS also contains an integral model, ROADFAC, which calculates emissions of gases and particulates from vehicles using SATURN traffic or vehicle count data. TEMMS integrates these models via a database exchanger, the MapInfo geographic information system, and a custom built Windows-based graphical user interface, allowing modelling and mapping of link-based vehicle flow and emissions, and grid based air quality. TEMMS applications include emission and air quality mapping, evaluation of associated transport policies and scenarios, and preparation of inputs to other (e.g. epidemiological) models. Within this context, TEMMS has generated considerable interest from potential end users in Local Authorities and air quality management support services. Validation of the integrated model is discussed, and an example application of TEMMS to a large UK city presented.

Key words: Urban transport; Traffic modelling; Emission modelling; Dispersion modelling; Air quality, SATURN, ROADFAC, ADMS-Urban, Airviro.

Software availability

Program title:	TEMMS
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Year first available:	2001
Hardware required:	PC Pentium II, 64 MB RAM or higher
Software required:	Windows 95/98 or NT, MapInfo, SATURN, Airviro or ADMS-Urban
Program language:	Visual Basic, MapBasic
Program size:	1.6 MB

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1 Introduction

Clean air is essential for the health of people and the environment, and although significant improvements have been made in many countries over the last two to three decades, air quality, particularly in urban areas, remains a priority issue on most national environmental agendas. The Dobris assessment (EEA, 1998a), Europe's State of the Environment report, concluded that, although air quality in most European cities has improved in the 1990's, problems remain with several air pollutants, including sulphur dioxide, carbon monoxide, nitrogen oxides and particulates, all of which sometimes exceed the World Health Organisation (WHO) guideline values. The European Environment Agency has estimated that in the 115 largest EU cities, there are 40 million people experiencing at least one exceedence of WHO air quality guidelines every year. Of these exceedences, 25 million are related to sulphur dioxide and particulates, and 37 million to ozone (EEA, 1998b).

In Western Europe motor vehicles have overtaken industrial processes and the combustion of coal as the major source of air pollutants. As vehicle traffic is projected to increase considerably, transport-related emissions are also expected to rise, exacerbating air quality problems, particularly in cities, despite the increasing use of abatement measures such as catalytic converters. This continual traffic growth has raised concerns over the impact of traffic emissions on human health and urban environmental quality, and has fuelled the demand for a coherent regulatory framework for the management of traffic, air quality and emissions at local, regional and national scales. In the United Kingdom, the 1995 Environment Act outlined central Government policy and objectives concerning local air quality management, and required the Secretary of State for the former Department of the Environment, Transport and the Regions (DETR) to publish a National Air Quality Strategy (NAQS) that would enable the UK to meet its air quality obligations as defined in EU treaties and other international agreements.

The UK NAQS (DoE, 1997), the first of its kind in Europe, defined policy, tasks and responsibilities for achieving goals for outdoor air quality. An external review of the strategy was completed in 1999 (DETR, 1999), and a final revised strategy was formally adopted in January 2000 (DETR, 2000a). The strategy defines Government's primary goal for UK air quality policy as the protection of human health and the environment from polluting emissions and ambient air quality. Therefore, the strategy defines health-based standards for eight key air pollutants, with targets to be met by 2005. It also identifies action to be taken at international, national and local level to achieve these targets, and provides a framework in which the contribution of relevant parties, such as industry, business and local government can be identified.

The strategy highlighted the results of earlier air quality modelling and mapping work, which suggested that transport was the major contributor to NO₂ and PM₁₀ concentrations, particularly in urban areas where the greatest exceedences of the objectives were forecast (e.g. Carruthers *et al.*, 1998; Stedman, 1998). The strategy recommended that a cost-benefit analysis of those measures that might remove exceedences of air quality standards was required, which in turn required forecasts of the level and location of exceedences of each pollutant for 2005. Such detailed information on the temporal and spatial variation of air quality in urban areas is also useful to Local Authorities and others with responsibilities for protecting air quality in cities, through, for example, the establishment of local air quality management areas (LAQMA's).

This paper describes the development and application of a model package designed to support urban Local Authorities in forecasting and managing urban air quality. By integrating a series of dynamic models and databases, TEMMS (Traffic Emission Modelling and Mapping Suite) models and maps traffic emissions from road networks in urban areas, combines these emissions with stationary source emission estimates, and inputs these combined emissions to

a dispersion model to facilitate regional air quality mapping on a small area basis (0.1-1 km²). Thus TEMMS can be used to examine the impact of, for example, forecast traffic growth, or proposed traffic management schemes on local air quality.

2 Transport - air quality modelling in TEMMS

TEMMS is a component of the Quantifiable City model (May *et al.*, 1995, 1996) that seeks to address a number of key urban processes relevant to questions of city sustainability. Within the wider Quantifiable City model, TEMMS facilitates the modelling of transport - air quality interaction through integration of several inter-linked steps. The first is the determination of traffic flow in urban areas using a traffic assignment model to provide, for each road in the network, data on traffic flow, speed and other related variables. Vehicle count data could also be used, but is rarely if ever, available network wide. Second, an emission model is used which applies emission factors for the vehicle fleet to modelled vehicle flows, to calculate pollutant loads emitted by vehicles. Thirdly, these mobile source emissions are combined with stationary source emissions (from industries etc.) to provide spatially and temporally resolved total emission estimates for the required pollutants. The relationship between emissions and pollutant concentration in outdoor air is complex, and dependent upon meteorology and physical geography. Hence the final step requires the application of an air pollutant dispersion model to predict temporal and spatial variation in urban air quality. The structure of TEMMS is presented in Figure 1 and described in detail below.

2.1 Traffic Modelling

To assess the impact of the predicted demand for road use, the interactive simulation and assignment model SATURN (Simulation and Assignment of Traffic to Urban Road Networks) is used. SATURN (Van Vliet, 1982) was developed at the Institute of Transport Studies, University of Leeds and is used in thirty countries, including application by 80 UK local authorities. SATURN is a tactical transport model that estimates the traffic volume on each link of a road network assuming a fixed trip matrix. This type of model is distinguished from assignment models used to model strategic transport by its very detailed representation of the road network and the modelling of turning movements at junctions.

SATURN requires two basic sets of input data: (i) a trip matrix, and (ii) road network data. The trip matrix, (also known as the origin-destination matrix), expresses the demand for travel and gives the number of trips between pairs of zones, i.e. between trip origins and destinations. Trips are usually expressed in passenger car units (PCU), defined as unity for cars and light duty vehicles, 0.5 for motorcycles, and 2 for buses and heavy-duty vehicles. Bus trips by public transport are not included in the trip matrix, but in the network data, because they follow fixed routes and cannot be subject to the assignment procedure. In SATURN, the road network is usually represented at two levels, with an inner simulation network containing data about road links and junctions (including detailed descriptions of roundabouts, priority and signalled junctions), and a buffer network (surrounding the simulation network), with data on roads but not junctions. The parameters required for nodes (junctions), links and turns include:

- number of links at the node;
- number of entry lanes for each link;
- traffic signals data (number of stages, duration of each stage, turning movements allowed at each stage);
- minimum gap for give-way turns at priority junctions and roundabouts;
- free-flow speed on the link, link length, and saturation flow for each turn.

Each link in SATURN is analysed separately whether it is a one-way link or one half of a two-way link. Outputs files for simulation and buffer links are produced separately in ASCII format, and may be processed further using integral DOS modules. Node numbers and their corresponding co-ordinates are output in one file, while link ID, traffic flow and speed are output to another.

SATURN is first run using the trip matrix for a selected traffic period (AM, PM or intermediate periods), which transforms the origin-destination matrix from ASCII to binary format. A separate module of SATURN is applied to transform corresponding network data to the binary format. The SATALL module within SATURN is then run with the origin-destination matrix ("demand for trips") and network binary files ("supply of routes"), which causes the assignment and simulation loops to run iteratively, until an equilibrium point is reached at which the costs (e.g. times) are optimised. This procedure considers parameters such as driver vehicle-vehicle minimum gap acceptance, junction type, number of lanes, turn data, traffic signal stages and cycle time, which all impact upon time spent at junctions, the key parameter fed back to the cost optimising routine. The final result is a detailed spatial representation of the traffic patterns on the road network. A full SATURN specification, including current input data requirements, is given in the user manual (Van Vliet, 1998).

2.2 *Emission Estimation*

A key element in the mapping and forecasting of urban air quality is the emission inventory, a detailed representation of emissions from all identifiable point (e.g. factory stack), line (e.g. road) and area (e.g. small scale diffuse activities such as domestic heating) sources. In some cases, continuous observations of emissions from a source are available, but usually direct measurements are unavailable, and emissions must be estimated. Emissions are usually proportional to the activity rate, hence the first step in estimation is to determine the activity rate (e.g. industrial output, vehicle kilometres driven) for all sources under consideration. The source emission is then a product of the activity rate and an emission factor, an empirically derived coefficient describing the relationship between the activity in question and the emission (e.g. g of NO_x per Kg of fuel used).

Emission inventories can be compiled in a "top down" approach with emission totals derived from aggregate data (such as national fuel use), and apportioned to smaller areas, often kilometre grid squares, using proxy data such as population density. However, for urban areas, a "bottom up" approach, where local source activities are described in detail is preferred, as this gives better estimates with greater spatial resolution. TEMMS facilitates the latter approach, with emission from line sources estimated separately from other sources using its integral model, ROADFAC (Namdeo and Colls, 1994). When TEMMS is applied in conjunction with a dispersion model, emission estimates from stationary sources must be obtained from elsewhere. Such data is often available through national programmes. In the UK for example, the government commissioned a "bottom up" study, the DETR Urban Inventories Programme, providing stationary source emission estimates for most major UK cities (see, for example, Buckingham *et al.*, 1998). These inventories are used for UK urban air quality modelling, including that conducted by local government under their statutory duty to estimate locations where air quality standards are likely to be exceeded.

A principal advantage of TEMMS is that it automates the laborious task of developing emission estimates (as rate in mass per km or second) for line sources. For an urban road network, TEMMS passes link specific data to the emissions model, ROADFAC, which estimates emissions (and also fuel use) for that link, and passes them directly to a spatially referenced database for mapping or import to an atmospheric dispersion model. The activity variables of the estimation procedure are the number of vehicles per unit time, mean speed per link, and the fleet composition. Flow and speed data are derived from traffic surveys, or

transport models such as SATURN, described above. Fleet composition data for all EU countries is available from the EC Fourth Framework Project MEET (Methodology for Estimating air pollutant Emissions from Transport) (European Commission, 1999). The UK data is available in the ROADFAC MS Access database, whilst data for other countries can readily be added. Five main vehicle classes are addressed (passenger cars, light and heavy duty vehicles, buses and two wheel vehicles) with sub-classes according to vehicle size (engine capacity or gross weight), the level of emission control technology (according to age and stages of EU emission control legislation), fuel type, engine type (2 or 4 stroke) and operational purpose (e.g. coach or urban bus for buses).

Emission factors (as g/km) for each of the numerous fleet sub-classes are also available in the ROADFAC database. These were originally drawn from TRL and the CORINAIR working group of the CEC (Eggleston *et al.*, 1991), but have since been updated using the MEET data which is more comprehensive, up-to-date and addresses a broader range of pollutants (CO₂, CO, NO_x, SO₂, total particulates, total VOC's,). Factors for additional pollutants, PM₁₀, PM_{2.5}, benzene and 1-3-butadiene, are also used, and are derived with reference to the corresponding main pollutant.

The emission factors are determined using a chassis dynamometer, where the engine is run over a test cycle and its emissions collected and analysed. The test cycles used by MEET were based on typical observed urban driving cycles, which have much greater variability than EU approved urban driving cycles, and hence give more representative emission estimates. These test cycles are repeated for different average journey speeds, so as to derive speed dependent emission factors. Improved factors are possible using an instantaneous emission matrix where emissions per second are recorded for a mix of operational variables, say speed versus speed times acceleration, but such factors are not yet widely available, hence the speed variable factors are used.

Higher emissions are observed under lower ambient temperature (for most fuel types), and also from cold engines, hence in urban areas, where journeys are often short, cold engine emission rates are an important consideration. ROADFAC uses the MEET recommended methodology to estimate cold emissions as the additional emission that might be expected over and above that were all vehicles running at their normal operating temperature. The cold emission is calculated as the product of the hot emission rate and a recommended relative emission factor, a ratio of hot to cold emission rates observed for vehicle type, driving behaviour, and ambient temperature (European Commission, 1999).

From the hot and cold emission rates, ROADFAC calculates a composite emission rate for each vehicle class, for one kilometre of characteristic road type. The proportion of road with cold emissions, the "cold mileage percentage", is determined using CORINAIR methods (Eggleston *et al.*, 1991) using engine and ambient temperature, trip length and road type. For each road link, total pollutant emission is then calculated as the product of the link length and the sum of emissions/km for all vehicles within each fleet class.

2.3 Dispersion Modelling

To properly assess the impact of variable emission loads on ambient air quality over a large area like a city, pollutant dispersion models are required. The most commonly used models for this purpose are Airviro (SMHI, 1999), ADMS-Urban (CERC, 1999) and several USEPA models (ICST and AERMOD). Some dispersion models, (e.g. CALINE-4, CAR, HIWAY) address mobile source emissions but exclude stationary source emissions, and hence are not suited to modelling urban air quality (Namdeo and Colls, 1996). Inputs to the dispersion models comprise data on emissions, meteorology and topography, with air quality predictions

in the form of seasonal or annual means, percentiles representative of air quality standards, or calculations for specific hours in the sequential meteorological data file

To date, TEMMS has been applied with the Airviro and ADMS-Urban dispersion models, although its structure means that other dispersion models could also be used. Airviro has a plume model based on a Lagrangian-Gaussian formulation, recommended for areas in which the topography is reasonably flat, and a Eulerian advection-diffusion grid model for large areas with complicated topography. ADMS-urban uses boundary layer similarity profiles to parameterise the variation in turbulence with height within the boundary layer, and also uses a skewed-Gaussian distribution to determine the vertical height of pollutant concentrations in the plume under convective conditions. Boundary layer stability parameters are calculated from wind speed, date and cloud cover, or wind speed, surface heat flux and boundary layer height. Both models have integral chemical reaction models to allow calculation of NO₂ from NO_x emission, and both have street canyon models for simulating air quality for a particular street segment surrounded by buildings. Both model air quality in response to emission from single or multiple emission sources, with results represented spatially as thematic or isoline maps.

3 TEMMS structure

3.1 TEMMS GUI

TEMMS is largely a Visual Basic (VB) application which contains the ROADFAC model, and which facilitates integration of ROADFAC with the traffic and dispersion models via data exchange, controlled from the graphical user interface (GUI). ROADFAC is run entirely from the GUI which enables a user to select and modify SATURN output files, process them in ROADFAC to produce emission estimates from traffic, and pass these estimates to the external atmospheric dispersion model. The database exchanger (DBE) is integral to the GUI and facilitates the internal linkages between ROADFAC and the external models, and also with the MapInfo Geographic Information System (GIS) for spatial mapping of emissions.

The TEMMS opening screen offers three principal TEMMS options: the Emissions Modelling option allows the user to process SATURN model output using ROADFAC; the TEMMS DBE option containing modules for file input/output to the GIS database, and some limited spatial operations and database manipulation; and the Integrated Mapping option allowing GIS mapping and querying functions.

3.2 Emissions modelling

Figure 2 shows the ROADFAC-SATURN-MapInfo interface screen. ROADFAC is run from here, but the SATURN data must be generated externally. Selecting Option 1 presents a dialog box that enables the user to read the appropriate SATURN output file containing data on link ID, flow, and speed, representative of the traffic scenario of interest. This option also runs the ROADFAC model (Figure 3) to calculate pollutant emission fuel consumption rates for each road link using the vehicle fleet structure, traffic flow and link variables supplied by SATURN.

Results produced under Option 1 relate to individual links. However, in reality most roads are actually two-way links, that is they are not usually one-way streets. To recognise this, the SatLinks program under Option 2 takes output from Option 1, and searches the SATURN network data file for those links that have shared node identification numbers but a different direction of flow. The traffic flows and emissions for both these links are then summed to give emissions for that two-way road, with the corresponding attribute data written to space-

delimited ASCII and comma-separated value (CSV) formats, the latter preferred by MapInfo. A second file is also created in which those links with shared node identifiers but different flow directions are given a new node identifier. This creates a second network file for use in network mapping, avoiding the potentially confusing situation of one road being represented by two links.

To map road networks and associated emissions from road traffic, the geographical location of all links must be known. Under Option 3, this information is extracted from the SATURN output file of node numbers and corresponding X-Y co-ordinates. The co-ordinates are transformed to six-digit reference numbers that give a location in metres based on the national co-ordinate projection, and are then written to a CSV file. Option 4 reads the file with the link and node numbers (the second file produced under Option 2), and the file with the node co-ordinates (produced in Option 3) to create a CSV file suitable for mapping road network and emissions in MapInfo.

After running all four options in the ROADFAC-SATURN-MapInfo interface, the user is returned to the main screen. From here, the TEMMS DBE must be run to import the files into the GIS. The import process produces two types of information: a geographical coverage, or road network, in which the road network is represented as a map layer built from road links; and an attribute table, containing a record for each road link, with data on pollutant emission, speed and traffic volume. MapInfo native format files are stored in binary form for compactness and increased speed.

3.3 TEMMS Database Exchanger

The TEMMS database exchanger (DBE), written in MapBasic, consists of a series of independent programs integrated under a VB interface. The DBE converts comma or space-delimited files, dependent on their format, using either a one or two-stage process, into MapInfo binary tables which form the GIS database. The initial file inputs are from SATURN-ROADFAC, and these inputs initialise the primary geographical database. The programs accommodate the database hierarchy by offering the user a structured means of selecting input tables. To avoid confusion the program prompts the user for all file inputs. The initial choice presented is for the network year (where several network years are available for comparison), and then a choice of traffic profiles is offered (AM, PM or intermediate peak conditions). The system offers the user the relevant input file for processing, then outputs the MapInfo table to the appropriate directory as “live” data, and as a date-stamped copy for future use.

Additional functions have been coded into the DBE to allow further spatial operations on the database. The “line in polygon” function calculates area-based emissions from network-based emission and so produces inputs suited to the TEMMS grid mapping module. A second function is used to derive annual average daily traffic data (AADT) from modelled or observed AM, PM and intermediate peak data, using an algorithm derived from the London Research Centre traffic model (Buckingham *et al.*, 1998). The AADT data is required to give long run averaged vehicles flows, and is used by Airviro so that it can reconstruct hourly flow profiles, and hence hourly mobile source emission estimates, corresponding to the hourly time step used in the dispersion models. ADMS-urban similarly requires hourly flow profiles, but has no internal algorithm for producing them from AADT data, and the hourly flow profile must be provided. Therefore, a third function allows ADMS-urban users to generate the required hourly flow profile from a single traffic flow period (AM, PM or intermediate peak), based on hourly observations of vehicle flows in Nottingham, UK, for different road types.

3.4 Integrated Mapping

The purpose of integrated mapping is to represent the modelled networks and emissions graphically and to allow the spatial interrogation of the geographically referenced database. Integrated mapping is a combination of VB and MapBasic programming, based on Object Linking and Embedding. The interface is written using VB forms and controls, that pass commands to the MapInfo object to modify the map and table displays, and to run scripted or geographical selection queries. This permits two ways of viewing the emissions data modelled by TEMMS, as a network or as grid area totals.

With network mapping, the user is able to map pollutant emission, fuel use, traffic volume and speed, over standard Ordnance Survey 1:50,000 scale colour raster maps. Values are mapped as proportional line widths, and can also be viewed in a data table. A map toolbox allows for zooming and panning, attribute queries for selected locations, and printing and querying of the map and table information. For clarity, at extreme scales of display, the raster map background can be toggled on and off.

Grid mapping allows the user to view the modelled emissions and fuel use by grid-square. Grid sizes and coverage can be user defined, although for normal use a one kilometre grid layer with a coverage extending to the district boundary is the default. This is a simplified method of viewing the information, allowing rapid display, and a single data table for the region, rather than treating the SATURN simulation and buffer zone network data separately. The data tables and geographical boundary files are created in the DBE by overlaying the combined buffer and simulation networks and associated data over a grid coverage, a "Line-in-Polygon" proportional attribute calculation.

4 TEMMS Validation

TEMMS facilitates the integration of vehicle flow, emission and atmospheric dispersion models to permit the prediction of urban air quality. With the exception of ROADFAC, the model integration is via data exchange from or to external extant models, hence to validate TEMMS it might be considered sufficient to just examine the performance of the ROADFAC model. However, as TEMMS was developed to permit the assessment of 'what if?' traffic scenarios on urban air quality, and because its integration with external models is fundamental, an assessment of the performance of the complete system is appropriate. One performance test is to consider the validity of individual models in the TEMMS 'chain'. For each model, the validity of the underlying assumptions can be tested; the concept of Wardrop user equilibrium assignment in SATURN, or Lagrangian-Gaussian dispersion in Airviro, for example. However, these theoretical considerations are beyond the scope of this paper which accepts the appropriateness of the basic assumptions, and readers are referred to the original literature where discussions on model theory and formulation can be found. Rather, the discussion here is on the more practical aspect of model validation, that of sensitivity testing and comparison of observed and predicted values.

4.1 SATURN validation

Matzoros *et al.*, (1987) describe a SATURN validation exercise conducted in Manchester, UK, where SATURN was used to assess the likely impact of a city centre pedestrianisation scheme requiring road closures. For the city centre network, with a radius of approximately 3km, observed data was collected and used to calibrate the model. For 73 links not used in calibration, observed-predicted link flows were within 7.8 to 16.3% depending upon flows in the surrounding buffer network, and generalised costs used in the assignment procedure. Following the road closure scheme, link flows were within 12% of the observed flow. These results were considered very good, considering that there was a 10% uncertainty in the

observed vehicle count. Journey times were predicted within one standard deviation of observed times, an acceptable result at the aggregate level. This lower degree of accuracy was attributed to the great sensitivity of travel times to delays at junctions when the network is near capacity.

SATURN is a static equilibrium model, intended to provide long run estimates of vehicle flow, rather than a snapshot of what happened on a particular day. Validation is difficult because the cost of obtaining network wide, long run observed counts is prohibitive, and because there is usually significant uncertainty in the observed count data. Validation is therefore conducted at the project scale, as in the Manchester example, rather than for an entire urban network. However, based on the experience of the 300 SATURN users worldwide, the model developers suggest that the aggregate error in a calibrated model should be <10%, and an error of >20% requires significant re-calibration (figures based on SATURN GEH value, a SATURN standardised observed-modelled difference statistic) (Van Vliet and Hall, 1998). When considering transport policies which may have a network wide impact (e.g. application of road pricing) it is important to note results of sensitivity testing on the model. These show that the model is remarkably stable at the aggregate level, but less so at the link level. That is, changes in key input parameters such as travel costs have little effect on total flows and travel times across the entire network, but can cause significant change in flow and journey time for individual links (Milne, 1997).

4.2 ROADFAC validation

Validation of urban emission models through comparison of observed-predicted values has never been done, as it is not feasible to monitor emissions from all vehicles travelling on a road, or from all point and area source emissions. Neither is it possible to accurately quantify uncertainties in emissions due to the complex and varied nature of the data and calculations associated with emission estimation (DETR, 2000b). The uncertainties are associated with:

- Activity data. For example, ROADFAC does not consider the effect of acceleration and deceleration at junctions, and has a uniform emission through a junction based on average speed. There is also uncertainty in vehicle flow estimates, although in TEMMS this error source is associated with the SATURN model or count data, not the emission model;
- Emission factors. These are based on limited observations, which may differ subtly from the activities to which they are applied;
- Temporal manipulation. For example, an annual estimation may be based on a limited number of daily observations of an activity variable (e.g. mean annual traffic from daily counts);
- Spatial manipulation. Activity data may only be available for major not minor roads, whilst area emissions based on household fuel consumption may be based on point of sale rather than point of use.

The principal sources of uncertainty in the MEET emission factors used in ROADFAC include (a) using a small vehicle sample to represent a vehicle fleet of millions; (b) defining a representative driving cycle; and (c) not considering all actual environmental conditions in emission estimation. MEET emission factors were derived for a wide range of vehicles (by type, engine size, age etc.) in use in Europe. For each class examined, speed dependent emission factors are given as average speed-emission best fit curves, with r^2 values ranging from 0.014 to 0.980. The low relationships are a product of the inability of the statistical models to address the large scatter in the observed emission data, produced as different emissions arise from vehicles in the same category, and even from the same vehicle tested at different times. Driving behaviour is also important, and significantly different levels of acceleration and deceleration produced a variation in measured emissions by a factor of 8, compared to variation in the average speed model of 15%.

Using observed driving cycles, the MEET emission factors predicted actual emissions to within 15% for NO_x, 25% for VOC's, 35% for CO and 4% for CO₂ (EU, 1999:41). MEET argue that, provided the samples of vehicles used to generate the emission functions are representative of those in use, then these average rates of emission are "reasonably accurate". ROADFAC applies these emission factors to the UK vehicle fleet, whose composition (type, size etc.) is described using vehicle sales data. Fleet composition for future years is forecast, based on an analysis of the current fleet composition, how the fleet has "aged" in the past, and current sales. It is assumed that the fleet composition in the region where the emission model is applied is representative of the composition nationally. The uncertainty in the mobile emission model has not been quantified accurately, but it seems reasonable to assume 5-10% variation arising from fleet composition, in addition to the uncertainty in the emission factors.

4.3 Dispersion model validation

The inaccuracies in the results of dispersion modelling arise due to: inherent variability caused by random turbulence; accuracy and coverage of the meteorological and emission input data; the effect of complex surface features such as buildings; and inherent model uncertainty (i.e. is the model formulation correct and appropriate to the required output?). Of these, inaccuracies in emission input data is the most commonly cited reasons for poor model performance. The way in which the model errors are dealt with depends on the error type. Systematic errors (bias), where the same error trend is apparent at all times can be addressed by calibrating the model, usually deriving a multiplicative correction factor. The reasons for applying the correction should be explained, the absence of any emission data from a known significant point source for example. Random error (uncertainty) may still remain after model calibration and comparison of model data with observations not used in the calibration exercise. In this case the error is quantified, often as the square root of the mean sum of the squared difference between modelled and monitored, and the result used to express a band around the modelled mean in which the true value is thought to lie.

Dispersion models are typically tested against five field data sets from the USA, where the data sets are sufficiently large to permit robust statistical evaluations, and represent a cross section of typical scenarios encountered by modellers (Hanna *et al.*, 1989). In each case, the tracer gas SF₆ is injected into a single stack, eliminating uncertainty due to emission estimates and chemical conversion, thus permitting a more robust model evaluation against the c.200 ground monitors. Evaluation of the ADMS model in this way, for example, shows that it underpredicts by about 20% for both long term average and peak values, with a scatter of a factor of two (Hanna *et al.*, 1999).

4.4 Validation of the integrated model system

To summarise, the potential error associated with the constituent models are approximately in the range of $\pm 12\%$ for vehicle flows, $\pm 4-35\%$ (depending on pollutant) for the mobile emission factors, perhaps another $\pm 5-10\%$ for fleet composition, and $\pm 20\%$ for the dispersion model, suggesting that the model system should be capable of predicting pollutant concentrations within 40-70% of observed concentrations. Advice from DETR, suggests that a prediction of a long term average concentration within $\pm 50\%$ of the observed indicates that the model performance is acceptable for use in statutory air quality assessments (DETR, 2000c).

Emission inventories and dispersion models have been applied to large urban conurbations in the UK, where observed pollutant concentration data are available, and have shown that systems using ADMS-Urban and Airviro generally perform well. Published validation studies include those for Birmingham (Veal and Appleby, 1997), West London, Swansea and Belfast

(Carruthers *et al.*, 2000), and Central and East London (Owen *et al.*, 2000). Summarising these studies CERC (2000) note that in urban areas dominated by traffic emissions, the annual mean prediction from ADMS-Urban is generally accurate to within 15% for NO₂ and PM₁₀, the 90th percentile of daily averages for PM₁₀ is accurate to within 20%, and the 99.8th percentile of hourly means for NO₂ is accurate to within 40%. In the dispersion modelling community, such accuracy is considered very good.

Table 1 illustrates validation of the model for Leeds, UK, a city with a population of c.750,000. The SATURN network for Leeds is large, with 1314 intersections, 327 priority junctions, 17 roundabouts, 534 buffer nodes, 8107 assignment links, 2143 simulation links, 843 buffer links, and 166 bus routes with fixed flows. The number of trips varies for each trip matrix, with the morning peak matrix, for example, comprising 80349 trips between 370 zones. The model performance was assessed for 1993, the only year for which the appropriate data (hourly sequential meteorological data, the SATURN network and trip matrix data, and observed air quality data at a suitable urban background site) were available. The location of the monitoring station was identified as a specific receptor point in the dispersion model (ADMS-Urban) and the hourly air quality data for the first six months of 1993 used to generate a multiplicative calibration factor that addresses the systematic bias thought to result in this case from background pollutant import from outside the study area (Bradford, a city of 1 million people lies approximately 15 km upwind). The factor was applied to modelled air quality for the latter six months of 1993, and compared to the corresponding observed data.

The results indicate a good agreement between observed and modelled air quality for the site in question. Further assessment of model performance would benefit from a validation exercise addressing multiple sites, but this has not proved possible to date due to the absence of the required observed air quality and modelled SATURN data. In general validation of systems like TEMMS is challenging due to a general lack of monitored data against which to compare component model performance. Indeed, the cost and difficulty of obtaining observed vehicle counts for a whole urban network, or measuring air quality across a whole city, for example, is a primary motivation in the development of these predictive models.

5 TEMMS application

TEMMS was applied to predict air quality in Leeds for 2005, the statutory forecast year for UK NAQS assessments. Hourly meteorological data for 1999 was used, as this year is most representative of the previous decade's meteorological years. Stationary source emissions were derived from the DETR's atmospheric emission inventories for the West Yorkshire conurbation (Buckingham *et al.*, 1998). The SATURN model addressed planned changes to the Leeds road network, including two major new arterial roads and completion of an inner orbital route, and also forecast changes to trip demand, derived from the national trip end forecast model (HMSO, 1997). Figure 4 illustrates traffic flows, expressed in PCU per hour, for a part of the network, with associated PM₁₀ emissions by link (g/km/hr) and by 1 km² grid in Figures 5 and 6 respectively, the latter developed using the TEMMS-Grid module. Figure 7 illustrates annual mean PM₁₀ concentrations by 200m grid cell, calculated from the hourly emission and meteorological data.

6 Conclusion

TEMMS is a software package that facilitates the integration of transport, emission and dispersion models, together with stationary source emissions, so as to permit detailed assessment of the air quality implications of urban road transport scenarios. The integral ROADFAC model allows link based emissions from a vehicle fleet to be calculated, whilst

the purpose built database exchangers and windows GUI allow easy integration of constituent models, and rapid preparation of mobile source emission estimates based on the SATURN tactical transport model, for input to a dispersion model. Validation of such an integrated model is difficult due to a lack of appropriate data: spatially distributed data is simply unavailable (e.g. vehicle counts, link based emission), or the model is usually applied so as to identify pollutant 'hot spots', a method of analysis that does not lend itself well to validation as a common base data year is rarely used (e.g. a meteorological year representative of a worst case scenario may be used in a precautionary approach). Nevertheless, the accuracy of the integrated model is sufficient for conducting strategic assessments of urban air quality. More certain identification of locations exceeding air quality standards would require re-application of the model to areas where the strategic appraisal indicates a likelihood of exceedence, using a higher spatial resolution, a functionality available in current dispersion models.

TEMMS can be applied with observed vehicle count data but is designed to operate with modelled traffic counts, so as to provide the facility to investigate the impact of alternative traffic scenarios on urban air quality. Current work by the authors, for example, is applying TEMMS to Leeds to assess air quality for 2015 assuming no management interventions ('business as usual'), road network development, and a range of road user charging scenarios addressing different charge cordons and tariffs. Road pricing scenarios are represented using the elastic assignment procedure in the SATURN model, which addresses reduction in demand for road trips (i.e. switching to non-private vehicle mode), as well as redistribution of trips on the network. These results will be used to conduct a health impact assessment of these management options using the respiratory disease burden model described by Mitchell *et al.*, (2000).

Thus TEMMS is currently capable of assessing the air quality implications of baseline trip demand, network development, a wide range of road traffic management schemes, and several urban transport policies which can be represented in SATURN. In future, TEMMS will be integrated with the START/DELTA land use-strategic transport model (Still *et al.*, 1997) to allow investigation of the effect of a wider range of transport policies on traffic (e.g. investment in public transport), and the effect of land use change on transport and *vice versa*. The final land use - transport - air quality - health interaction package will be a valuable tool to support land use and transport planners seeking to promote more sustainable cities.

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TABLES

Table 1. Calibration and validation of the integrated model for Leeds, UK.

24hr Mean (July-Dec 1993)	NO₂ µg/m³	CO mg/m³	PM₁₀ µg/m³	SO₂ µg/m³
Modelled	32.50	0.62	13.41	5.71
Monitored	26.75	0.91	25.74	9.98
Calibrated *	25.73	1.11	29.88	9.92
Deviation of calibrated from monitored (%)	-3.8	+12.1	+16.1	-0.6

* Calibration factor derived from monitored and modelled data for Jan-Jun 1993

FIGURE CAPTIONS

Figure 1: TEMMS Structure

Figure 2. ROADFAC-SATURN-MapInfo interface

Figure 3. ROADFAC emission database manager

Figure 4. Link vehicle flows (PCU/hr) mapped in TEMMS

Figure 5. Link based emissions of PM₁₀ (g/km), for Leeds in 2005.

Figure 6. Grid based PM₁₀ (g/grid cell) emission in the TEMMS grid manager, Leeds 2005

Figure 7. Modelled annual mean PM₁₀ ($\mu\text{g}/\text{m}^3$), Leeds 2005 (200m grid cell)

Figure 1: TEMMS Structure

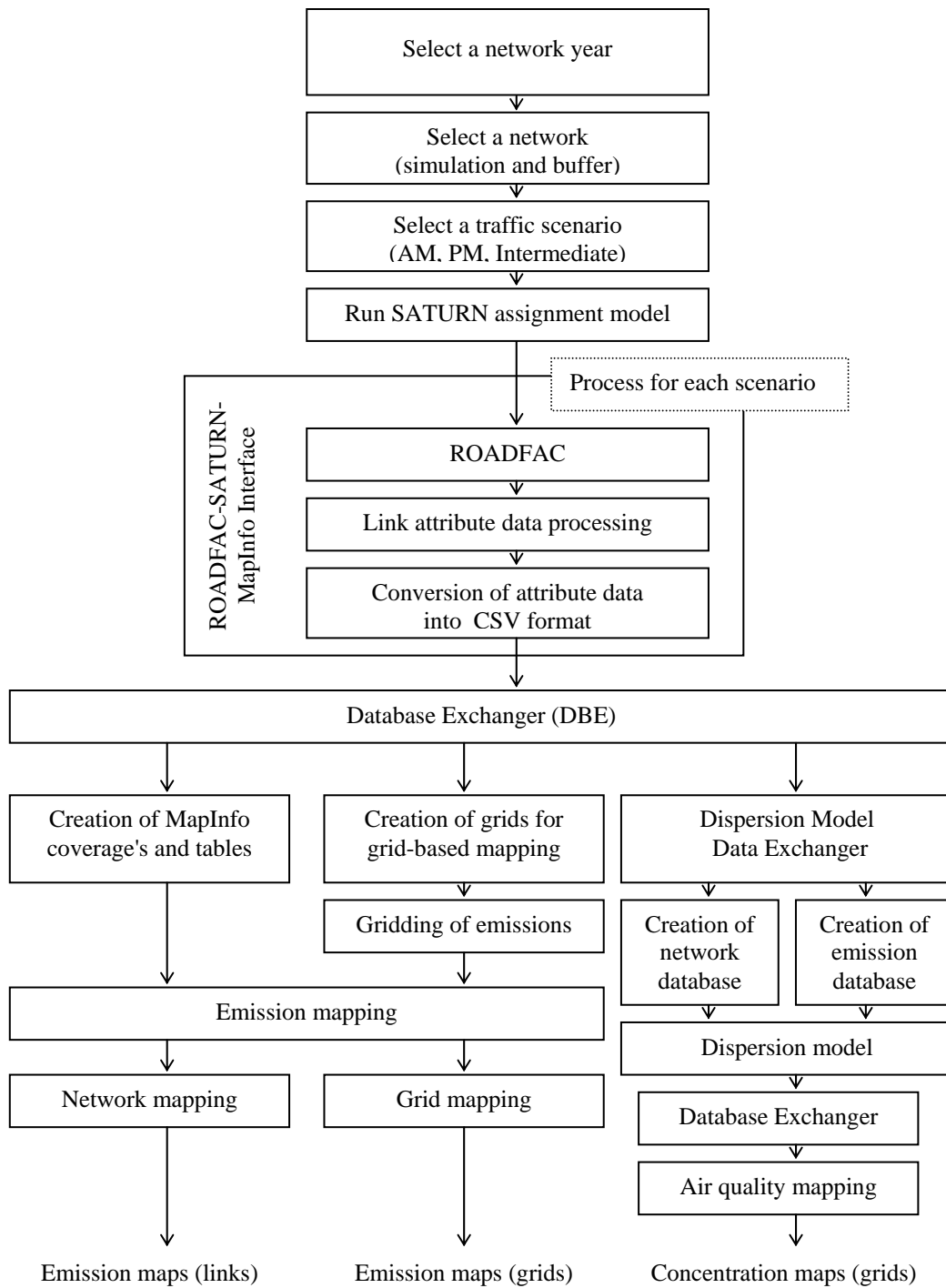


Figure 2. ROADFAC-SATURN-MapInfo interface

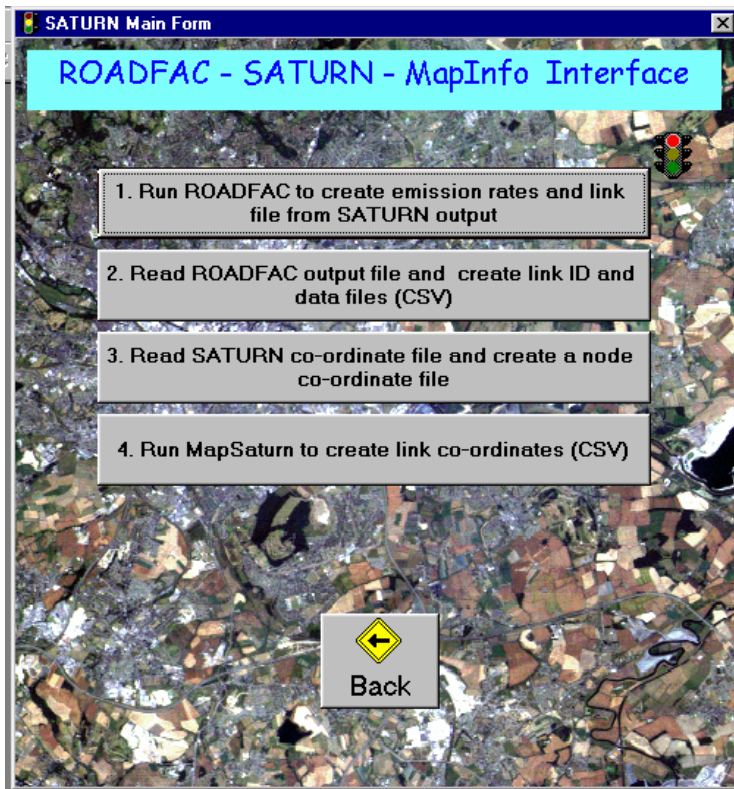


Figure 3. ROADFAC emission database manager

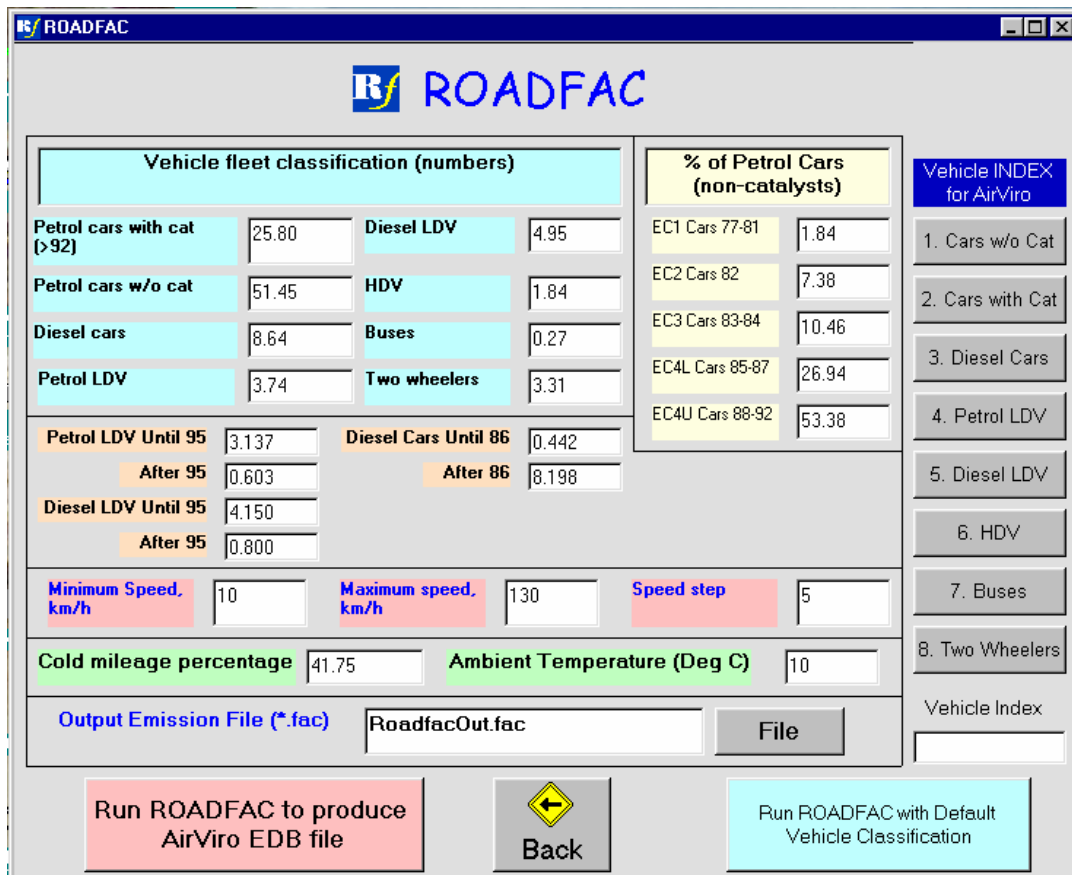


Figure 4. Link vehicle flows (PCU/hr) mapped in TEMMS

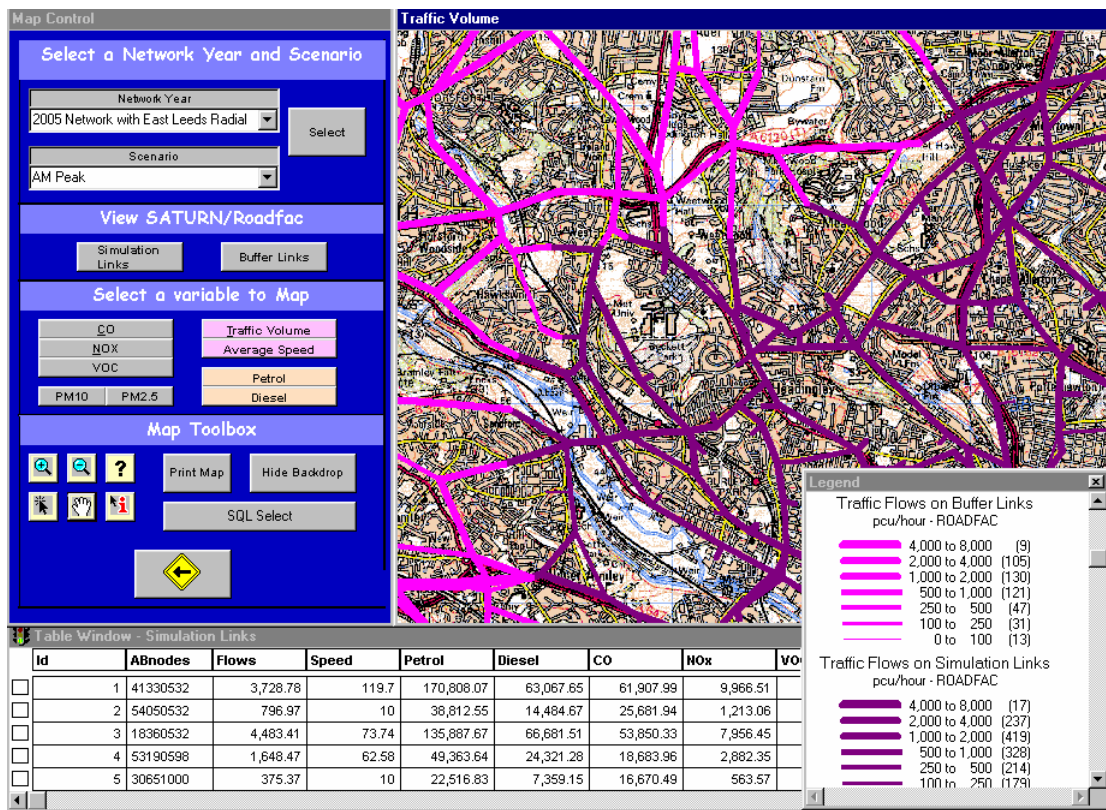


Figure 5. Link based emissions of PM₁₀ (g/km), for Leeds in 2005.

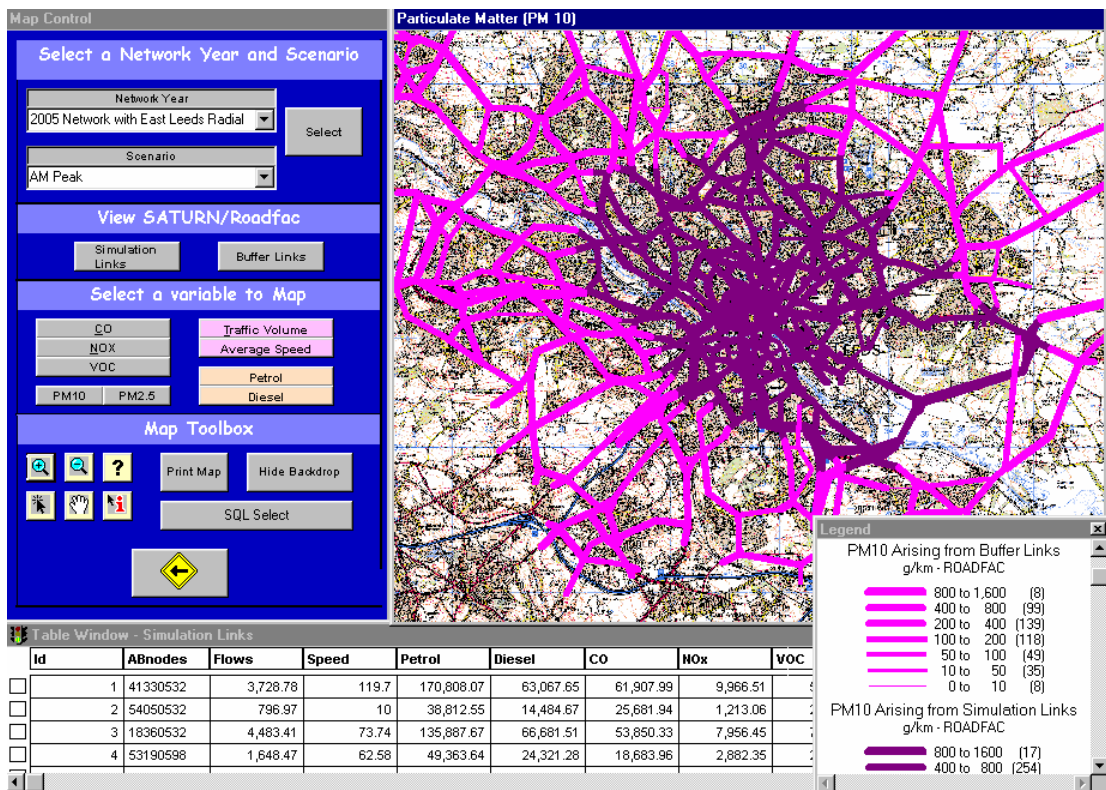


Figure 6. Grid based PM₁₀ (g/grid cell) emission in the TEMMS grid manager, Leeds 2005.

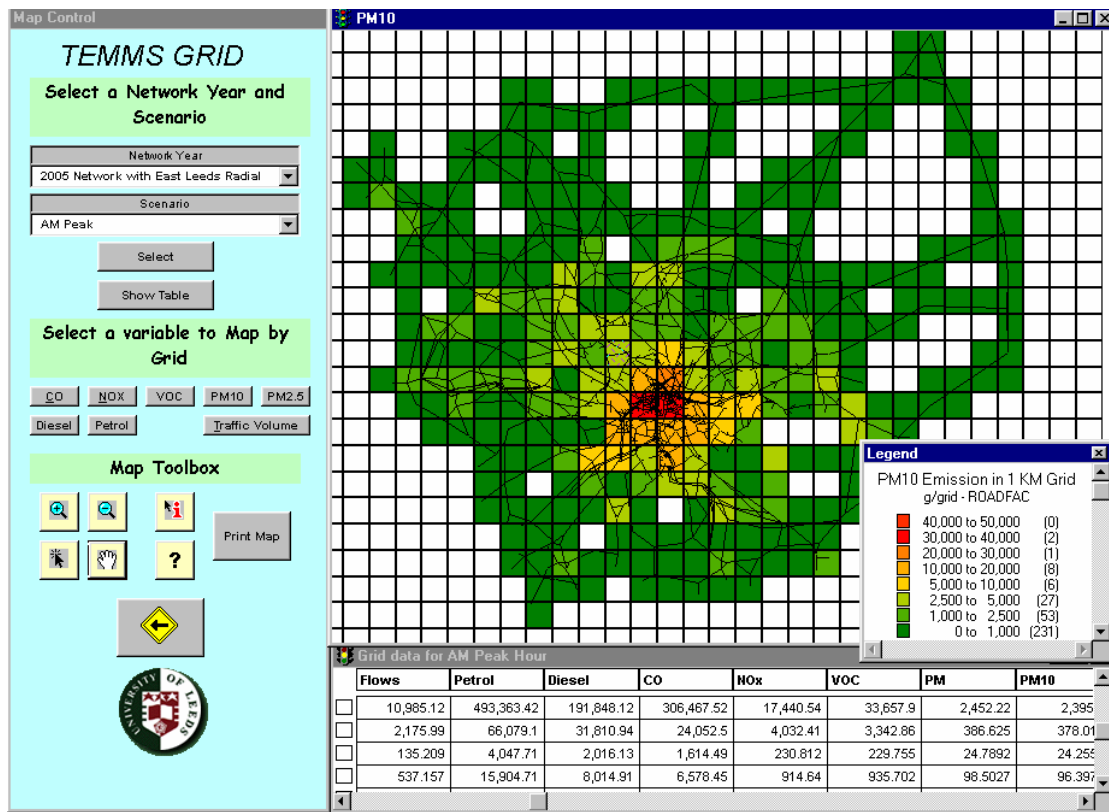


Figure 7. Modelled annual mean PM₁₀ ($\mu\text{g}/\text{m}^3$), Leeds 2005 (200m grid cell)

