**European Cooperation
in the field
of Scientific and Technical
Research**

COST 319

Estimation of Pollutant Emissions from Transport

Final Report of the Action

Scientific State-of-the-art and Network of European Scientists

**European Commission
Directorate General Transport**

A great deal of additional information on COST Transport is available on the World Wide Web. It can be accessed through the CORDIS server (http://www.cordis.lu/COST-Transport/home.html)
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Contents

Abbreviations

2W	two wheelers
CEC	Commission of the European Community
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
COPERT	European computer programme to calculate emissions from road traffic
CORINAIR	core European inventory of air emissions
COST	European co-operation in the field of scientific and technical research
DGV	Digitised Graz method
DME	dimethyl ether
DRIVE	Dedicated road infrastructure for vehicle safety in Europe
ECE 15	European urban driving cycle (also called UDC)
EEA	European environment agency
EMEP	Co-operative program for monitoring and evaluation of the long range transmission of air pollutants in Europe
ETC/AE	European topic center on air emissions
EU	European Union
EUDC	European extra-urban driving cycle
EV	electric vehicle
FC	fuel consumption
FCEV	fuel cell electric vehicle
FTP	United States federal test procedure
GDP	gross domestic product
HBEFA	Handbook of emission factors
HC	hydrocarbons
HDV	heavy duty vehicle
HEV	hybrid electric vehicle
HFO	heavy fuel oil
HGV	heavy goods vehicle
IPCC	Intergovernmental panel on climate change

LDV	light duty vehicle
LPG	liquefied petroleum gas
MEET	Methodologies for estimating air pollutant emissions from transport
MOBILE	United States Environmental Protection Agency's mobile source emission factor model
MODEM	Modelling of emissions and consumption in urban areas
NG	natural gas
NH_3	ammonia
N_2O	nitrous oxide
NMVOC	non-methanic volatile organic compounds
NOx	nitrogen oxides
O/D	origin-destination
PAH	polycyclic aromatic hydrocarbons
PC	passenger car
PM	particulate matter
RME	rapeseed methyl ester
RVP	Reid vapour pressure
SOx	sulphur oxides
TWC	three way catalyst
UDC	European urban driving cycle (also called ECE 15)
UNECE	United Nations economic commission for Europe
VOC	volatile organic compounds

1. Introduction

The first real European initiative for developing emission inventory methods, beyond local initiatives taken by a number of laboratories or at the request of national authorities, was the *CORINAIR* working group on emission factors for calculating emissions from road traffic. The working group, comprising five experts on car emissions, began in 1987 with the aim of developing a methodology, including appropriate emission factors, for the estimation of vehicle emissions in the reference year 1985 [Eggleston *et al.* , 1989]. The methodology was transformed into a computer program (*COPERT*) which was used by many European Union (EU) countries. In 1991 the same group of experts proposed a revised set of emission factors to be used for the 1990 inventory, including a partial revision of the underlying methodology [Eggleston *et al.*, 1993]. As for the 1985 methodology, the results of this work were translated into a computer program - *COPERT 90* [Andrias *et al.*, 1993]. A new version of the model was developed in 1997 (*COPERT 2*). This makes use of interim results from the current research.

COPERT is now being used not only by EU Member States but also by most countries of Central and Eastern Europe. Moreover, *COPERT* is providing emission estimates for other international activities such as the Intergovernmental Panel on Climate Change (IPCC) and the European Modelling and Evaluation Program (EMEP) of the United Nations Economic Commission for Europe (UNECE) - see annex 1. In the corresponding guidebook [EEA, 1996] as well as in the IPCC guidelines [IPCC/OECD/IEA, 1997], methodologies for estimating national emissions from other transport modes are also included (aircraft, ships, rail).

During a similar period, a consortium of three European laboratories developed a modal model for estimating emissions from passenger cars called *MODEM*.. This model was based on new measurements performed using various specially developed driving cycles [Joumard *et al.*, 1995a]. In 1989 Germany, joined later by Switzerland and Austria, initiated a project to provide a new and comprehensive data base of emission factors [Infras, 1995]. For passenger cars, this was an attempt to combine the *COPERT* method based on average speed with a method based on instantaneous emissions [Hassel *et al.*, 1994]. For heavy vehicles, the model is based on the results of a vehicle-related model combined with engine emission maps [Hassel *et al.*, 1995].

The small number of researchers who took part in the *CORINAIR, MODEM*, and other national or multilateral projects, initiated a wider network of co-operation aimed at reviewing the available knowledge of traffic emissions in Europe. This co-operation was included in the wider framework of the *COST* program, and its results are presented here.

1.1. COST 319 objectives

In general terms, the estimation of transport-related emissions can be based on the equation $E = e . a$, where E is the amount of emission, e is the emission rate per unit of activity, and a is the amount of transport activity. This equation applies at every level, from a single engine to a whole fleet, and from a single road to the whole of Europe. In order to obtain an estimation with acceptable accuracy, the collaboration of a number of experts is required. Experts on traffic engineering are required to provide data on transport activity and on the nature and pattern of this activity, and experts on engine and vehicle emissions are required to provide emission rates which suit the transport patterns.

In addition, the method of estimating emissions must be used to assess various policy options by developing different complex scenarios. It is therefore likely that experts in fields other than those already mentioned would also be required during the whole evaluation process.

The overall objective of COST 319 was to co-ordinate European research activities relating to emissions of regulated and unregulated pollutants, fuel consumption, and energy use of transport. Specific objectives were:

- To analyse the methods used and the results obtained,
- To make a synthesis of the available data and to develop appropriate tools,
- To co-ordinate research.

For the first time the 4 transport modes (road, rail, air and sea) were considered together, as were all levels of calculation - from local and instantaneous emissions to a world-wide estimation.

1.2. Program of the COST 319 action

To fulfil these objectives, the *COST* 319 action "estimation of pollutant emissions from transport" was launched in May 1993 for a period of 4 years, later extended 5.5 years (i.e. until October 1998). The corresponding "Memorandum of Understanding" (see annex 2) was signed by 17 countries, including members and non-members of the European Union (Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, the Netherlands, Slovakia, Spain, Sweden, Switzerland and United Kingdom).

The wide field covered by the action, as well as the large number of experts involved (more than 80 from 24 countries), necessitated the formation of four main working groups, specialising in:

- *Road transport emission factors and functions*: quantification of emission rates per unit of activity and studies of the factors that influence them (engine maps, instantaneous vehicle emissions, hot and cold average vehicle emissions, evaporative emissions, alternative fuels, new vehicle technologies, life cycle emissions),

- *Road traffic characteristics*: the operation of the road transport sector and how it is affected by technical, social, policy and economic factors (traffic management, driving behaviour, traffic composition, factor analysis and models of mobility),
- *Road inventory tools*: study and evaluation of procedures to assess road transport's environmental impacts (bottom-up and top-down approaches),
- *Non-road transport*: emission factors, traffic characteristics and inventorying tools specific to non-road transport (rail, air, and water-borne transport).

Each main group has been further divided into 22 sub-groups which were required to meet when necessary. An animator supervised the work in each working group or sub-group (see annex 3), the meetings of which are listed in annex 4.

1.3. The MEET project

The financial support for the *COST* action is very low for carrying out comprehensive research. The studies assessed by the action were very numerous and were usually funded by national and international bodies. Much synthesis of work was required for compliance with the objectives of the action. A specific project partially covering the program of the action was carried out by 16 of the participants. The European Commission funded this project under the transport research and technological development program as part of the 4th framework program. The 3 main objectives of the project, called *Methodologies for Estimating Air Pollutant Emissions from Transport (MEET)*, were:

- To provide a set of data and models, allowing various users of the project to calculate the pollutant emissions and the fuel or energy consumption of the various transport modes at strategic level.
- To provide a comprehensive method of calculation using the set of data and models.
- To make sure that this comprehensive method corresponds to the requirements of the potential users in terms of accuracy, simplicity and input data availability.

The project has now been completed. It covers a large part of the action program, but does not cover the engine emission maps or transport analysis and models, and contains only written methodologies. No software packages have been developed.

1.4. Outputs

The results obtained were used to develop a set of methodologies for the calculation of emission which have been accepted by most of the European experts. The methodologies are presented in this report. The use of common methods to evaluate emissions and energy consumption levels all over Europe and possibly more widely will make the different studies and assessments comparable. Simultaneously the actions undertaken allowed the participating laboratories to compare and co-ordinate their research methods, and the European countries to co-ordinate their research programs in order to fill in the knowledge gaps.

For the COST 319 action, and the MEET project which is a part of it, a large number of reports were written, each of them being a synthesis of the European knowledge available, expressing a common opinion of the involved scientific circles. These reports, listed in the literature list at the end of this report, are summarised in section 3. They are readable on the web at http://www.inrets.fr/infos/cost319/index.html. The final inventory methodologies with all the necessary data concerning the emission factors and the traffic characteristics are presented in the final MEET report (see its publication data form in Annex 11). It allows any user to carry out an inventory.

The aims of the present report are quite different: it discusses the available data and their accuracy, and it presents the synthesis methods and the assumptions. It should be considered as a scientific report, especially useful for those interested in the building of methods of estimation of pollutant emissions from transport, rather than for users.

In addition, the report presents the scientific and user network, which can be used to contact European experts, and also the future research needs in the fields covered by the action.

1.5. Fields of application

The methods that have been developed for calculating pollutant emissions and are considered as state-of-the-art by the COST action, cover all possible applications and user needs. They range from calculations at a microscopic scale (i.e. for a single vehicle, or for a street) to a macroscopic calculation (i.e. regional, national and global levels) through the inventory of an urban transport network. In some cases, such as when calculating input emission data for a physio-chemical model, an absolute estimation of vehicle emissions is required. But in most applications, only a relative estimation is required - for example when comparing two traffic types, or when calculating the impact of traffic management or the emission evolution over the years.

Therefore, the state-of-the-art has been established for the various types of application. The applications can be categorised according to the level on which they operate and the transport mode considered. The types are:

- Disaggregated modal road transport models required for accurately assessing the impact of changes in vehicle speeds. A comparative and critical analysis of the available models has been performed.
- Base emission models for road transport which use a detailed fleet description, and take into account vehicle kinematics through the average speed. They are suitable for most of the recorded needs. A comprehensive model has been developed (MEET) and is presented in this report.
- Aggregated or simplified road models, corresponding mainly to macroscopic uses, are not detailed in this paper. Simplified models should be calculated by simple integration of the base model.
- Non-road models (air, rail, waterborne): a model is developed for each transport mode from currently available knowledge.

Therefore the field of application covered in this report is wide and is liable to be of interest to most specialists and experts in the transport-related emission field.

2. Scientific and user network

The first outcome of the COST action is the formation of a new or stronger co-operation between many European experts, whose outputs are presented later.

2.1. European expert network

The result of this co-operation was the establishment of a network comprising over 200 experts from Europe and, to a lesser extent, from non-European countries. The network therefore extends further than 17 signatory countries. Two types of expert are involved: specialists (generally researchers) in developing inventory methods for transport-related emissions (emission factors, traffic characteristics, models and tools), and inventory models users whose requirements have been analysed [Carrié & Noppe, 1997].

The specialists' network is listed by country in Annex 5. The list covers about 130 active members of the COST action who agreed to benefit from the mutual exchange of knowledge and results, either by participating in the working group sessions, by making available data or models, or by taking charge of synthesis work. Their spheres of activity are given in terms of the structure of the working groups listed in Annex 3, corresponding also to the structure of section 3 (scientific approach) of this report. This provides easily accessible information on most of the European researchers specialising in a given field.

The whole network is presented in Annex 6, where a distinction is made between active researchers and users, specifying their addresses, contact details, and the scientific field in which they are working.

2.2. Exchange of emission data

The first task of the network was to put together the knowledge, data, and results available in the European laboratories involved. A synthesis has been made and a set of inventory methods has been drawn up. This work is presented in section 3.

It soon became apparent that the available data were not homogeneous. This is not surprising since the data were obtained from various independent research projects carried out over a number of years. The aim of the present research was not to carry out measurement campaigns, but to analyse existing data and knowledge. The possibilities of analysis and synthesis were limited by the inconsistency of the data in terms of traffic characteristics (see section 3.2) and emission factors. In the latter case, the experimental conditions were often not available or were incomplete.

In order to avoid these problems during further exchanges of data, a minimum list of parameters to be measured and included in the data files has been proposed for all emission measurements relating to road vehicles (Annex 7). These are conventional parameters which can be easily obtained. They must be considered during the planning of the measurements and data files in order to make further co-operation between laboratories more useful.

3. Scientific approach

In addition to the measures taken for structuring the research studies, the working groups, and the data exchanges, the principal objective of this European co-operation was to assess the state of the art by reviewing all of the data and information available in Europe. This synthesis study was carried out by each working group under the control of a supervisor. Then, other experts in the particular field made critical observations either through bilateral exchanges or through more formal meetings (Annex 4).

The findings of each working group are presented in this report. The working groups are specified in the introduction and in Annex 3. This structure also corresponds closely to the structure of the MEET project, which cannot be dissociated from the COST action, at least from a scientific standpoint. Thus, each sub-section of this review corresponds to a MEET report or, for the few topics that were not considered in MEET, a COST report. For these reasons the name, address, and other contact details of the author of each section are mentioned at the beginning of this document. Each item, and the whole scientific approach adopted, have been agreed by all the active members of the action.

3.1. Road emission factors and functions

3.1.1. Engine emission maps and vehicle simulation models

By Olavi H. Koskinen and Robert Joumard

An engine map is primarily a research and development tool that allows engineers to characterize the fuel consumption and emissions of an engine. More recently, simple engine maps (like the ECE 13-mode test) have been used by legislators to determine the approved limits of emissions for engines of heavy duty vehicles.

An engine map can be used to assess pollutant emissions and fuel consumption on the basis of vehicle parameters which are distinct from engine parameters. It is necessary to review the advantages and disadvantages of using engine emission maps to determine emissions for vehicles rather than just for engines.

3.1.1.1 Description and availability of engine maps

Engine mapping occurs normally on test benches. Fuel consumption and emissions depend on the operational state of the engine, which can be presented on a 2-dimensional plane. One dimension is the engine speed and the other is the torque. The third dimension represents the fuel consumption or the emission rate [kg/h]. These can be represented as isocurves (surfaces of constant value) on the map. In general, the specific fuel consumption or emissions [g/kWh] are expressed as isocurves, but they can also be stated as constant flow rate [kg/h] values (see an example Figure 1). The latter approach is better suited to those cases where engine maps are used for vehicle motion simulation purposes (see next section).

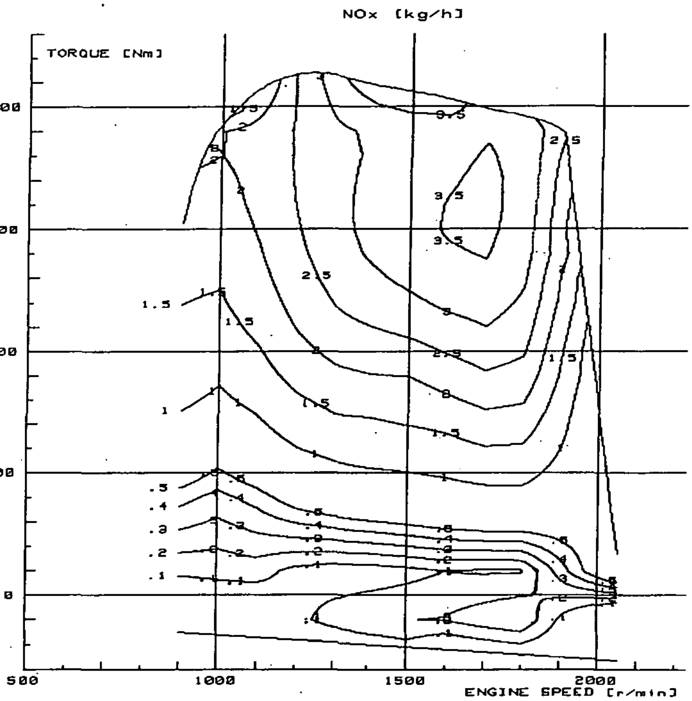

Figure 1: Example of NOx engine map in kg/h.

As a general definition of an engine map it can be said that it describes the fuel consumption and the emissions as functions of the engine speed and the engine torque. The denser the grid of measurement points, the better the accuracy of the engine map. A complete and accurate map requires tens of measurement points.

For the type approval of engines the following test types are of interest:

- stationary tests (e.g. ECE 13-mode test, see below new ECE test). Emissions are measured at different steady states for given engine speed and torque (load) values. A weighted average for the specific emission [g/kWh] is calculated, and this must not exceed the legislative value for each pollutant.
- emissions in transient cycles (e.g. US transient cycle, future ECE test). In this case average emissions during the cycle (bag values, integrated modal values) are evaluated, or instantaneous values are recorded.

These approval tests do not yield engine maps directly. In general, more measurement points and/or more work are required for proper engine mapping. Engine mapping using bench tests is quite time consuming because of the preparatory work required. Work can be reduced if the vehicle is tested on a chassis dynamometer. However, the accuracy of the results is not as good because power train losses must be estimated. This could be done at zero and full load with some assumptions, together with a linear interpolation for the intermediate loads.

Another problem concerning heavy duty vehicle measurements of this kind is that heavy-duty chassis dynamometers are very expensive and not widely available.

The present European legislation requires a set of steady-state tests: the specific emissions [g/kWh] of an engine for a heavy duty vehicle must not exceed certain values. These represent the weighted averages of 13 steady-state measurements conducted at two engine speed values and five engine load (torque) values, plus three measurements made at idle (i.e. there are 11 measurement points in total). This is called ECE 13-mode test. The authorities require the maximum values for the weighted averages, but not for the individual measurement points. In a few years the 13-mode test will be changed slightly: the total number of measurement points will remains at 13, but the test will cover three engine speed values and the load/torque values will be scattered. However, the new test will only be temporary, because after five years it is intended that a transient test will be introduced. The transient test will be similar to the one currently being used in the United States.

In order to accurately characterize the emissions from an engine, 11 or 13 measurement points are not sufficient. Additional points should be tested for research purposes.

During the period of the COST 319 action 48 engine maps became available, containing usually fuel consumption, CO, HC, NOx, CO_2 and particulate measurements. These covered:

- 9 passenger cars, either from the Neste Oil Company (FIN, mainly on vehicle bench), or from VTI (S)
- 39 heavy duty vehicles on engine bench, mainly from TÜV Rheinland (D), but also VTT (FIN), Neste Oil Company, Cummins (UK) and KTI (H).

In addition there are numerous data dealing only with the fuel consumption of heavy duty vehicle engines; they can be used for calculation the fuel consumption in different road and traffic conditions. But for emission calculations the number and the quality of the available engine maps are surely not enough, especially when it is the only way to assess emissions.

3.1.1.2. From engine maps to vehicle emissions

The use of engine maps for determining emission factors is particularly relevant for heavy duty vehicles. The first reason for this is that the same engine type is usually installed in a lot of vehicle types. In addition, the conditions under which they are operated - from motorways to bad forest roads or construction sites - differ from the conditions under which passenger vehicles are operated. This requires the consideration of various power transmission ratios, even for the same engine, and leads to an incredible number of combinations of engine/transmission ratios and vehicle type. Also, with the variation of vehicle mass from unloaded to fully loaded (e.g. a road train from 18 to 60 tons in some European countries), and with the variation in rolling and wind resistances due to the different number of axles and body shapes in use, such a wide a range of engine operation states exists that it is far too tedious and expensive to simulate them all on chassis dynamometers. The road gradient also plays a very important role (it is as important as the speed in terms of power consumption). Thus, vehicle mass, engine power, road slope, and vehicle speed are also strongly connected. Therefore consideration of road gradient would increase further the necessary number of direct measurements of vehicle emissions.

The most promising way of using engine maps is in combination with vehicle motion simulation. A vehicle with predefined technical characteristics is driven on a road that also has predefined characteristics. The way of driving is also defined and the output of the simulation can be used to derive engine speed and torque (load). Engine maps can be used to calculate instantaneous fuel consumption and emissions, and average values if necessary. As steady-state engine maps are usually used in the simulation models, it is assumed that the actual engine operating conditions (i.e. transient modes) are equivalent to a succession of steady-state modes. The differences (i.e. the influence of the dynamic driving behaviour) must be analysed in depth and taken into account in the development of the models. For instance, it was taken into account through empirically -derived correction functions by [Hassel, 1995]. Such work forms the basis of the assessment of emission factors for heavy duty vehicles (see section 3.1.7).

Even so, several vehicle simulation models also exist. These should be analysed, compared and validated. A validation under controlled conditions, such as on a chassis dynamometer, is necessary. When considering emissions from a vehicle, the engine-related information has to be adjusted to account for power train losses, road resistance, wind resistance (due to vehicle body size and shape), etc. Chassis dynamometer (= vehicle bench) tests can be used to measure the emissions of the whole vehicle according to very well defined boundary conditions. Such conditions include real-world driving cycles, vehicle loads, etc. On-board (or on-the-road) measurements can also deliver vehicle-related emission information, although the boundary conditions cannot be defined as accurately as they can for chassis dynamometer tests (especially with respect to the repeatability of test conditions). On the other hand, the representativity of the driving and environmental conditions is very good. This means that certain vehicles have to be tested on a chassis dynamometer, and that, in addition, their engines have to be measured on a stationary -as performed in [Infras, 1995]- or transient test bench. If possible, the same vehicles should also be tested on the road.

Driving resistance (wind resistance and rolling resistance) play a very important role in determining fuel consumption and emissions. The air resistance coefficient may vary widely from one vehicle type to another, especially for heavy-duty vehicles. A comprehensive contribution in this respect has been given by Hammarström (1998), who compiled a literature review on air resistance factors. His conclusion was that there are sufficient data for passenger cars, if data from manufacturers are accepted as representative. For other vehicle types the available data are not sufficient to estimate representative air resistance coefficient values, and consequently representative emission factors.

3.1.1.3 Conclusion and outlook

Because it is difficult to measure and analyse directly emissions from heavy-duty vehicles, and because many heavy-duty vehicles that have different body shapes and masses can be equipped with the same engine, emission and fuel consumption models based on engine-related emission data alone must be used. Therefore, it is essential to improve the database of engine emissions, including the transient state. This can be done by mapping the emissions from a large number of engines on test benches or, possibly from vehicles on chassis dynamometers (vehicle benches).

The next step will be to compile the available vehicle simulation models developed by the research laboratories and other bodies and experts in order to check their assumptions and methods of calculation. By comparing them methodological improvements will be possible. Subsequently, inter-comparisons will be made and the models will be validated (i.e. compared to vehicle bench or on-the-road emission measurements).

3.1.2. Instantaneous vehicle emissions

by Peter Sturm

At the moment the majority of road traffic emission estimates are based on average speed information. However, this is often not sufficient to characterise the emission level of real-world driving behaviour because any number of different driving situations with different dynamics and emissions can have more or less the same average speed. The introduction of additional parameters to describe driving dynamics, and hence emissions, may improve the quality of emission estimates in some circumstances -for example when the introduction of traffic calming measures results in changes in driving behaviour. For such purposes, instantaneous emission models can result in much more reliable estimates. In the context of the work described here "dynamics" refers to the severity of the driving cycle in terms the demand it imposes on the engine. A driving cycle having "high dynamics" would tend to include frequent gear changes and many rapid and prolonged accelerations and decelerations, whereas a cycle having "low dynamics" would be less severe.

Therefore, the COST 319 working group A2 "Instantaneous emissions" has dealt with the methodological aspects, applications, and possible improvements of the "instantaneous emission modelling" approach. This report is a summary and conclusion of work which was carried out in the frame work of the COST 319 action [Höglund, 1999] and mainly the MEET project [Sturm *et al.*, 1998].

To determine emissions from road traffic it is necessary to describe the emission behaviour of vehicles according to real-world driving behaviour. The approach adopted to obtain emission functions or factors varies.

One method is based on chassis dynamometer tests which are carried out using different driving patterns for an extensive number of vehicles. These driving patterns represent the driving behaviour for categorised driving situations on specific types of roads. The emission factors derived using this procedure are then taken to be representative for that certain driving situation.

The other approach uses instantaneous emission modelling (modal modelling). This means that emission quantities are recorded continuously during chassis dynamometer tests and stored in a two-dimension matrix as a function of vehicle (engine) load, defined by parameters such as velocity and acceleration. Having the two-dimensional emission matrix on the one hand, and recorded driving patterns (defined by analogous modal values of acceleration and speed) on the other, it is possible to calculate the emissions corresponding to different driving patterns. This technique of filling instantaneous emission records from an emission matrix, and mapping the latter with a driving pattern is called “modal modelling”. Using this methodology emission factors for statistically-derived driving patterns, as well as estimates of emission quantities for certain driving situations can be obtained.

3.1.2.1. *Instantaneous emissions approach (modal modelling)*

In what is termed "modal modelling" (or modal analysis) emissions are measured continuously at the exhaust during chassis dynamometer tests and stored at a particular time interval (usually every second). The operational condition of the vehicle - defined in current models by instantaneous driving speed and acceleration (calculated from the speed – time curve) - is recorded simultaneously with the emission rate. In this way, it is possible to generate emission functions by assigning exactly-defined emission values to particular operational conditions. For example, the emission function for each pollutant can be defined as a two-dimensional matrix, with the rows representing a velocity interval (in km/h units), and the columns being assigned to an interval of acceleration times velocity (in m^2/s^3 units). All instantaneous emission data are put into one cell of the emission matrix, according to the velocity and acceleration of the measured vehicle at that time. The emission function is the arithmetic mean of all emission quantities in each cell of the emission matrix. Hence, the emission function is stepwise and two-dimensional, assigning a mean emission level to every pair of velocity and acceleration values. Once such an emission matrix exists for a vehicle, it should then be possible to calculate emission amounts for any driving pattern which is defined as series of modal value-pairs of speed and acceleration.

3.1.2.2. *Differences between existing emission calculation methodologies*

The average speed approach is the commonly used method to estimate emissions from road traffic, e.g. COPERT II [Ahlvik *et al.*, 1997]. This approach is based on aggregated emission information for various driving patterns, whereby the driving patterns are represented by their mean speeds alone. All this information is put together according to vehicle technology, capacity class and model year and a speed dependent emission function is derived. This means that in addition to vehicle type, the average speed of the vehicle is the only decisive parameter used to estimate its emission rates. This restricts the approach to regional and national emission estimates. The dynamics of a driving pattern - which are especially important during urban driving - are only taken into account implicitly.

A comprehensive application of an instantaneous emission model was performed to establish the Emission Factor Workbook [Hassel *et al.*, 1994; Keller *et al.*, 1995]. Real world driving behaviour was recorded on the road. From recorded real-world driving behaviour, representative "real-world" driving patterns were derived by statistical means. Using emission functions based on continuous emission measurements from various chassis dynamometer tests, emission factors for real-world driving patterns were derived. The parameters used in the Workbook to calculate emissions are a qualitative description of the road and traffic situation combined with quantitative information concerning the cycle dynamics (e.g. inner-city stop and go behaviour; the mean velocity would be 5 km/h), rather than the average speed of that specific driving profile.

In general, emission factors serve to describe the emission behaviour of vehicles in those road networks where the traffic is densest. For local traffic, this naturally refers to the main street traffic. It is not the aim of emission factors to estimate emissions when the driving behaviour is quite different from that from which the emission factors are derived (e.g. within specific road sections, crossings, etc.). This belongs to the field of instantaneous emission models, whereby it should be possible to calculate emissions even when small changes in driving behaviour have to be taken into account.

3.1.2.3. Methodological aspects and discussion of the instantaneous emission approach

The use of arithmetical models based on modal emission data should make the calculation of emissions for real-world driving conditions possible. However, since a great number of different vehicle categories are to be found in road traffic - differentiated by engine type, engine capacity, model year, etc. -, the corresponding information must be available for all of them.

Indeed, modal emission data are currently available for a great number of private motor vehicles [Hassel *et al.*, 1995; Joumard *et al.*, 1995a; BUWAL, 1994; Reiter, 1997]. These data records have mostly been generated on chassis dynamometers using special driving cycles. Parameter studies with these data are restricted, since legislative driving patterns are used, and details regarding emissions relating to actual driving behaviour are missing, or vice-versa

Since restrictions are encountered when obtaining the basic emissions data set , the extent to which the emission data, and the models developed from the data, are applicable must be clarified. For this purpose, studies were carried out to systematically investigate the following parameters:

- The influence of the measurement set-up
- The influence of measurement programme
- The influence of model parameters

The nature of the measurement set-up and vehicle sample used for testing result in uncertainties which are typical of all methodological approaches, and which influence the quality of emission estimates for standard (average speed) approaches as well as for instantaneous ones. The measurement program for creating the emission matrices seems to have the biggest influence on the quality and usability of instantaneous emission data. Therefore, the investigations focussed mainly on the selection of appropriate driving patterns for the chassis dynamometer tests used to generate instantaneous emission values, and also on the application range of currently available emission data and models.

3.1.2.4. Application range of currently available emission data and models

The investigations were mainly based on gasoline vehicles equipped with a three-way catalyst and diesel cars (model years 1992 to 1994). At the moment, only hot emissions can be calculated using instantaneous emission models. The following conclusions arose from the work:

- All the calculations made in this report show that the quality of the emission matrix used (i.e. which driving patterns were used to generate the emission data) plays an important role. For many applications the uncertainty of the emission estimation is in the range of ±10 to 20 %.

- The use of instantaneous emission approaches (modal modelling) is recommended when emissions have to be estimated in situations where driving behaviour and dynamics are of major interest. Standard average speed models are not appropriate for such tasks.
- However, it has also been shown that for single applications (particular driving cycles) the uncertainty is much higher, and it is even possible for an instantaneous emission model to predict wrong trends when evaluating measures which result in minor alterations to driving behaviour. For such applications the predicted changes in emissions must be significant to be reliable. If this is the case it can be expected that at least the indicated trend is reliable.
- During highly dynamic real-world driving cycles all vehicles had high CO and HC emissions. The use of emission information derived using legislative cycles resulted in low values in the emission matrix, and therefore caused a remarkable underestimation of the emissions over real-world driving cycles.
- When using modal modelling certain requirements must be met when constructing the emission database (emission matrix).
- In the case of real-world driving cycles it turned out to be imperative to include emission data from such cycles in the emission matrices, or to exclude data from legislative cycles.
- The generation of emission matrices has to be based on driving cycles which cover the whole region of relevant emission matrix cells.
- The cycle dynamics, which are implicitly taken into account when creating the emission matrix, have to be similar to those in the real-world driving pattern for which the emission estimate is being made. This means that an additional parameter (in addition to modal values of acceleration and velocity) has to be taken into account to describe the dynamics of such a driving pattern.

In the near future the task will be to improve instantaneous emission models by introducing an additional parameter to classify the driving dynamics and to assign it to proper emission matrices. The basic idea is to develop emission matrices which fulfil the requirements of normal driving behaviour, and special functions for high and low dynamic situations. However, at the moment it is not clear how to define the dynamics as an additional parameter. Due to the different engine management concepts and gear-shift philosophies, which are adapted and specific to each model, it will be difficult to develop a universally applicable estimation of emissions based solely on the dynamics of the driving pattern (e.g. engine enrichment functions for 3-way catalyst).

Which calculation methodology is the most appropriate depends upon the application. For the majority of applications emission factors will allow emission estimates with sufficient accuracy. But there are certain application ranges were driving dynamics plays an important role and emission changes due to changes in driving dynamics have to be estimated (e.g. traffic calming). In such cases the use of instantaneous emission models will lead to more reliable results, not necessarily in the quantitative way but qualitatively (trend). However, at present the changes in driving behaviour have to be significant if reliable results for the emission estimates are to be obtained.

3.1.3. Average hot emission factors for passenger cars and light duty trucks

by Zissis Samaras and Leonidas Ntziachristos

This part of the report focuses on the production of hot emission factors which can be considered representative for large scale road traffic applications. It was carried out in the frame of the MEET project and the COST 319 action, which has made available a large number of emission measurements to MEET: see the whole report in [Samaras & Ntziachristos, 1998]. The objectives of the specific task were:

- to collect European hot start emission data measured as average (bag) values for passenger cars (PCs) and light duty vehicles (LDVs) over a number of different driving cycles
- to analyse these raw data and process them in order to understand the main parameters which explain the variation of emissions
- to build emissions sub-models specific for different vehicle categories.

The final product should be harmonised with the CORINAIR/COPERT activity of the European Environment Agency (see Annex 1). Then, it has been decided that it should fully adopt the methodology developed by MEET for the Road Transport sector. To meet this aim, emission factors dependent only on average speed were thought as constituting the best approach. This expression of the emission factors is considered to be sufficient for calculating total emissions for a relatively low spatial and temporal resolution (e.g. city over a day) and requires a low degree of input information. However, emissions of finer resolution, or the influence of driving dynamics on emissions described by the modal approach discussed in section 3.1.2, cannot be modelled using this approach.

Speed dependent hot emission factors presented in [Samaras & Ntziachristos, 1998] correspond only to PCs and LDVs falling in the following vehicle categories:

- Gasoline PCs complying with EURO I (91/441/EEC) emission standards
- Diesel PCs complying with EURO I (91/441/EEC & 88/436/EEC and US83) emission standards
- Conventional Gasoline LDVs
- Conventional Diesel LDVs
- Gasoline LDVs complying with EURO I (93/59/EEC) emission standards
- Diesel LDVs complying with EURO I (93/59/EEC) emission standards

In order to provide a consistent set of emission factors covering all categories, conventional fuel types and emission control technologies for four-wheel vehicles, emission factors developed in the frame of MEET are combined with those developed in earlier programmes (e.g. COPERT 90). Thus, the set of emission factors presented in the Report enables the potential user to calculate emissions from all gasoline, diesel or LPG PCs and LDVs from the introduction of the first ECE Directive (1971) and on.

Only the so called conventional pollutants are covered (CO, NOx, HC, CO_2). Non regulated pollutants (such as NH_3, N_2O, PAHs, CH_4, NMVOC species, etc.) have not been treated because of the lack of available data. Moreover, fuel consumption has been derived based on the carbon balance between tailpipe emissions and engine-in conditions. All emission and consumption factors are expressed in g/km.

3.1.3.1. Vehicle sample and driving cycles

A database was created including emission data from PCs and LDVs tested in the following laboratories:

- EMPA, Switzerland: data from the Swiss/German project for the production of representative emission factors
- INRETS, France: data from various national and international projects
- LAT/AUTh, Greece: data from an international project
- MTC, Sweden: data from various national projects, specifically compiled for this purpose
- TNO, the Netherlands: data from national and international projects
- TRL, United Kingdom: data from national and international projects
- TUG, Austria: data from a national project
- TÜV Rheinland, Germany: data from national and international projects.

A total of 2522 vehicles, and the results from 9039 emission tests conducted over several cycles, are included in the database. Only the data corresponding to cycles not used in vehicle type approval were used in order to avoid possible emission underestimation due to the low driving dynamics of legislative cycles. Thus, the emission factors are considered to originate from real-world representative cycles developed by different laboratories to describe actual driving situations in the corresponding countries. In this respect, results have been obtained over 41 different real-world cycles covering an average speed range of 5.2 km/h to 130 km/h. Moreover, vehicles not randomly selected (e.g. high emitters from remote sensing tests) were excluded so as not to bias the representativity of the sample. Figure 2 presents the number of vehicles and the respective number of measurements conducted over real world cycles by each laboratory.

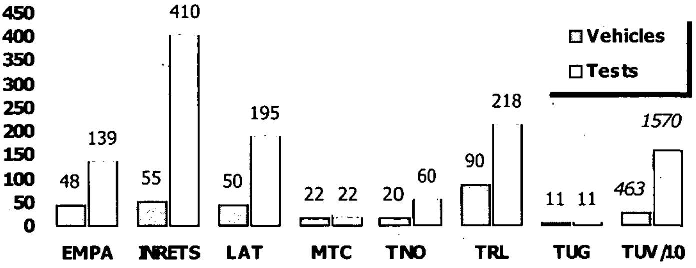

Figure 2: Number of vehicles and respective tests in real-world cycles (for acronyms see bullet list above).

Based on the previous criteria, the data used for the production of the emission factors include results from 2164 emission tests on gasoline PCs, 313 tests on diesel PCs, 62 tests on gasoline LDVs and 74 tests on diesel LDVs. 82% of gasoline PCs comply with Directive 91/441/EEC while almost equal numbers of tests on diesels fall under ECE1504 and again 91/441/EEC. The remaining vehicles are distributed according to different emission standards, with a few of them complying with Directive 94/12/EEC but not in sufficient numbers to derive emission factors for this vehicle category. Table 1 summarises the number of PCs and LDVs and respective measurements over real world cycles included in the database. The classification is based on the fuel used (gasoline, diesel) and compliance with the respective emission regulations. Vehicles of the pre EURO category comply either with the ECE 150x regulations or with the intermediate "Improved Conventional" and "Open Loop" technological levels.

Table 1: Summary of vehicles and tests in real world cycles included in the database.

Category	Gasoline PCs		Diesel PCs		Gasoline LDVs		Diesel LDVs	
	Vehicles	*Tests*	Vehicles	*Tests*	Vehicles	*Tests*	Vehicles	*Tests*
pre EURO	182	*455*	39	*179*	16	*26*	20	*50*
EURO I	399	*1766*	55	*128*	19	*36*	15	*24*
EURO II	8	*24*	2	*6*	0	*0*	0	*0*

3.1.3.2. Methodology

Emission functions relating to average speed were obtained by first plotting the individual emission measurements conducted over different cycles vs. the average speed of the cycle. Then, the best-fitting curve was drawn to correlate emissions with speed. Based on the distribution of the emissions, binomial regression analysis was applied to give the best correlation coefficients. The different steps and decisions taken during the production of the emission factors included:

- An attempt to improve the correlation coefficients by distinguishing between different speed regions, which would potentially be described by different equations, had no effect except for CO_2. In the case of CO_2, and consequently fuel consumption, a discrete change in the emission (consumption) behaviour was found below the region of 13 km/h and was described by a different equation.
- No distinction was made between early catalyst PCs and more recent ones, since initial studies gave no distinct differentiation between such vehicles.
- The split between the three different engine capacity classes (i.e. ≤ 1.4 l, 1.4 to 2.0 l and > 2.0 l) was kept for EURO I cars, with different emission factor equations for each of the three capacity classes. This has been done for compatibility reasons with the CORINAIR/COPERT methodology.
- It was not possible to make any distinction between engine capacity classes for the diesel passenger cars. This was also the result of the small available sample of these vehicles.
- It was not possible to differentiate LDVs by weight. Therefore it was decided to provide equations for all LDVs of a weight less than 3.5 tonnes.

Some of the decisions taken are considered only as compromises imposed by the limited sample, especially for LDVs. Therefore they should be reconsidered and possibly revised if future relevant studies are based on a more consistent and complete data set.

3.1.3.3. Analysis of the results

Low correlation coefficients were observed for most of the emission curves, despite the efforts to provide emission factors in close correlation with the individual measurements. This implied that there were large inconsistencies between the sample values which were probably induced by parameters other than those selected for the classification of the vehicles. Therefore, an analysis of the available sample was conducted to reveal if significant differences existed between vehicles meeting different criteria. Specifically, the effect on emissions of engine size, the total mileage driven, and the laboratory conducting the emission test was studied to see if such parameters can be considered responsible for discrepancies in the data.

The analysis was mainly based on legislative cycles, over which a large number of vehicles have been measured. It is assumed that the parameters listed above will have an equal impact on emissions over both legislative and real-world cycles.

This analysis did produce conclusive results because large gaps existed in the data between the different classes, and the sample was not specifically compiled for the purposes of such activity. However, definite trends were observed, and these can be summarised as follows:

- Large differences in the average emissions resulted from measurements carried out in different laboratories, even in the case of legislative cycles. At maximum, a factor of 3.5 was found between the upper and the lower average emission level between samples of vehicles with similar characteristics, as measured by different laboratories. Such discrepancies can either be the result of differences in the testing conditions (including driving cycles) or just reflect the overall condition of the laboratories national vehicle populations.
- Mileage had a significant effect on emissions for all pollutants other than CO_2, especially in the case of legislative cycles. To a large extent, the high dispersion of emission rates, which is responsible for the low correlation of the emission factors, can be attributed to the effect of mileage. Differences in average emissions from samples with different mileage classes was as great as a factor of 5.
- The effect of engine capacity was not that evident, as might have been expected for CO, NOx and HC. No consistent variation in emissions with engine capacity was found in case of the UDC and EUDC, with only a minor variation about an average value. Moreover, emissions of the above pollutants over real world cycles were also found to be at the same level for all capacity classes, if the vehicles fell into the same mileage class.

3.1.3.4. Mileage effect

The observation that mileage has a significant effect on average sample and, consequently, fleet emissions led to the need to correct the proposed emission factors according to mileage. The quantification of mileage effect on emissions will help the potential user to the following:

- To accurately compare emissions from European countries with different average fleet age. The total mileage driven in the life of the vehicles differs between countries and this should be taken into account.
- To provide information for the evolution of emissions for different fleet renewal scenarios. The promotion of fiscal incentives for the replacement of older vehicles is a widespread strategy in European countries and its effectiveness should also be seen in the light of mean fleet mileage reduction.
- To make possible emission predictions based on the current fleet composition.

The problem associated with such an approach is that although the increase in emissions with mileage is obvious, the increase is different at different speeds, probably because the mileage effect is also dependent on average speed. This has led to the decision to provide a partial speed-dependent mileage correction for the emission factors, based on the emission degradation observed over the UDC and the EUDC, with respective speeds of 19 km/h and 63 km/h. Initially, the emission degradation over these cycles was quantified. Then, the emission degradation proposed for a specific mileage and for the speed region lower than 19 km/h was considered to be equal to the one over the UDC and equal to that over the EUDC for the region higher than 63 km/h. A linear interpolation between the degradation values corresponding to those two cycles was proposed for the intermediate speed region to provide a continuous emission degradation correction over the whole speed range.

However, the original emission factors proposed in the first part of the report should be used to calculate emissions from different national fleets. Correction for mileage should only be applied to compare relative trends, as is demonstrated by the bullet list in this paragraph. It is interesting to note that emissions seem to stabilise after a mileage point which can be defined in the region of 120 000 km. Based on the method developed, emissions are predicted to be up to 3 times higher than the original values for vehicles having travelled for more than 120 000 km.

3.1.3.5. The effect of "external" parameters

The effects of ambient temperature and cabin air-conditioning on emissions were also studied. The application of the hot emission factors in European countries having a different yearly average temperature might require correction. The data showed an increase in emissions as ambient temperature reduced (down to -20 °C), but the increase did not occur in a consistent way for different vehicles. However, linear correlation showed that average emissions increase up to 108 % between -20°C and 22.5 °C in the case of CO emissions over the stabilisation phase of the FTP 75 cycle. Thus, linear equations independent of speed were proposed for CO, NOx and HC. These may be used to show the relative effect of ambient temperature on emissions.

Moreover, the increasing penetration of air-conditioned vehicles into the new car market provides a potential risk to accurate estimation of fleet emissions if its effect is neglected. Data collected over the EUDC with and without the air-conditioning in operation were compared for 12 gasoline and 12 diesel PCs. In both cases, CO_2 emissions seem consistently to increase by about 20% when the air-conditioning was operating. All other emissions from gasoline vehicles increased but not in a consistent way, whilst CO and HC emissions from diesel vehicles actually decreased. Although air-conditioning operation results in differentiation of hot emissions, any correction is subject to the limitations imposed by the large scatter in the data.

3.1.4. Start emissions

by Robert Joumard, Eric Sérié and John Hickman

Excess start emissions are an important part an emission inventory model for two principal reasons. Firstly, the average trip length of passenger cars in Europe is about 5 to 8 km [Laurikko *et al.*, 1995; André *et al.*, 1999], whereas urban trips are even shorter (2 to 4 km). Consequently, a high proportion of mileage is driven under cold start conditions. Secondly, the engine temperature affects the emission rate, and the ratio of cold start emissions to hot start emissions has been shown to vary between around 1 and 16 according to the vehicle technology, the pollutant, and other parameters [Joumard *et al.*, 1995b].

The methodology developed previously in Europe for calculating cold start emissions was based on a very small set of measurements. The approach was to introduce a relative cold start emission factor (cold/hot emission ratio) which was dependent upon ambient temperature and trip length (CORINAIR/COPERT: Eggleston *et al.*, 1993), as well as parking time and average speed (HBEFA: Infras, 1995). The present model is also empirical and is based upon available data (see the full report: Sérié & Joumard, 1997).

3.1.4.1. Data

In January 1994 39 European laboratories studying vehicles emissions were asked to supply data obtained under cold start conditions. We obtained original data from INRETS (France - see Joumard *et al.*, 1995b), LAT (Greece), TNO (The Netherlands - see TNO, 1993), TRL (England), TÜV Rheinland (Germany - see Hassel *et al.*, 1994). The data related to gasoline cars with and without a 3-way catalyst, and diesel cars with and without an oxidation catalyst. The parameters of interest were test vehicle type and characteristics, driving cycle, ambient temperature, start condition, and emissions. Emission measurements were taken with each vehicle being driven from both cold start and hot start over the same cycle. For each vehicle, 3 types of cold and hot cycles were followed: standardised cycles (ECE15, FTP 72-1), short Inrets cycles (nearly 200 sec long, repeated 15 times), and long TRL cycles.

If a single measurement is defined as one made with a vehicle operated over the same cycle from both a hot and cold start, irrespective of the pollutants measured, the total number of measurements obtained was 2568. This total comprised 460 gasoline cars without a catalyst, 1784 gasoline cars with a catalyst, 315 diesel cars without a catalyst, and 9 diesel cars with a catalyst. At each test laboratory, all the vehicles were selected so that the distribution was representative, to some extent, of the fleet composition in the country: the whole sample can therefore be considered to be representative of the whole European fleet.

Most measurements were carried out within the temperature range 13.0 to 19.6 °C. Data measured at different ambient temperatures (-9 to 26 °C) were used to assess the influence of ambient temperature on cold start emissions.

The data from different studies showed a large amount of variation. Before analysis, it was necessary to standardise the data in two ways. Firstly, a large number of measurements had been obtained using FTP cycles (with non representative conditions), and a small number of measurements had been obtained using representative real-world driving cycles. Excess cold start emissions obtained during real-world driving cycles were therefore standardised by adjusting the measured values according to how far they deviated from measurements made over the FTP cycle. Secondly, because at the end of a standard cycle the engine is not always hot, a light adjustment was made for each pollutant.

3.1.4.2. Influence of various parameters

Excess emissions as a function of the cycle speed - Emissions were measured at different cycle speeds just using the Inrets short representative cycles. A linear regression was applied in order to determine the excess emission [g] as a function (f(V)) of the average speed V [km/h]. It should be noted that the regression was calculated using only three data points, with each point corresponding to an average of ten measurements.

Excess emissions as a function of ambient temperature - In order to assess the influence of ambient temperature, only the data obtained over complete cold starts (i.e. when the engine start temperature corresponds to the ambient temperature) were used. The data were very scattered. An example of CO emissions from catalyst-equipped cars is shown in Figure 3. A linear relationship g(T) was established between the excess emission (g) and the ambient temperature T. A good correlation was not observed between emissions of CO_2 and NOx and ambient temperature for gasoline cars, and g(T) was thus assumed to be constant. These results are comparable to those found by Lenner (1994) and Joumard *et al.* (1990). Concerning CO, HC, and FC, a reasonable correlation was found, and it could be seen that, in most cases, the increase in excess emission corresponded to a decrease in ambient temperature.

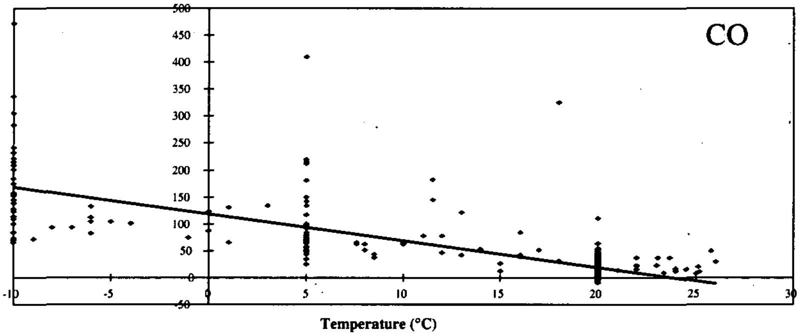

Figure 3: Excess emissions of CO (g) as a function of ambient temperature for gasoline cars with a catalyst. A point represents a data and the line the regression curve associated to these data.

Excess emissions as a function of distance travelled - So far, absolute excess emissions have only been modelled during the whole cold start period (i.e. over the distance required for the stabilisation of emissions). But if the distance travelled is lower than this cold start distance, excess emissions are lower. In order to determine the relationship between excess emissions and distance, the cold start distance d_c was calculated as a function of vehicle speed, technology, temperature and the studied pollutant [Joumard *et al.*, 1995b] . The distance travelled was then made dimensionless by dividing it by the calculated cold start distance, and the equation describing excess emissions was determined as a function of the distance travelled.

From the only three measurement points available, the functions were obtained by linear regression. Thus, if the travelled distance was higher than d_c then the excess emission was equal to the calculated one in previous sections. Otherwise, it was necessary to calculate the excess emission as a function of the distance travelled d, which had been made dimensionless by dividing it by the cold start distance d_c ($\delta=d/d_c$). We proposed one equation per pollutant and per vehicle technology.

3.1.4.3. Calculation method for light-duty vehicles

Using the aforementioned methods, the excess start emission for gasoline cars and for diesel cars without catalysts could be expressed in terms of the mean speed - f(V), the ambient temperature - g(T), and the travelled distance - h(δ). The parameters f and g could be combined by either multiplicative or additive extrapolation. The main drawback of multiplicative extrapolation is error multiplication. Additive extrapolation was therefore preferred so that the total errors were minimised. This assumption was necessary because no cross-distribution value for these two variables has been made available. The excess emission in g could then be expressed as:

$$\text{excess emission} = \omega \cdot [f(V)+g(T)-1] \cdot h(\delta), \text{ with } h(\delta)=\left[1-\exp(-a \cdot d/d_c(V))\right]/(1-\exp(-a))$$

where f and g are undimensionalised by their values at 20 °C and 20 km/h, h is dimensionless and ω is the total reference excess emission (at 20 °C and 20 km/h) expressed in g.

For diesel cars equipped with an oxidation catalyst and light-duty vehicles, the model has been greatly simplified.

Excess emissions for trips starting with the engine at an intermediate temperature - The results of the DRIVE-MODEM and Hyzem studies [André *et al.*, 1999] showed that only 19% of trips are actually started with a completely cold engine (i.e. with the engine temperature equalling the ambient temperature), and about two fifths are started with the engine temperature lying between ambient temperature and the normal operational engine temperature (70°C). It has been assumed that excess emissions are not dependent on ambient temperature, but on engine temperature at start-up, or in other words that excess emissions for an intermediate engine temperature are equivalent to excess emissions from a completely cold start at an ambient temperature equalling the intermediate temperature. This amounts to considering that the parameter T above corresponds to engine temperature at start-up rather than to ambient temperature.

Inventory of cold-start-related excess emissions - In a number of cases (e.g. for some micro -scale inventories) assessing excess cold start emissions for a single trip is sufficient. However, most emission inventories require a calculation of cold start emissions for the whole traffic. The formula initially applied to a single trip must be extended to the whole traffic using the available statistical data relating to characteristic traffic parameters (see section 3.2.2). The proportion (in kilometres) of the distance travelled on trips started with a fully warmed-up engine (i.e. not including cold start emissions) must be determined. This percentage depends on the season and the global average speed [André *et al.*, 1999].

In a second step, only trips started under cold or intermediate engine temperature conditions were considered. The formula given above was applied to these trips. A relationship was established between the variables above and the input variables of the general emission model:

- average speed distribution under cold conditions versus overall average speed,
- distribution of engine start-up temperature (in number of trips) versus ambient temperature class,
- cold start trip distribution versus trip length. Such a distribution depends both on average speed with a cold engine and on the season.

Finally the traffic excess emission E_c for a given pollutant (in g) was calculated using:

$$E_c = \sum_i \left(tf_i \cdot \frac{cm(s,\ v_i)}{100} \cdot \omega_i \cdot \sum_j \sum_k \sum_m \left[\frac{p_j \cdot p_k \cdot p_m}{10^6 \cdot d_m} \cdot \left(f(V_j) + g(T_k) - 1\right) \cdot h\left(\frac{d_m}{d_c(V_j)} \right) \right] \right)$$

where tf_i, v_i, i and s are external data, and other parameters correspond to model internal data:

tf_i = traffic flow for the studied vehicle type i (in km.veh)

v_i = traffic overall average speed for the studied vehicle type i (km/h)

i = vehicle type

s = season (winter, summer, middle)

cm (s, v_i) = percentage of mileage recorded under cold start or intermediate temperature conditions for season s and overall speed v_i (%)

ω_i = reference excess emission for vehicle type i (g)

j = speed class with a cold engine

k = class of start-up engine temperature

m = trip length class

p_j = percentage of the trips travelled at speed j with a cold engine, for the overall average speed considered (%)

p_k = percentage of the trips travelled with a start-up engine temperature T_k (%)

p_m = percentage of trips started with a cold engine and distance d_m, for speed V_j with a cold engine (%)

d_m = average distance of the trips under cold start conditions of class m (km)

V_j = average speed with a cold engine corresponding to class j (km/h)

T_k = average start-up temperature of class k (°C)

f, g, h and d_c are functions defined above.

3.1.4.4. Heavy goods vehicles and buses

There are very few relevant data for this type of vehicle. Nevertheless, it is possible to give a rough estimate of their excess emissions based on the analysis of results from tests on ten heavy duty engines using the US heavy-duty transient tests cycle [Kurtul & Graham, 1992]. Tests were carried out with a cold engine (approximately 20 °C start temperature) and repeated with a hot start. The coolant temperature was usually found to reach the hot start value around 600 - 800 seconds after a cold start. The total test duration was 1200 sec. It may therefore be assumed that the tests included the whole of the cold start period, and that the difference between the emission from the hot and cold tests gave a measure of the cold excess emission. Because the measurements only used one operating cycle and were only performed at one ambient temperature, it was not possible to determine whether the excess emission was affected by these parameters, as it is for passenger cars. The influence of the engine or vehicle size was calculated and only found to be systematic for CO_2 and NOx. The results of this exercise were excess emissions in grammes per cold start for the main regulated pollutants and the four classes of HGV used in the MEET classification system.

Due to the lack of operational data for HGVs, and the frequency of cold starts, it has been assumed that each vehicle makes, on average, just one cold start per day. This assumption is made on the basis that the commercial use of HGVs is likely to mean that they are started from cold at the beginning of each working day, and then used throughout the day without being stopped for long enough for their engines to cool down significantly.

Buses and coaches are powered by the same diesel engines as HGVs. The cold excess emissions may therefore be assumed to be the same as for HGVs of the same weight class. Whilst there are significant variation in the weights of buses and coaches, depending on their size and seating capacity, the most common weight class is probably 16 to 32 t. In the absence of precise information, it can again be assumed that each vehicle makes just one cold start per day.

3.1.4.5. Conclusion

This model can be applied on different geographic scales: on a macroscopic scale (national inventories) using road traffic indicators and temperature statistics, or on a microscopic scale for one vehicle and one trip. Where a model user cannot access the necessary statistics, it is recommended that statistics recorded at national level are integrated into the model in order to further the model use and obtain a national average excess emission directly.

In the future, this model could be improved by using new data as soon as it becomes available, by considering crossed distributions for different speeds and ambient temperatures, and by considering intermediate engine temperatures - i.e. when engine start temperature does not correspond to ambient temperature ("cool starts").

3.1.5. Evaporative emissions

By Zissis Samaras and Rudolf C. Rijkeboer

Evaporative emissions occur as a result of fuel volatility combined with the variation in the ambient temperature during a 24-hour period or the temperature changes in the vehicle's fuel system which occur during normal driving.

In general there are four types of evaporative losses:

- Filling losses occur when the vehicle's fuel tank is filled and the contents of saturated vapours are displaced and usually vented to the atmosphere.
- Diurnal breathing losses are the result of the night-day temperature cycle, causing the contents of the fuel tank to expand, pushing saturated vapour out on expansion.

- Hot soak losses occur when a vehicle is switched off and the equalisation of the temperatures leads to the evaporation of the fuel in certain parts of the engine.
- Running losses. These evaporative losses occur during the operation of the vehicle.

Filling losses are usually attributed to the fuel handling chain and not to the vehicle emissions. They are not covered by this study. Hot soak and diurnal losses constitute the main part of evaporative losses. In newer vehicles these losses should largely be captured by vapour traps (carbon canisters). Depending on the temperature of the engine at switch off, one can differentiate between warm-soak and hot-soak losses. For a short period plastic fuel tanks were introduced. However, these suffered from diffusion of fuel through the plastic, and in later years covered plastics (so called "sealed" plastic tanks) were used for fuel tanks to counteract this effect. Running losses are the least documented source of evaporative emissions. On cars equipped with carbon canisters the canister should capture any running losses but there are reports which show that running losses would occur nevertheless. On vehicles without carbon canisters running losses are a reality, but little is known about such cases. Evaporative losses from vehicles are known to depend on four major factors:

- vehicle technology (equipped with or not with carbon canisters)
- ambient temperature and its diurnal variation
- gasoline volatility (depending on the temperature variation)
- driving conditions (average trip length, parking time etc.)

The effects of these factors on evaporative emissions were the subject of a number of research studies. The first study at European level was carried out by CONCAWE in 1985. The results from this project formed the basis of a more sophisticated methodology developed in the framework of CORINAIR. An updated methodology was proposed in 1990 by CONCAWE [McArragher *et al.*, 1987; Concawe 1988, 1990] and was incorporated in the CORINAIR methodology of 1993 [Eggleston *et al.*, 1993] and included in the COPERT programme. A methodology was also developed by RWTÜV [1993] based on a specifically designed test programme and was included in the German/Swiss Emission Factor Handbook [Infras, 1995].

Another methodology, called MOBILE 5a [USEPA, 1991], was also developed by the U.S. Environmental Protection Agency. MOBILE incorporates a more detailed procedure for the estimation of evaporative losses. Nevertheless, this methodology was developed taking into account all special characteristics of the vehicle fleet of the United States and requires a number of appropriate modifications for its application in European conditions.

3.1.5.1. Comparison between the CORINAIR, CONCAWE and German/Swiss methodologies

Table 2 summarises the options available in the three methods for estimating evaporative emissions. CORINAIR distinguishes between warm and hot (concerning soak and running losses) emissions, and provides appropriate equations for the estimation of all types of evaporative emissions. CONCAWE provides more aggregated expressions than CORINAIR for the estimation of hot soak and running losses. Finally, RWTÜV for the estimation of diurnal and hot soak emissions, takes into account regional driving and climatic characteristics.

Table 2: Proposed options in evaporative emission estimation.

Motor Vehicle Evaporative Losses	Methodologies		
	CORINAIR	CONCAWE	RWTÜV
Diurnal	✓	×	✓
Hot Soak	✓	✓	✓
Warm Soak	✓	×	✓
Hot Running	✓	✓	×
Warm Running	✓	×	×

(✓ = calculation method available, × = calculation method not available)

Since the CONCAWE and CORINAIR methods are very similar, the comparison was just performed between CORINAIR and German/Swiss Handbook. This showed that:

- The estimated total evaporative emissions do not vary significantly, especially, when CORINAIR running losses are left out. Nevertheless, significant differences are observed between the specified evaporative emissions types, especially where the variation of fuel volatility affects the evaporative emissions (CORINAIR method) in contrast with RWTÜV, in which the Reid vapour pressure (RVP) does not (directly) influence the emission estimation.
- The efficiency of the evaporative control system in all cases varies between 90% and 99% except in the cases of diurnal emissions estimated according to the CORINAIR method, where an 80% efficiency of the carbon canister is introduced.
- In order to understand the differences between the three methods, it has to be stressed that:
- CORINAIR methodology enables the estimation of diurnal, hot soak and running evaporative losses, while CONCAWE provides appropriate expressions for hot soak and running losses calculations and RWTÜV for diurnal and hot soak emissions.
- The evaporation control system exercises the most important influence on evaporative emissions. The evaporative control system efficiency depends on fuel properties or ambient temperature variation (CORINAIR and CONCAWE hot soak emissions, RWTÜV diurnal losses), or on driving conditions (RWTÜV hot soak emissions) or an overall control system efficiency is assumed irrespective of RVP or temperature properties (CORINAIR diurnal and running losses).
- CORINAIR provides the same expressions as CONCAWE for hot soak and running losses. CORINAIR also provides a separate expression for warm soak losses. The only difference is that running losses in CORINAIR are a linear function of mileage, whilst CONCAWE uses a constant daily rate based on average driving conditions.
- In the CORINAIR and CONCAWE methods the basic parameters are fuel volatility and daily variation of ambient temperature, while RWTÜV provides a driving conditions dependent expression with no obvious connection to fuel or climatic properties. Furthermore, the RWTÜV method is modified for the evaporative emission estimation for Germany and several parameters (e.g. the correction factors k_n and k_f,

- describing seasonal and operational influences) are not directly available or easy to estimate.
- The estimation of hot soak emissions according to the RWTÜV method requires a large number of modified data (frequency distribution of trip length and parking time), while the use of average trip lengths and parking times, which the RWTÜV method was not designed for, leads to a significant overestimation of hot soak emissions. Furthermore, the expressions provided by RWTÜV do not normally respond to the boundary values of their parameters (parking time, daily ambient temperature changes).

3.1.5.2. Comparison between the calculated emissions and measured data

A number of actual tests were performed by TRL. The resulting figures were compared to the calculated values according to CORINAIR and RWTÜV reports. The results show a wide dispersion of measured data. The resulting average figure for the hot soak losses (uncontrolled situation) did, however, agree with the calculations. The resulting average figure for the diurnal emissions (equally the uncontrolled situation) showed a significant discrepancy relative to the calculated figures, by a factor of about 4 relative to the CORINAIR figure and a factor of about 1.5 relative to the RWTÜV figure. There are no measured data concerning controlled cars, however.

3.1.5.3. Proposal for the selection of an appropriate methodology

The following conclusions have been drawn:

- There are significant differences between various models in the estimated evaporative emissions of each type; all models, however, lead to emission factors of the same order of magnitude - and this is valid for the MOBILE 5a emission factors too.
- There were significant differences between the various models in the estimation of the different types of evaporative emission. However, all models, including MOBILE 5a, produced emission factors that were of the same order of magnitude.
- When it came to total evaporative emissions, individual differences between the models were eliminated. The aggregated results of CORINAIR and RWTÜV were similar, particularly for emissions from controlled cars. This is important because uncontrolled vehicles are continuously being phased out.
- RWTÜV may be more suitable for the estimation of spatially and temporally disaggregated emissions, because it makes use of detailed "microscale" data (distribution of trip length and parking time).
- RWTÜV does not account for running losses, which are not negligible and must therefore be included in the calculation procedure to be adopted by MEET.
- The CORINAIR method is transparent, whereas that of RWTÜV has some uncertain points (e.g.: How is the correction factor for diurnal emissions defined? Which are the actual values of the correction factor for hot soak losses?).
- Finally, there is no method that is based on a comprehensive experimental data set (which would be the most important advantage of a calculation procedure). This is further demonstrated by the comparison of experimental data from TRL, which are

greatly dispersed among different vehicles, with the calculations of CORINAIR and RWTÜV.

Taking into account the above considerations, it seems reasonable to propose to use the CORINAIR methodology for estimation of evaporative emissions in the framework of MEET (see [Samaras *et al.*, 1997] for a more detailed approach).

3.1.6. Gradient influence for light-duty and heavy-duty vehicles

by Dieter Hassel and Franz-Josef Weber

See [Hassel & Weber, 1997] for a more detailed approach.

The gradient of a road has the effect of increasing or decreasing the resistance of a vehicle to traction. As has been shown during the development of emission functions, the power employed during the driving operation is the decisive parameter for the pollution emission of a vehicle. Even in the case of large-scale considerations, however, it cannot be assumed that - for example - extra emissions when travelling uphill are balanced by a corresponding reduction in emissions when travelling downhill.

Because of the higher vehicle mass the gradient influence is even more important for heavy duty vehicles. Within the frame of the German Emission Factor Programme methods have been developed for the calculation of emission factors for gradient classes. The methods are different for light and heavy duty vehicles and will be described in the following chapters.

For light duty vehicles a special test programme was carried out on the exhaust gas stand of the Rhineland TÜV. In the so called basic test programme the emission measurements were based on the following cycles:

- New European Driving Cycle
- US FTP 75
- US Highway Driving Cycle
- Special German Autobahn Cycle

Taking account of the gradients usually encountered in the Swiss and German road networks, it was decided to undertake the emission measurements for gradient classes of -6%, -4%, -2%, 0%, 2%, 4% and 6%, where the numbers given designate the centre of the class in each case. The traction resistance line simulated by the roller-type test stand is displaced in parallel to correspond with the specified gradients.

In the case of slight gradients - in the range between -2% and 2% - it can be assumed with sufficient accuracy that these do not affect the driving behaviour. In the case of steeper gradients, this assumption is no longer permissible. For this reason, special surveys have been undertaken in Switzerland on sections whose gradient is within the classes from ±4% and ±6%. So special driving patterns could be derived for gradients beyond +2 % resp. -2 %.

The measurements were based on nine passenger cars with 3 way-catalyst and controlled air/fuel mixture, three conventional spark-ignition passenger, cars and three diesel passenger cars.

Emission factors for the gradient classes were calculated by multiplication of a gradient factor with an emission factor for gradient class 0 %.

The gradient factor is an emission ratio. The gradient factors for the pollutant components and fuel consumption were calculated for the vehicle concepts investigated as a function of the gradient classes and the average vehicle speed of all the driving patterns and speed classes for uphill and downhill sections.

The development of the emission and consumption functions for heavy duty vehicles is described in detail in the final report of the German Emission Factor Programme [Hassel *et al.*, 1994]. The parameters of the function are L_{WR} which is the power for overcoming the wind, rolling, and gradient resistance and L_B which is the power for overcoming the inertia of the mass during acceleration. In contrast to the parameters of the functions for the passenger cars the parameters of the function for heavy duty vehicles include gradient resistance according to the equation for L_{WR}:

$$L_{WR} = \left[\frac{\rho}{2} \cdot c_w \cdot A \cdot v^2 + m \cdot g \cdot (f_r + \sin\alpha)\right] \cdot v$$

where

ρ = air density

c_w = drag coefficient

A = cross sectional area of vehicle

g = acceleration due to gravity

f_r = coefficient of rolling friction

α = gradient angle

The heavy-duty vehicle fleet is analogous to the passenger car fleet in that it can be divided into layers (strata). The definition of the layers takes into account for each heavy duty vehicle category the following parameters:

- vehicle mass,
- body style,
- model year.

Layer-specific emission factors were calculated by using the appropriate emission function and the L_B and L_{WR} distribution functions of different driving patterns. These distribution function were derived for all vehicles in a layer. Using the equation of motion and the vehicle data sets, the driving patterns were transformed into L_B and L_{WR}-distribution functions. The emission factors of each single vehicle in a layer were combined unweighted for the emission factor of the layer.

The layer-specific emission factors were obtained for six road categories. Each category was divided into four types of traffic flow condition, and each of these conditions was split into five classes of gradient with two different load factors per gradient class. The set of layer-specific emission factors for the heavy-duty vehicle fleet consisted of about 5200 data per component.

As described earlier, the gradient factors were derived for Swiss and German driving patterns which are representative of special traffic situations on different road categories. Where information on detailed driving behaviour is not available, gradient factors can only be calculated on the basis of the mean speed.

For light-duty vehicles it is possible to use these gradient factors in connection with country-specific emission factors. The minimum information needed for local emission assessments is the composition of the vehicle flow, the mean gradient of the road, and the mean vehicle speed.

For heavy-duty vehicles the Swiss and German model for the calculation of emission factors includes the gradient influence, so that no special gradient factors have to be derived. Nevertheless, it is possible to determine gradient factors by calculating the ratios of the emission factors at different gradients referring to gradient class 0 %. Thus, gradient factors can be determined on the basis of the mean speed alone. Local emission assessments than can be done in the same way as for passenger vehicles.

As the mean speeds in different countries, and for different road categories, may be different, one option for representing the gradient factors is to conduct a regression analysis on the basis of the emission data from the German work-book. The mean speed of several driving patterns is not identical for the different gradient classes and for level terrain. By means of the following method it is possible to formulate general relationships for the gradient factors:

- regression analysis for level terrain, so that emissions on level terrain can be calculated for every speed of the driving patterns on different gradients
- calculation of the emission ratio for each driving pattern in relation to the emission at gradient 0 %
- regression analysis for each gradient class, based on the calculated emission ratios

Due to the regression analysis there will be a certain smoothing of the ratios, though this can be neglected.

3.1.7. Hot emission factors for heavy duty vehicles

by John Hickman

Only relatively few data are available on emissions from heavy duty vehicles, and it is not therefore possible to derive emission factors to the same level of detail as for passenger cars. Compared with cars and light goods vehicles, heavy duty vehicles are more diverse in some ways: they include a large range of weights and sizes (from 3.5 tonnes gross weight to around 40 tonnes in most EU countries, but as much as 60 tonnes in some), and their operations range from very disrupted trips (such as refuse collection and urban bus journeys) to high speed transport of goods and passengers on long motorway journeys. In other respects, though, there is less variation: almost all heavy duty vehicles use diesel engines and the history of their emission control standards is shorter than for light duty vehicles, so there is less diversity of engine and emission control technology.

The European type approval test for this class of vehicle is based on the engine's performance, and not the whole vehicle. It involves the measurement of emissions under 13 steady-state operating conditions defined in terms of the speed and load of the engine, and many of the available emission data have been measured in that way. This has prompted the development of procedures by which emission factors representing the on-road performance of a vehicle may be derived from the steady-state engine emissions, some aspects of the vehicle's specification and some representation of the on-road conditions to be simulated. Models have been developed by TNO and TU Graz and are summarised in [Cost, 1996].

The most recent thorough compilation of emission factors is that presented in the Swiss/German handbook of road traffic emission factors [Infras, 1995]. The Workbook provides emission factors for all types of vehicle, including heavy lorries and buses, for a variety of driving patterns. Other features taken into account are the road gradient and, for heavy goods vehicles, the load state of the vehicle. These factors are more important in the case of heavy duty vehicles because the load carried by a lorry, as a proportion of the total weight of the vehicle is much greater than for light duty vehicles, and their low power to weight ratios make the effect of the road gradient significant. In the Workbook, both heavy goods vehicles and buses are subdivided into a number of classes according to their weight. The emission factors were derived using data from engine test-bed measurements that provided emission data for thirty steady-state engine conditions; the influence of the dynamic driving behaviour has been taken into account by empirically derived correction functions [Hassel, 1995].

The emission factors from the Workbook have been compared with data derived from vehicle-based measurements performed by TRL in the early 1990s, and with the two emission models, developed by TNO and the TU Graz. The comparisons in each case showed an acceptable level of agreement, bearing in mind that each of the data sets is based on limited measurements on different samples of engines and vehicles and following different experimental procedures. The comparison is described in more detail in the corresponding MEET report [Hickman, 1997]. Because of their comprehensiveness and because their general level of accuracy was largely confirmed through the comparisons, the factors from the Workbook have been used as the basis for the derivation of average speed related emission functions, with correction factors for the vehicle load and gradient. These functions apply only to heavy duty vehicles manufactured before the introduction of EC directive 91/542/EEC (EURO I). No experimental data were available for more modern vehicles, so their emissions are estimated by applying reduction factors to the pre-EURO I factors (see Section 3.1.9).

3.1.7.1. Basic speed-emission functions

The Workbook provides emission factors for each of a number of discreet, pre-defined driving patterns. However, when they are displayed as a function of the average speed of each of the driving patterns, the emission factors tend for the most part to fall on a reasonably smooth curve (see, for example Figure 4). It was therefore possible to generalise the Swiss/German emission factors as continuous functions depending on the average vehicle speed.

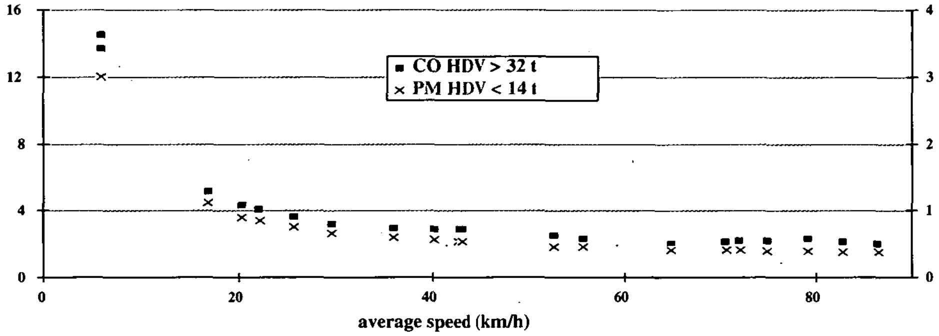

Figure 4: Examples of emission factors from the Swiss/German Workbook plotted as a function of average vehicle speed.

The functions were derived by statistically fitting the data to curves of the form:

$$\varepsilon = K + av + bv^2 + cv^3 + \frac{d}{v} + \frac{e}{v^2} + \frac{f}{v^3}$$

where:

ε	is the rate of emission in g/km for an unloaded goods vehicle, or for a bus or coach carrying a mean load, on a road with a gradient of 0%
K	is a constant
a - f	are coefficients
v	is the mean velocity of the vehicle in km/h

The procedure that was used was able to determine the statistical significance of each of the terms in the equation, and in many cases only a few of them were needed to give a close fit to the data, resulting in zero values for a number of the coefficients (*a* - *f*). Equations were derived for four classes of heavy goods vehicle (3.5 to 7.5 tonnes, 7.5 to 16 tonnes, 16 to 32 tonnes and 32 to 40 tonnes) for urban buses and for coaches. The pollutants considered were carbon monoxide, carbon dioxide, hydrocarbons, oxides of nitrogen and particulates. For heavy goods vehicles, the equations give emission rates for vehicles with no load, and travelling on a road with zero gradient. For coaches and urban buses, the emissions are also for roads with zero gradient, but for vehicles with a medium load. Correction factors for load (HGVs) and gradient (all classes) may be applied for other situations, and are described below.

For situations other than the base case (no load, zero gradient for goods vehicles and mean load, no gradient for buses and coaches) corrections factors may be applied to the standard functions so that:

$$\varepsilon_{\lambda,\gamma} = \varepsilon \times \Phi(\lambda) \times \Psi(\gamma, s)$$

where:

$\varepsilon_{\lambda,\gamma}$	is the emission rate corrected for the load (λ) and the gradient (γ)
ε	is the base emission factor
Φ(λ)	is the load correction function
Ψ(γ,s)	is the gradient correction function

3.1.7.2. Correction factor functions for gradient

Hassel and Weber (1997) provide gradient factor functions of the following form (see also section 3.1.6):

$$\Psi(\gamma,s) = gv^6 + hv^5 + iv^4 + jv^3 + kv^2 + lv + m$$

where:

$\Psi(\gamma,s)$	is the correction factor for gradient class *s*
$g - m$	are coefficients
v	is the mean velocity of the vehicle in km/h

These functions are given for gradient classes of 2%, 4%, 6%, -2%, -4% and -6%, and for the same vehicle size and type classifications as the basic speed-emission functions.

3.1.7.3. Correction factor functions for load

Load correction factor functions ($\Phi(\lambda)$) are of the form:

$$\Phi(\lambda) = \kappa + n\gamma + p\gamma^2 + q\gamma^3 + rv + sv^2 + tv^3 + \frac{u}{v}$$

where:

$\Phi(\lambda)$	is the load correction factor
κ	is a constant
n - u	are coefficients
γ	is the gradient in percent
v	is the mean velocity of the vehicle in km/h

The functions provide factors by which the base emission rate (zero load) may be corrected to that for a fully loaded vehicle. Data for intermediate load states are not available, but if necessary, it may be assumed that the emission rate varies linearly between the zero and full load values.

3.1.7.4. Validity of the functions

The emission functions, and those for the load and gradient correction factors are in some cases rather complex, and it is important that they should not be extrapolated beyond the ranges of the variables from which they were derived. For example, some of the emission functions for urban buses give negative results if they are used in the high speed range. The functions are, however, valid for most, if not all, of the normal operating conditions encountered by these types of vehicle (again taking the example of urban buses, they do not normally travel at high speeds, so the performance of the functions at high speeds is unimportant). In general, the emission functions for heavy goods vehicles are valid over a speed range from 5 to 85 km/h, those for coaches are valid between 5 and 100 km/h and those for urban buses between 5 and 40 km/h. The range of gradients for which the functions are valid is, in all cases from -6% to +6%. In recognition that vehicles will travel more slowly on roads with steep gradients, the valid speed ranges reduce as the gradient (positive or negative) increases.

3.1.8. Emission factors for mopeds and motorcycles

by Rudolf C. Rijkeboer

See the full report for a more detailed analysis [Rijkeboer, 1997].

3.1.8.1. Mopeds

For mopeds there is an ECE Regulation (ECE R47), valid since 1981. But not all Member States of the European Union have adopted this Regulation. Switzerland has a more stringent legislation, known as FAV 4, valid since 1988. Austria has a similar legislation. For the European Union more stringent limits are planned, but not yet valid. The emission factors have been determined for the following stages:

- Unregulated
- According to ECE 47
- According to FAV 4

The emission factors for the unregulated mopeds are based on the CORINAIR figures of 1989, modified on the basis of TNO in-house experience. The exact values are difficult to establish, however, since this category of vehicle is subject to a large degree of do-it-yourself maintenance and modifications ("tuning") which obviously influences the emission behaviour. Real data are scarce and the figures given should be assumed to indicate the general order of magnitude, with a large degree of uncertainty as to their actual value.

The emission factors of the regulated mopeds have been derived from a Swiss-German investigation [Keller *et al.*, 1995]. These data are somewhat better based than those of the unregulated vehicles, but the sample measured was still small and the degree of uncertainty still substantial. Also, depending on the country concerned, there may be a large degree of "tuning" performed in the field. According to in-house experience at TNO this may especially influence the emission of HC, which may increase as much as an order of magnitude when exhaust systems are changed.

The figures given for the emissions of mopeds are speed-independent figures, since it is assumed that the use of mopeds is influenced very little by the traffic or the environment in which it is operated, and as a rule it is almost always operated to its maximum capabilities. So there seemed little point in a differentiation between different operating conditions, even if there had been information available.

3.1.8.2 Motorcycles

With regard to motorcycles the only source of information found was the Swiss-German investigation mentioned above [Keller *et al.*, 1995]. A significant problem with motorcycles is the large variety in vehicles in terms of mass, power, configuration (motorcycle / motorscooter, off/on-road), working principle (2/4-stroke), etc. The report concerns 24 different vehicles divided over 6 different categories, which still makes for an average of only 4 vehicles per category.

The legislative situation is similar to that with mopeds. There is an ECE Regulation (ECE R40) valid since 1979, amended in 1988. There is a Swiss national legislation, known as FAV 3, and there is an EU proposal. Since the exhaust gas limits for ECE R40-00 and even for ECE R40-01 were not in any way restrictive, most countries have not adopted this legislation. The motorcycles have therefore been divided into two categories only:

- Unregulated
- FAV

The category unregulated has been subdivided into

- 2-stroke
- 4-stroke < 250 cm^3
- 4-stroke 250 - 750 cm^3
- 4-stroke > 750 cm^3

The category FAV has been subdivided into:

- 2-stroke (< 125 cm^3)
- 4-stroke (> 125 cm^3)

The data measured in the Swiss-German programme were related to a small number of standard driving cycles and some constant speeds under motorway conditions. By splitting the cycles into their constituent parts a number of points with different average speeds were created. Together with the constant speeds, 10 speed points per vehicle were obtained (8 for the smaller 2-strokes), ranging from about 20 to 140 km/h (110 km/h for the 2-strokes). As stated earlier, existing driving cycles were used. These cycles were actually derived for cars. No attempt was made to measure the vehicles under driving conditions that would be more representative for actual motorcycle use, since no operational information is yet available. This will probably mean that the figures given will underestimate the real emissions from motorcycles. For the moment there is nothing that can be done about this.

So that the data could be handled more easily during calculations, trends have been fitted to the data points. Second order polynomials were fitted to the speed ranges 20 - 60 km/h and 60 - 140 (110) km/h respectively. In the case of Nox emissions this procedure produced ambiguous results. Because of the small number of vehicles per class, and the peculiar behaviour of some individual vehicles, the calculated trends of different classes overlapped in an illogical way. In this case an average shape of the general trend was therefore determined and combined with the average level of each class in order to determine the actual trends per class.

3.1.9. Alternative fuels and future technologies

by Zissis Samaras, Robert Coffey and Franz-Josef Weber

This section considers alternatives to current technologies and fuels as well as those being developed for the future, including the near future. It looks at the emissions factors for these technologies and fuels and considers those most likely to emerge.

3.1.9.1. Near future fuels and vehicles

Improved fuels

New fuels (both gasoline and diesel) that are likely to reduce emissions are expected to appear on the market by the turn of the century. Additional legislation will also come into force by the year 2005, with stricter specifications for the conventional market fuels. However, for the calculation of the effects of these improved fuels on exhaust and evaporative losses, few data exist. These data are to be found in the results of the EPEFE [Acea and Europia, 1996] programme and the evaluation of the American Auto/Oil activities conducted by the first working group of the European Auto/Oil programme [Acea *et al.*, 1995]. Despite the fact that these data refer exclusively to new and well tuned engines and emission control systems, they can be used as an indicator of the expected effects on the emissions of actual vehicles.

The improved market fuels of the near future will have the following characteristics: for gasoline reduced lead, sulphur content, aromatics, benzene, olefins, Reid vapour pressure, and increased oxygenates, mid range and tail end volatility; for diesel reduced sulphur content, polyaromatics, back end distillation, and increased cetane number. The effects of a change of each of these properties are deduced from the aforementioned studies and presented in [Hickman *et al.*, 1999].

Near future vehicle categories

The assessment of the emission factors of the near future vehicle categories is possible if the future emissions standards are known. This is the case for passenger cars, light and heavy duty vehicles, but not for two-wheel vehicles.

For passenger cars and light duty vehicles, in order to comply with the standards the automotive manufacturers can either reduce the hot emission level or the cold start excess emission, or both. Therefore our intention is to assess reduction rates for both hot emission factors and cold start excess emissions from a reference standard to a future one. The method used consists of 3 steps:

- Calculation of an average hot emission factor for the driving cycles ECE15 and EUDC, and an average cold excess emission for the ECE 15, for each pollutant and each vehicle technology complying with the reference standard. As the emission factors given in sections 3.1.3 and 3.1.4 concern EURO 1 vehicles, EURO 1 is the first reference standard considered. The data bases of the Swiss/German emission factor programme [Hassel *et al.*, 1994; Infras, 1995] and of the Inspection / Maintenance project [Samaras *et al.*, 1998b] of the European Commission were used.
- Application of the hot emission factor and the cold excess emission a priori specific reduction rates. Thus new emission factors over the whole NEDC were produced, corresponding to the vehicles complying with the future standard.
- Calculation of the overall reduction rate of the emission factors over the NEDC for vehicles complying with the reference standard and those complying with the future one. This reduction rate was then compared with the reduction rate of the emission standards themselves as they appear in the legislation. In order that the distance to the standard remained constant, when the two rates were different, the a priori specific reduction rates were proportionally modified into the final specific reduction rates.

A very specific case is the assessment of reduction rates for EURO 3 vehicles, since the test procedure will be modified. To account for this modification, which will result in an increase in emissions, an additional step was used. Firstly, new emission factors for the modified procedure for the vehicles complying with EURO 2 were calculated on the basis of the EC directive for future emission standards. For comparative reasons this directive contains corrected EURO 2 standard levels for the modified test procedure. Assuming that the difference between the standards relates to an additional excess emission in the cold phase, the EURO 2 excess emissions for cold start were increased. Then the corrected EURO 2 standard levels were taken into account instead of the real ones for the calculation of the reduction rates between vehicles complying with EURO 2 and EURO 3.

This way, the reduction percentages of the emission level which can be achieved by introduction of future steps of legislation were calculated [Samaras *et al.*, 1998c]. Some of them are presented Figure 5.

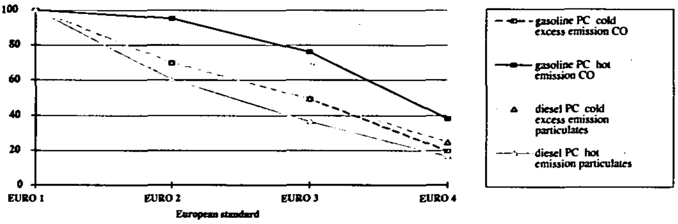

Figure 5: Proposed evolution of some emission factors for the near future passenger cars.

For heavy duty vehicles and buses, the basic emission factors (see section 3.1.7) apply to EURO 0 vehicles. By analogy to the passenger vehicles reduction factors have to be derived in such a way as to follow the evolution of the standard levels. Firstly, average values of the emission factors of the 13 mode test were evaluated from available measurements. This allowed us to assess firstly the reduction rates from EURO 0 to EURO 1 vehicles by comparing the above calculated emission factors with EURO 1 standard levels, and then the reduction rates corresponding to the future standards. The reduction rates between the standards levels are not automatically translated into reductions in the emission factors: in some cases different reduction rates were assumed because of the foreseen technology evolution, or for other reasons. The proposed reduction rates are presented in [Hickman *et al.*, 1999].

3.1.9.2. Alternative fuels

An area that shows an important potential for the reduction of emissions from engines (in particular diesel engines) is the use of alternative fuels. The following alternative fuels were considered:

Natural gas

One fuel proposed is natural gas (NG), most commonly in the compressed form (CNG) but also liquefied (LNG). Its use was demonstrated on both gasoline (light-duty applications) and diesel engines (both light and heavy duty applications). Especially as regards heavy-duty diesel engines, NG requires the replacement of the diesel with a spark ignition gas engine. Gas engines can run either with a three-way catalytic converter (TWC) or in the lean burn mode

Alcohols

Alcohols, such as methanol and ethanol are widely promoted as 'clean fuels', as they have many desirable combustion and emission characteristics, including good lean burn combustion characteristics, low flame temperature. With an octane number of 110+ and excellent lean combustion properties, methanol and ethanol are good fuels for lean-burn Otto-cycle engines. Due to cold starting problems, pure alcohols are not suitable for automotive use; blends of up to 85% methanol (M85) or ethanol (E85) are used instead. These fuels are not well suited as diesel fuels, and require the use of specially designed engines or the addition of expensive ignition improvers. Methanol can be produced from natural gas, crude oil, biomass, and urban refuse. Ethanol can be produced by processing agriculture crops such as sugar cane or corn.

Dimethyl ether (DME)

Partially oxygenated hydrocarbons produced from natural gas have been shown to be viable alternative fuels for the diesel engine, showing favourable combustion characteristics, similar to that of diesel fuel. Dimethyl ether (DME) has recently emerged as an attractive alternative for diesel engines. DME can be made from a wide variety of fossil feedstock, among which natural gas and coal, and from renewable feedstock and waste. DME is currently produced in smaller quantities, primarily as a cosmetic propellant.

Biodiesels

Biodiesel is defined as the mono alkyl esters of long chain fatty acids derived from renewable lipid feedstock, such as vegetable oils and animal fats, for use in compression ignition (diesel) engines. Many vegetable oils and animal fats have been suggested and investigated as diesel fuel substitutes. They are renewable energy sources and, as such, have been supported by several pieces of legislation and government sponsored initiatives in the USA and in Europe. These oils are converted into methyl esters, before they are used as diesel fuel. Biodiesels, which are currently under investigation, include rapeseed oil methyl ester (RME) and soy methyl ester (SME).

Liquefied petroleum gas (LPG)

Data for light duty applications already exist in section 3.1.3. LPG has also been used in bus applications with similar benefits as with natural gas, but its efficiency is even lower than that of natural gas engines.

The literature survey [Samaras *et al.*, 1998c] concluded to the summaries presented in Table 3 and Table 4. Table 3 presents an overview of the main advantages and disadvantages of the alternative fuels. Table 4 shows the effects on the regulated emissions as reported in the literature.

Table 3: Advantages and disadvantages of alternative fuels.

Alternative fuel	Advantages	Disadvantages
Natural gas	• Very low particulate emissions compared to diesel • Low NOx emissions compared to advanced diesel engines • Zero sulphate and SO_2 emission	• More complex refuelling system • 4 times larger tank size requirement • Engine efficiency in bus operation is approximately 20 % lower than that of the diesel engine • Lean burn NG engines often have problems with methane emissions, but at very low NOx emission levels.
Alcohols	• High octane number • Low NOx emissions • Zero sulphate and SO_2 emission • Low evaporative losses	• Cold start problems • Increased aldehydes • More corrosive than hydrocarbons • Larger fuel tanks • Safety and handling problems
Dimethyl ether	• Little modification to the diesel engine required • Very low particle emissions • Zero sulphate and SO_2 emission • Lower engine noise • Low NOx levels without after-treatment	• Lower viscosity • The injection system needs to be developed
Biodiesel	• Higher cetane number • Good lubricity • Zero sulphate and SO_2 emission • Particulates of lower toxicity (same mass emissions)	• Their corrosion properties • Lower heating value • Higher freezing point • Increased NOx emission • Increased odour

3.1.9.3. Emissions factors for new technology vehicles

The following new vehicle categories have been introduced by this report:

• Electric vehicles (EVs):	- Passenger car, - Light Duty Vehicle
• Hybrid electric vehicles (HEVs):	- Gasoline passenger car, - Light Duty Vehicle
• Fuel cell electric vehicles (FCEVs):	- Methanol passenger Car, - Light Duty Vehicle, - Urban Bus

To help understand the factors that have been given in the report, the emissions have been calculated and compared for each new technology passenger car. Where possible this has been done over two speed ranges, assuming an average vehicle weight of 1.5 tonnes. The values calculated here could be used as simplified emissions factors. However, for the original factors and a full description of the methodology and assumptions one must refer to [Samaras *et al.*, 1998c].

Table 4: Effects of alternative fuels on the regulated emissions. In parentheses the range of scale factors is indicated as ratio of the emissions with the alternative fuel over the emissions with the conventional fuel.

alternative over conventional fuels	vehic. type	CO	HC	NOx	PM
NG over gasoline	TWC LDV	Decrease (0.4 - 0.5)	Increase (1.5 - 2.0)	Decrease (0.4 - 0.6)	n/a
NG over diesel	HDV(1)	Decrease (0.1 - 1.0)	Increase (0.2 - 6.0)	Decrease (0.1 - 1.0)	Decrease (0.05 - 0.2)
Methanol over gasoline	TWC LDV	No change (0.7 - 0.9)(2)	Decrease (0.7 - 0.8)(2)	Decrease (0.8 - 1.0)(2)	n/a
Ethanol over gasoline	TWC LDV	No change (0.4 - 1.4)(2)	Increase (1.0 - 1.3)(2)	Decrease (0.4 - 1.0)(2)	n/a
Methanol over diesel	HDV	No change (0.8 - 3.0)(2)	No change (0.6 - 3.0)(2)	Decrease (0.2 - 0.4)	Decrease (0.2 - 0.6)
Ethanol over diesel	HDV	Increase (1.1 - 1.3)(2)	No change (0.7 - 1.5)(2)	Decrease (0.87 - 0.9)	Decrease (0.2 - 0.6)
DME over diesel	HDV	n/a	n/a	Decrease (0.2 - 0.5)	Decrease (0.05 - 0.3)
Biodiesel over diesel	HDV	Decrease (0.75 - 0.8)	Decrease (0.2 - 0.8)	Increase (1.1 - 1.2)	No change (0.6 - 1.2)

(1) Range reflects operating principle (lean burn or stoichiometric)

(2) A much larger scatter is indicated by the U.S. data

Table 5: Vehicle emission factors from new technology vehicles in g/km., with the spread of data for the HEV.

	HEV	FCEV	EURO I gasoline car <1.4 l	
speed range	20-100 km/h	20-100 km/h	20-50 km/h	50-100 km/h
CO_2	112 ±31	113	175	120
CO	0.17 ±0.12	0.00	3.00	1.00
NOx	0.02 ±0.01	0.00	0.30	0.40
HC	0.01 ±0.01	0.00	0.25	0.10

Table 6: Full energy cycle emission factors for new technology vehicles: average factor and spread of data in g/km.

	Electric Vehicles		Hybrid Electric Vehicles	Fuel Cell Electric Vehicles	
speed range	20-50 km/h	50-100 km/h	20-100 km/h	20-50 km/h	50-100 km/h
CO_2	122 ±55	94 ±39	126 ±34	150 ±17	140 ±10
CO	0.02 ±0.01	0.02 ±0.01	0.17 ±0.12	0.04 ±0.02	0.03 ±0.01
NOx	0.31 ±0.14	0.24 ±0.10	0.09 ±0.03	0.16 ±0.07	0.12 ±0.04
HC	0.29 ±0.13	0.05 ±0.02	0.13 ±0.04	0.25 ±0.11	0.18 ±0.07
SO_2	0.71 ±0.32	0.55 ±0.23	0.36 ±0.09	0.03 ±0.01	0.02 ±0.01
PM	0.04 ±0.02	0.21 ±0.09	0.00 ±0.00	0.01 ±0.00	0.01 ±0.00

Table 7: Average energy consumption values for new technology passenger cars of 1.5 tonnes weight in Wh/km.

	Speed range	
	20-50 km/h	50-100 km/h
Electric Veh.: electricity cons. for recharging	266	206
Hybrid Electric Vehicle: gasoline	442	442
Fuel Cell Electric Vehicle: methanol	471	343

The vehicle emission factors have been shown in Table 5. These represent the pollutants being emitted at the point of use. Obviously, the EV has not been included as the point of use emissions are zero. Due to the lack of data, both the HEV and FCEV emissions estimates have been given as constants and only one speed range has been used. The spread of data has been shown where possible. Note that only one set of data was used for the FCEV, and therefore no spread has been given. The average emissions of a EURO I car [Samaras & Ntziachristos, 1998] over two different speed ranges have also been included for comparison.

The analysis would not be complete without understanding the full energy cycle emissions. These include the pollutants incurred at every stage of fuel production and usage and are shown in Table 6.

To calculate the non-vehicle emissions for each EV the energy consumption data within a given speed range has been averaged (Table 7), and, in each case, this figure has been used to derive the emissions figures from fuel and electricity production emissions factors. Where vehicle emissions have been incurred these have been included. Both the average emissions and the ranges have been summed to give the overall figures. The range in HEV emissions, for example, includes the spread due to both the vehicle emissions data and the variation in fuel production emissions owing to differences in energy consumption.

The quantity of pollutants incurred by the electric vehicle are simply proportional to the energy consumption and thus reduce with higher speed up to a point. These values represent the pollutants being emitted from the average European power station.

It should be noted that the vehicle emissions and energy consumption data used for both the HEV and FCEV was very limited and represent tests with average speeds within the 20-50 km/h range. Hence, estimates are likely to be more valid for the lower speed range.

3.1.10. Life-cycle emissions analysis of fuel use

By Paul Davison

This section presents a review and analysis of the methodology for preparing air pollutant emissions from the production of a range of fuels for use in the transportation sector (see Lewis (1997) for a more detailed analysis). The fuels considered are diesel, gasoline, liquefied petroleum gas (LPG), kerosene, heavy fuel oil (HFO), compressed natural gas (CNG), electricity and rapeseed methyl ester.

3.1.10.1. Crude oil based fuels

The crude oil based fuels, namely gasoline, diesel, LPG, kerosene and heavy fuel oil can be considered together due to their similar production routes, consisting of :

- Extraction (of crude). The analysis is based on crude oil extraction in the North Sea, as data for this are easily obtained. These data have also been applied to Middle Eastern production, and the split of crude oil is assumed to be 60% from the North Sea and 40% from the Middle East.
- Transportation (of crude). It is assumed that all North Sea and Middle East crude oil is transported by tanker, typically in the size range of 70,000 and 250,000 tonnes respectively. In addition to emissions from marine engines, hydrocarbons (HCs) are emitted through evaporative losses during loading, unloading and transit and an estimate of these is included in emissions calculations.
- Refining. The refinery process involves a range of complex steps that can be optimised to meet the product mix required. To analyse the energy use, emissions and economics of refining, it is necessary to consider a number of issues:
- the crude oil feedstocks; in this case Brent Blend and Arabian Light crude.
- the refinery configuration; a standard typical configuration was defined for each refinery type (using the three most common units, namely simple, FCC and hydrocracking)
- the demand for products; the products that the refinery model optimises on are: LPG, naphtha, unleaded gasoline, kerosene, diesel, gas oil, heavy fuel oil and bitumen.
- the specifications of products. Gasoline specifications were based on 95 octane ('premium') unleaded grade as it is the dominant specification in Europe

  These elements were modelled using least-COST linear optimisation modelling. The throughput of each process was then allocated to each of the final products, and the energy and emissions for that process were allocated to the relevant product (Gasoline, Diesel, LPG, Kerosene, HFO). Small variations were observed between the results for different countries. The variations relate primarily to the types of refinery that are used in each country, as certain types of refinery are more suited to certain products than others. No account has been taken of trading of refined products between countries, as this would necessitate a higher level of demand modelling.
- Distribution. It has been assumed that all fuels are transported by pipeline from the refinery to a terminal, where the fuel is then transferred to a road tanker for onward transportation to the point of end use. A characteristic distance is then taken for each country to represent the distance travelled from the terminal to the point of end use. Energy use during pumping is also included, as are VOC emissions through evaporative loss.

In calculating total production emissions, the summation stage has been carried out without reference to the location of the emission. Therefore emissions which occur away from population centres, such as during the extraction or tanker distribution phases, are added directly to those originating in highly populated areas, for example during road distribution.

3.1.10.2. Compressed natural gas

Compressed natural gas (CNG) is dissimilar to the other fuels in that the final product requires much less processing than the other alternatives considered here. The processing is limited to removal of impurities, including water. A much higher proportion of the emissions come from the distribution stage for CNG compared to the other fuels. This is due to its gaseous nature, which also gives rise to a greater potential for fugitive hydrocarbon emissions. Transportation is via pipeline which is assumed to be powered by in-line gas turbines, with negligible emissions consequences.

An investigation of the conformity of the distribution systems between different countries was outside the scope of the research: the UK distribution system is taken as the typical model.

In addition to energy consumption (and emissions consequences) of gas pumping, there are four types of gas loss that need to be considered when assessing the total losses from the system:

- uncontrolled continuous (fugitive) gas leaks;
- maintenance related losses;
- regular or operating losses, such as natural gas in compressor exhausts;
- isolated losses from accidents and pipeline fractures.

Gas losses from operations in the filling station are considered to be negligible, although energy is required for operation of compressor-filler units.

Although based on UK operating parameters and conditions, the emissions data calculated for CNG should be considered as generic values for all countries in Europe, as few data are available on the differences between the fuel supply networks in different countries.

3.1.10.3. Electricity

The main stages in the production of electricity for use as a transport fuel are:

- feedstock extraction and transportation of fuel;
- processing of fuel;
- transport of finished fuel to the power station;
- electricity generation;
- transmission and distribution of electrical energy.

The emissions from the production of electricity are much greater than for the production of other fuels. However, electric vehicles produce no emissions at the point of use, so the actual environmental impact of electricity emissions (usually in rural areas) may be substantially lower than the impact of equivalent internal combustion engine emissions in more densely populated areas. The data show wide variations in the emissions per useful energy output between the countries considered. This is because a wide range of energy sources are used for the production of electricity depending on local conditions. Furthermore, even for one fuel type, there are variations in the emissions abatement technologies used in different locations. The mix of fuels and emissions reduction technologies employed in the European electricity supply industry has undergone significant change over the last few years, and will continue to do so into the future as a result of the complex relationships between the technical, economic, political and environmental factors that shape this market. The data available for most countries date from around 1994, and so the COST 319 research should be seen as a 'snapshot' of the position at that time. In the longer term the possible introduction of new legislation on emissions from power stations would clearly reduce the life-cycle emissions of electric vehicles.

Specific individual examples of electricity generation, such as lignite combustion in Germany and Greece, peat burning in Ireland and the combustion of waste gases from blast furnaces in Luxembourg have been included in the analysis.

It is anticipated that electric cars would be recharged at night, when electricity demand is at its lowest and when vehicles tend to be inactive. Electricity producers tend to operate their plant under two regimes: base load plant tends to run 24 hours per day, whereas peak load plant tends to operate only at periods of peak demand. This results in differences in the fuel mix during the night compared with times of high demand. Data on these two regimes were not available within the time-scale of the research and therefore this aspect has not been fully investigated. A exercise for the UK (in 1993) indicates that emissions of all pollutants (except NOx with a 2% increase) would be reduced if most charging is carried out at night.

3.1.10.4.Biofuels - RME

Biodiesel can be produced from a range of vegetable oils. Rapeseed oil is considered as one of the main oilseed crops grown in the European Union and the most frequent feedstock for conversion to a transport fuel. The fuel produced from rapeseed oil is known as rapeseed methyl ester (RME), or more commonly, biodiesel.

The main stages in the life-cycle of RME for use as a transport fuel are:

- agriculture - production of oilseed rape;
- transport - rapeseed to crushing plant to produce oil;
- transport - rapeseed oil to processing plant;
- processing - rapeseed oil to rape methyl ester;
- distribution and storage - RME to filling station.

Main emissions arising from oilseed rape production are from fuel used in farm machinery and from the production and use of fertilisers and pesticides applied to the crop. Results show that the emissions from the production of RME are highly dependent on the assumptions made regarding the intensity of agricultural inputs to the growing of oilseed rape, especially in the degree of straw use as heat source in processing.

The distribution of biodiesel is assumed to be independent of the mineral diesel network and therefore will involve greater distances of travel by tanker. This is because mineral diesel is piped to distribution terminals and then tankered relatively short distances. Evaporative losses from RME are also assumed to be negligible.

3.2. Road traffic characteristics

3.2.1 *Traffic management*

by John Hickman

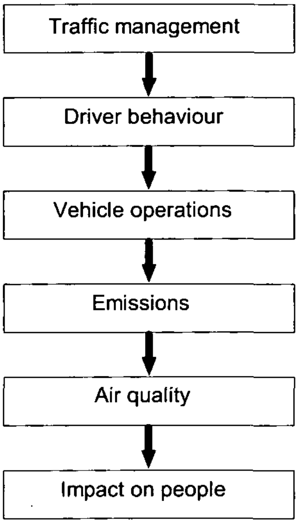

Figure 6 : Links between traffic management and air pollution impacts

Traffic management systems are usually used to try to reduce congestion and improve road safety. Recently, though, an interest has developed in their effect on vehicle emissions and air pollution. In this context there are two main objectives: firstly, where a traffic management system's function is to address a safety or congestion problem, it should also be designed so that it does not increase emissions unduly, and secondly, systems may be developed specifically to reduce emissions. The design and optimisation of a low-emission traffic management system depends on an understanding of several links in a rather complex process, since the management system itself does not directly affect rates of emission. A simplified schematic of the various stages is shown in Figure 6. The initial impact of a traffic management system is on the driver, and often involves a number of decisions. Depending on the type of traffic management system, drivers may choose whether or not to obey a speed limit, they may change their route or mode of transport if priorities are given to public transport vehicles, and so on. Any change in the behaviour of drivers will result in a change in the way their vehicles are operated, and will perhaps also influence the operation of other vehicles. In any case, changes in vehicle operation will cause changes in emissions. There are various ways in which this could take place; there may, for example be a change in the total number of vehicle kilometres driven, in the composition of the traffic or in the speed profiles of the vehicles, and each of these, or any combination of them, can affect the emissions produced by the traffic. The emission changes will modify local air pollution levels, but there will not be a change that is directly proportional to the change in emissions as air pollution levels are also influenced by many other factors such as non-traffic sources, background concentrations, photochemical transformations and the weather. Finally, by altering their exposure to air pollution, or their perception of it, changes in pollution levels will have an effect on people nearby. Because the COST 319 Action was concerned with the modelling of vehicle emissions, the last two stages in this sequence were not explicitly considered, but they are important nevertheless.

3.2.1.1. Types of traffic management system

Many different types of traffic management system are available. Some of the most common types are very briefly reviewed in the following paragraphs, with an indication of assessments that have been made of their likely effects on vehicle emissions and fuel consumption.

Urban traffic control

A number of studies have shown that improved urban traffic control can reduce fuel consumption. Fixed systems such as TRANSYT have shown improvements of up to about 15% [Abbot *et al.*, 1995; Skabardonis, 1994]. Systems that are responsive to traffic conditions (*e.g.* SCOOT and MOVA) may provide additional savings of 5 to 10% compared with a fixed system [Mulroy, 1989; MMT, 1993; Busch, 1996]. Evidence of reductions in pollutant emissions is less well documented but may be up to 15% [Krawac, 1993; André *et al.*, 1996; Robertson *et al.*, 1996]. As urban traffic control systems are already in use in many cities, there may be limited potential for further improvements.

Control of on-street parking

Reducing on-street parking can reduce congestion and journey times, and allows vehicles to travel more smoothly than if their progress is impeded. The effect on rates of emission was studied by Wood and Smith (1993) and Seika (1996) who estimated reductions between 1 and 17% using an emission model.

Parking control in urban areas

Reducing the number of parking places, reducing parking duration or charging high fees can reduce the number of journeys made by private cars. The doubling of parking fees in Gothenburg reduced car park occupancy by 20%, but within a year it had almost returned to the previous level [OECD, 1994]. Dasgupta *et al.* (1994) modelled the effect of halving the number of parking places in the central area of a city and found a 36% reduction in car use. However, much of the travel was redistributed outside the central area and the overall reduction was only 3 to 5%. In Enschede (Netherlands), parking management measures including restricting the number of spaces, increased charges and improved enforcement caused the number of inner city visitors to fall by roughly 50%.

Park and ride

Park and ride schemes aim to reduce city centre traffic by providing a facility on the outskirts where motorists can transfer to public transport. Park and ride scheme may encourage additional and longer trips and may cause some trips formerly made entirely by public transport to be transferred in part to cars. No long term reductions in traffic levels (or, by implication, emissions) have been identified in any existing scheme.

The effect on cold starts and the associated excess emissions is important for any traffic management system that influences parking behaviour.

Central area traffic restraint

Restraint of traffic in cities can take a number of forms, such as pedestrianised areas from which traffic is permanently excluded, selective exclusions including schemes in which access is allowed on alternate days based on vehicle number plates (*e.g.* Turin, Athens) and schemes allowing access only to cars with advanced emission control systems (*e.g.* Graz). Restrictions may be permanent or invoked only when pollution levels are expected to be high (*e.g.* Paris).

Vincent and Layfield (1977) reported that a system in Nottingham was discontinued after a year as it failed to reduce car traffic or increase bus patronage. Pedestrianisation in Chester was estimated to reduce emissions in the centre, but to increase network emissions by about 5% because overall journey lengths were greater [Chiquetto, 1997]. The alternate number plate scheme in Turin reduced traffic by about 10%; that in Athens produced initial benefits that were eroded as there was a large increase in the number of vehicles (suggesting that many people acquired a second car with a number plate complementary to that of their first car).

Public transport systems

A new or improved public transport system has the potential to reduce emissions by replacing car trips and reducing congestion. Experience has shown that this is not always achieved. One reason for this is that many passengers transfer from modes of transport other than cars. The new London Underground Victoria Line (opened in 1984), drew about 80% of its passengers from other public transport modes [Younes, 1995], and an extension of a rapid rail system in Berlin caused a major shift from buses but only reduced car traffic by about 3%.

Public transport fare reductions might also attract passengers from other modes. Dasgupta *et al.* (1994) suggested that halving fares might reduce car use by 1 to 2%, with a corresponding reduction in emissions (although they also estimated that walking would reduce by 7%). A subsidised bus card scheme in Finland was found to increase bus travel by 20 to 30% with a shift from car use of 15 to 25%. The average reduction in energy use was estimated as around 1 MJ per passenger kilometre [Pekkarinen and Dargay, 1996].

Bus priority schemes can reduce journey times and improve the reliability of services. This may have a direct effect on emissions from the buses and may attract additional passengers. Possible systems include bus lanes and selective vehicle detection at intersections. However, unless the total road or junction capacity is increased, such schemes will delay other traffic. Studies in Southampton and Eastleigh [TRL *et al.*, 1997a, b] showed reduced delays for buses, and emission reductions of around 20%, but increased delays to other traffic (mainly cars) occurred, and their emissions generally increased, so no overall improvement was achieved.

Road tolls, area licensing and congestion charges

Pricing policies aim to reduce car travel by increasing its cost, and the driver's awareness of the cost. A toll introduced in Oslo, where car and lorry drivers must pay to enter the city was introduced primarily to finance improvements to roads and public transport in the area, and did not reduce traffic volumes, though a similar scheme in Trondheim produced a slight reduction in car traffic. The Singapore Area Licensing Scheme has been more successful, and has reduced by half the number of work trips into the city by car. It was also reported that average pollution concentrations were reduced by 10% [OECD, 1994].

Emissions in congested traffic are high, and there may be some benefits from charging motorists according to the level of congestion. Guensler and Sperling (1994) proposed that speeds should be maintained in the range between 25 and 65 km/h to give reduced emissions.

Traffic calming schemes

Traffic calming schemes are used to reduce vehicle speeds and improve road safety (a speed reduction of 1.5 km/h can be expected to reduce the number of accidents by 5%). They may include many features such as reduced speed limits, road markings and physical restraints (road humps, chicanes, *etc*). The effect on emissions of a calming scheme will depend on how the scheme influences the average speed of the traffic and the amount of acceleration and deceleration. A number of theoretical and experimental studies have examined these effects, and Table 8 [Boulter, 1997] summarises some of the available literature.

Table 8: Summary of reported effect of traffic calming schemes on vehicle emissions

Country and reference	Type of measure	Type of vehicle	Change in emissions			
			NO_x	HC	CO	CO_2
Single road sections with road humps						
Australia [Van Every & Holmes, 1992]	5 road humps, 100 m spacing	n/a	n/a	n/a	n/a	+36 to +73%
UK [Webster, 1993]	Road humps, 75 m spacing	Petrol car,	-20 to 0%	+70 to +100%	+70 to +80%	+50 to +60%
UK [Boulter, 1996]	2 road humps, 60 m spacing	Petrol car, catalyst	-10 to +20%	0 to +30%	+5 to +35%	+15 to +35%
		Petrol car, non-catalyst	-35 to -10%	+35 to +60%	+30 to +60%	+10 to +30%
Sweden [Höglund, 1995]	1 road hump	Petrol car, catalyst	+18%	n/a	+20%	+4%
		Petrol car, non-catalyst	+22%	n/a	+11%	+5%
	10 road humps	Petrol car, catalyst	3 fold increase	n/a	3 fold increase	+37%
		Petrol car, non-catalyst	3 fold increase	n/a	2 fold increase	+51%
Austria [Züger & Blessing, 1995]	6 road humps, 200 m spacing	Petrol car, catalyst	10 fold increase	n/a	3 fold increase	+25%
Speed limits and traffic calming schemes						
Austria [Sammer, 1992]	30 km/h limit	1992 fleet average	-24%	no change	+4%	no change
Germany [GFMPTE, 1992]	30 km/h zone, limited calming	Petrol car, non-catalyst	-31 to -5%	-23 to +2%	-20 to +28%	-6 to +14%
	Extensive calming	Petrol car, non-catalyst	-60 to -38%	-25 to -10%	+7 to +71%	+7 to +19%
	50 km/h limit on main road	Petrol car, non-catalyst	-33 to -15%	-20 to +2%	-10 to +7%	-13 to -4%
Denmark [Herrstedt, 1992]	40 km/h limit with calming	n/a	n/a	n/a	n/a	-9%
Denmark [Vejdirektoratet, 1997]	21 towns, various calming	Average car fleet, 1995	-4 to +6	0 to +20	0 to +20	+1 to +11

While these results vary widely, and in some cases conflict, it seems likely that road humps will generally increase rates of emission. This is not surprising since the driving pattern they encourage is one of alternate decelerations and accelerations as each hump is negotiated. On the other hand, the less well defined schemes shown in the second half of the table, involving speed limits and various other calming measures are shown often to give emission reductions. There remains, however, considerable uncertainty and, further research is needed.

3.2.1.2. Estimating the effect of traffic management schemes on vehicle emissions

To estimate the effects of a traffic management system on emissions, it is necessary to know how the system will modify the operation of the traffic, and how those modifications will affect rates of emission. Fundamentally, this information could be derived from experimental observations, but the wide range of possible traffic management systems and the different circumstances in which they may be implemented mean that a comprehensive measurement programme would be almost impossible. Thus, models are necessary to simulate traffic management systems and their impacts.

For some types of traffic management system, there are well established models that can predict the behaviour of the traffic (indeed, some urban traffic control systems are responsive to traffic conditions and use computer models optimise their operation). In many other cases, though, current generation models are unlikely to be able to estimate changes in vehicle operation with sufficient accuracy, and the same is also true of vehicle emission models. Much effort has been devoted to the determination of vehicle behaviour and emissions under normal and representative driving conditions, whereas the intention and effect of some traffic management systems are to modify normal driving. In section 3.1.2, it has been shown that emission models based on a certain type of driving behaviour are not able to predict emissions accurately from vehicles operated differently.

It is clear, therefore, that further studies are necessary to improve the models so that they are able to assess the impacts of traffic management with greater precision and accuracy. Because this requirement applies equally to both vehicle operations and emissions, co-ordination of the research of traffic engineers and emissions specialists would be useful to ensure compatibility between their respective developments.

3.2.1.3. Conclusions

Most traffic management systems have been designed and used to improve road safety and congestion, but their effects on vehicle emissions are receiving greater attention. However, few thorough evaluations of this aspect have been conducted. Improvements are necessary to both vehicle operation models and emission models to increase the accuracy with which they predict the effects of traffic management.

3.2.2. Traffic and driving characteristics

by Michel André and Ulf Hammarström

A wide range of traffic-related statistics is required for estimating air pollutant emissions from road transport: traffic quantity and composition, driving behaviour, usage and operating conditions of the vehicles. Such data can be either derived from statistics, if they exist, or using models. In a European inventory, or for international comparisons, it is necessary to ensure that the statistics provided by the members are consistent (methods used, data quality). With this aim, research has been conducted to define accurately which statistics are necessary, to make sure of the data availability and of its compatibility with the objectives, and to analyse it. A detailed analysis of traffic-related statistics from a limited number of countries was proposed in [André *et al.*, 1999], and this work is summarised here.

A knowledge of micro-scale driving behaviour (speed and acceleration profiles, gearbox handling, etc.) can be necessary as input data (in fact, it is also necessary to set emissions factors) for precise emissions estimations (e.g. to assess traffic management, very local situations, etc.). Vehicle instrumentation and driving modelling tools contribute to the available data. The work conducted in this area has been summarised.

3.2.2.1. Traffic related data analysis

Data requirements and approach

An estimation of total road traffic emissions - the sum of hot emissions, cold start emission evaporative emissions - requires firstly the quantification of the transport activity (number of vehicles, traffic volume, number of starts, fuels quantities, etc).

Pollutant emissions are influenced by a number of parameters : vehicle type and age, driving patterns, vehicle load, fuel volatility, thermal conditions, usage characteristics. Driving patterns are themselves linked to road characteristics, geographical location (urban, motorway, etc.), time period, etc. For emissions estimations, some of these variables are envisaged as categories (vehicle categories, geographical location), other as correction factors (gradient, load transported, etc.), and emissions functions can be speed and temperature dependent.

Then, for each of the different categories (vehicle types, geographical location, as well as a function of gradient or surrounding conditions), a description of the previous variables and the distribution of the transport activity is needed (Table 9). Correction factors have to be applied to statistics, if they exist, such as gradient distribution, load statistics, etc.

Table 9: Crossed configuration of the traffic-related data requirements.

	BY : - Geographical area (by country and according to : urban - road motorway), - Road characteristics (gradient, size, speed limits), and as a function of surrounding conditions and time periods
BY: - Transport mode, - Vehicle type (technology and age)	Traffic quantity (vehicle x kilometre), annual mileage, etc. Driving patterns (speed, speed profiles, accelerations, veh. load) Vehicle usage (description of trips, parking conditions, etc.) Operating conditions (ambient and engine temperatures, etc.) Fuel characteristics

To determine the availability of data and to collate it, a questionnaire has been sent to international and national organisations and statistics offices. [André *et al.*, 1999] provides a comprehensive list of these statistics, a characterisation of the investigation methods (surveys, vehicle instrumentation, etc. see also [André, 1998a]), and a detailed analysis of traffic-related statistics.

International sources provide harmonised, easy-to-manage, but macro-scale data (yearly, per country), as well as trends and comparative indices. The methods and results of national surveys and specific studies are not harmonised. Data is often dispersed between many institutions, and is difficult to obtain and to understand as most often results are expressed in the national language and relate to particularities of the country.

Apart from the discrepancies observed between different sources within the same country, and the difficulty in obtaining data for each country, vehicle category, and road type, a significant number of results and conclusions has been derived using mainly data from France, Sweden, Great-Britain, Switzerland and Germany.

Road network description and usage

Although the road network seems to be well understood, roads are not always defined in the same way. In addition, whilst there is a differentiation between public and private roads, traffic statistics only relate to public roads, though the private ones can represent a high share of the total length (50% in Sweden and Austria) and traffic volume (35% in Finland). Most often, the network description does not allow us to distinguish between urban and non urban roads. Where available, the urban / non urban rates indicate that there are clear differences in the definition of urban areas.

Given that a harmonised classification is required to combine emissions data and traffic data, it is surely preferable to adopt internationally recognised classifications and definitions. Even if this approach can result in some inconsistencies, it is desirable for international assessment and comparison.

Traffic quantification and distribution

An assessment of the available statistics has revealed the weaknesses in the data: for goods vehicles and 2 wheel vehicles data were very variable from one source to another one. Large gaps were observed between different estimations of urban traffic volume.

This contributes to the difficulty in estimating the urban part of the road network. A large proportion of urban traffic included motorway and main road traffic.

Passenger cars account for 75 to 90% of the total traffic volume (in vehicle.km), whilst goods vehicles represent 9 to 20 % depending on the country. Buses and two-wheelers account for about 1 to 2%. Light-duty vehicles seems to represent a high share (9% in Great-Britain, 15% in France).

The crossed distribution by vehicles categories and road types (or geographical areas) is rarely available and is seldom harmonised. However, it does indicate the differences in usage profiles : heavy-duty vehicles are more often used on motorways, whilst small cars seems to be used more in urban areas.

Driving conditions, vehicle speeds

The large amount of data has allowed us to improve significantly our knowledge of speeds.

A network and traffic assignment model based on Swedish data has been used to estimate speed as a function of vehicle type, road configuration (urban or rural roads, motorway, junction density), and traffic flow. Such a tool allows us to estimate speeds locally, even for a whole network. The proposed figures and speed measurements, which correspond to the road and traffic classification in Switzerland and Germany, provide a large set of reference data for cars and duty vehicles. The analysis of real-world speed profiles has also allowed us to characterise vehicle usage in the form of typical driving cycles.

The statistics have highlighted the impact of numerous factors on speed: road characteristics, weather conditions, time-period, gradient, etc. The significant variations in speed according to the time of day and area of a city, and the large dispersion of the values for a given situation, raise the question of using a single average value rather than a distribution, and its subsequent effect on the emissions estimation (see Table 10).

Table 10: Urban vehicle speeds (km/h) and variations with routes and time-period.

	Average speed (km/h)	variation according to the area or the routes	variation according to the time period
London (UK)	25 - 31	18 to 37	(18 to 37)
Thessaloniki (GR)	25		23 to 35
Graz (A)	20	18 to 21	16 to 22
Amiens (F)	22	16 to 30	17 to 28
Niort (F)	29	23 to 35	(22 to 46)

Finally, the estimated "overall average speeds" (i.e. including urban and rural roads and motorways) for passenger cars ranged between 35 and 50 km/h. An estimation using the "reference values" (average speeds, annual mileage and split into urban, rural and motorway areas, proposed in [Kyriakis *et. al.*, 1998] for each of the European countries by the respective national experts) lead to overall speeds ranging between 50 and 70 km/h. These estimates are - in all likelihood - too high, and indicate the necessity of a validation.

Usage conditions and other operating conditions

Detailed analysis of annual mileage and trip characteristics have also been conducted. This has highlighted the numerous factors affecting these parameters, and the discrepancies between methods of investigation (Figure 7). Some data concerning load factors and gradient is also proposed.

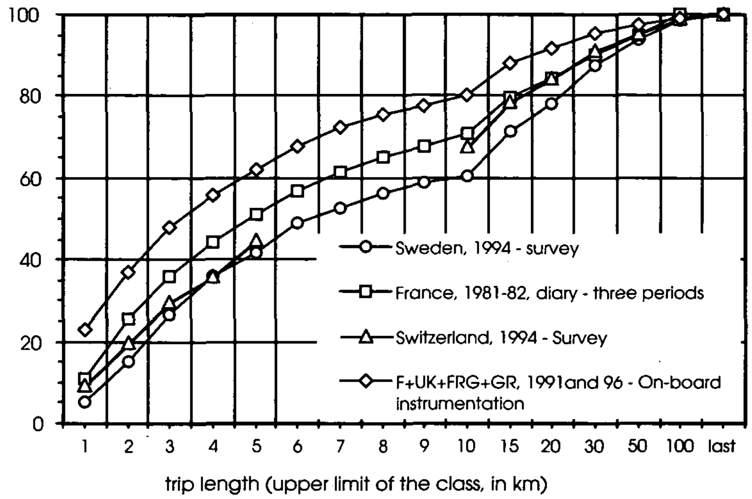

Figure 7: Trip length distributions from various surveys and vehicles instrumentation.

On-board measurements including temperatures have been analysed for the modelling of the cold start impact and for evaporative emissions estimation. Statistics on engine and ambient temperatures at engine start, trip length, distance travelled with a warming-up engine, driving speeds and daily usage have been established.

3.2.2.2. Driving patterns through modelling

Traffic simulation models have been widely used for many years in road planning. Such models normally include some description of driving behaviour. The description may range from a complete driving cycle to approximate data on average speed.

The main idea when using a model is to reduce the amount of measurements which else must be performed. The condition for this is that there is a good correlation between driving behaviour and factors describing the road, traffic situation etc. One example could be a network flow model, which can be used to describe the frequency of "events" in a road network. For these events measurements can be used to describe the driving profiles for stops, etc. [Edwards, 1997].

An advantage of a model is its ability to simulate and evaluate various future scenarios, including traffic management measures. With the aid of models, new driving cycles can be simulated as a function of the future conditions applied in the scenarios.

An inventory [Hammarström, 1996] has shown that there are many models potentially suitable for driving behaviour simulation and for calculations of vehicle exhaust emissions. In many cases these models include routines for exhaust emission calculations.

When modelling driving behaviour, the following definitions are used:

- Micro, i.e. a complete driving cycle for each vehicle
- Macro, i.e. a simplified description as an average for groups of vehicles.

The calculation of total exhaust emissions uses a combination of direct driving behaviour data and emission functions. There is no definite boundary between data needed for micro and macro models. The closer a model comes to "macro", the more the driving behaviour data will have to be integrated into the emission functions.

A model could probably never describe a complete driving cycle influenced by all the variables that exist in reality. With this restriction, the designation "complete driving cycles" is used here.

Micro simulation models for free-moving vehicles corresponds to the original project idea of COST 319. In this type of model the description of both the road environment and the vehicle is comparatively detailed. Driving attitude could be described as follows:

- Desired speed in relation to vehicle type, road width, speed limit, horizontal radius, wearing course and road condition
- Deceleration level as a function of speed in different situations
- Changing gears as a function of engine speed
- Proportion of throttle opening used in different situations.

For rural roads with traffic flows not too close to capacity, this type of model should be acceptable in most cases.

Micro simulation models including vehicle interactions are available both for urban and rural roads. The basic data is the same as for free- flow models, but is extended to include routines for car following, overtaking, and interactions in junctions.

Macro models and especially network flow models are frequently used. The road network described could represent a town or a region. An application for describing average speed as a function of area type, road type, speed as a function of area type, road type, speed limit, junction density and traffic flow is presented in [André *et al.*, 1999].

3.2.2.3. Conclusions

The synthesis of traffic-related statistics has allowed us to highlight various aspects:

- Significant discrepancies were observed between the statistics provided by different international organisations and institutions within the same country, and between the methods used. Even data that appear to be "normal" (network length, traffic volume distribution by transport modes, etc.), can be shown to be highly unreliable. Difficulties were encountered in obtaining data for the detailed vehicle categories and categorising traffic volumes and driving conditions according to urban - rural - motorway areas, to gradient, etc.

- A high number of speed values have been observed. These show the impact of numerous factors, and also the necessity to validate the reference speed values used in emissions inventories.

- Finally, a very large quantity of diverse traffic-related statistics have resulted from this work, highlighting the complexity of the subject. Further work should be conducted to extend this synthesis and to set the methodological basis of further data collection and ensure the harmonisation and quality of the results collected by the European countries.

The overview of traffic simulation models has shown that there are many types of model available, and in many cases they include subroutines for exhaust emissions. Probably due to a lack of contact between experts in road planning and specialists of exhaust emissions inventories, it has been difficult to combine both types of work.

3.2.3. Road traffic Composition

by Nikos Kyriakis

For the purposes of COST 319, road traffic composition refers to the breakdown of the vehicle fleet into a number of categories, which are defined in terms of emission factors and/or usage.

In theory, it should be possible to achieve the breakdown using statistical data. However, these data are usually not available, at least at the level of detail required. Therefore, some kind of modelling is needed to fill the unavoidable gaps.

Existing European vehicle fleet data and breakdown methodologies were reviewed by the working group B3 of COST 319. This work was finalised in MEET project, were it was enriched with a forecasting methodology that allowed road traffic composition to predicted up to the year 2020. The overall work is presented in detail in [Kyriakis *et al.*, 1998]. The text that follows is a summary of this deliverable, presenting comparative results.

3.2.3.1. Vehicle categories

The emission factors (see section 3.1) and the activity data (see sections 3.2.2 and 3.2.4) vary significantly according to the vehicle category. The categorisation of the vehicles is therefore a synthesis of the needs of the emission description and the possibilities of the activity data description.

The first, gross, split of vehicle pool is based on usage. Accordingly, the vehicle categories recognised are: passenger cars (PC), light duty vehicles (LDV), heavy duty vehicles (HDV) and two wheelers (2W). Each of these major categories is further divided in sub-categories, based on engine fuel and/or engine size (PC, LDV, 2W) or gross weight and usage (HDV). Each sub-category is further subdivided, according to the emission standards at the year of production.

On this basis, the vehicle fleet is finally divided into a large number of sub-sub-categories. This categorisation is made possible with the aid of appropriate models operating on a national level, and in certain cases on smaller scale (major cities etc.).

3.2.3.2. *Fleet evolution / turnover*

A large number of attempts to simulate the ageing and technology substitution processes of automobiles can be found in the literature. These either use economic parameters as explanatory variables for the vehicle ownership and technology substitutions forecasts, or apply system dynamics approaches - see for instance [André, 1998b]. Alternatively, an engineering approach can be used, whereby forecasts are based on phenomenological analysis of past trends. This approach was adopted for the MEET purposes.

A key feature of this approach is the sigmoid shape of the vehicle density curve (vehicles per inhabitants) as a function of the calendar year. The parameters of this curve, as well as its saturation value, can be determined as long as sufficient and reliable statistical data exist for the past. Based on the same data, the probability of a vehicle of a certain age being present can also be determined. The combination of the above allows the road traffic composition to be predicted.

3.2.3.3. *Results*

Figure 8 presents the passenger car densities of the European countries in 1970 and 1995, and the forecast for the year 2020 since this results from the application of the forecasting methodology described in outline above.

Figure 9 presents the mean passenger age of the European countries for the year 1995.

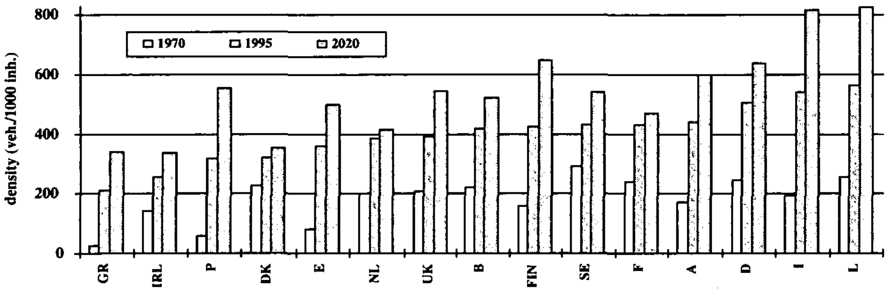

Figure 8: Passenger car densities of the European countries.

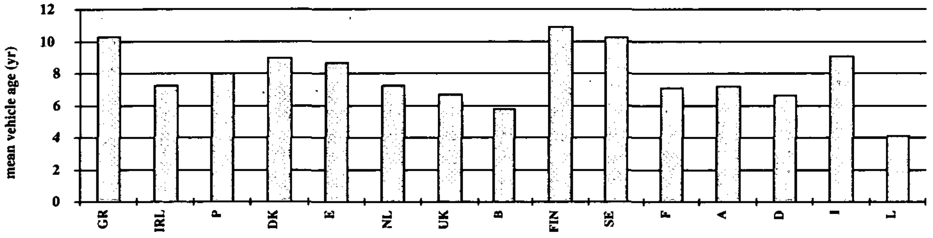

Figure 9: Mean passenger car age of the European countries (1995 data).

As it can be seen in Figure 8 and Figure 9, there are significant differences between the European countries. Regarding the passenger car density (Figure 8), it is clear that there is a factor of almost 3 for the year 1995 between Greece and Luxembourg. About the same factor exists between the mean passenger car age of Luxembourg and Finland for the same year.

Annex 8 shows the effect of vehicle age on the average annual mileage of the passenger cars (1990 data). There is a sufficient trend towards usage reduction with car ageing. Also, there is a general trend for more intense usage of the diesel and the larger gasoline passenger cars. Complementary data on annual mileages and age effects can be bound in [André *et al.*, 1999].

Figure 10 presents the passenger car fleet distribution over the main engine type categories (gasoline < 1.4 l, gasoline 1.4 - 2.0 l, gasoline > 2.0, diesel and LPG). As it can be seen, again the distribution is strongly depended on the country, in general the most popular category being the gasoline < 1.4 l. It is of interest to note that LPG vehicles have an important participation only in Italy and the Netherlands. Similar comments can be made for the commercial vehicle (light- and heavy duty vehicles) split, the less populated category being that of the HDV > 32 t (see Annex 9).

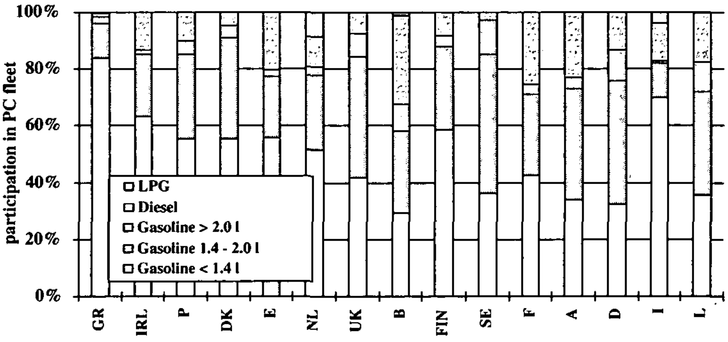

Figure 10: Passenger car fleet distribution (1995 data).

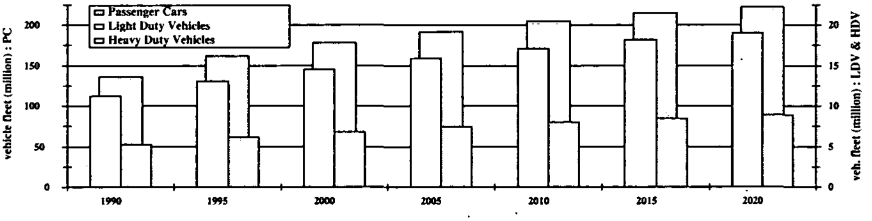

Figure 11: The evolution of Passenger Cars and Light- and Heavy Duty vehicles in the EU 15 countries.

The forecast evolution of the three main vehicle categories for all EU 15 is shown in Figure 11. On the basis of this forecast, it is expected that LDVs will continue to be less than 1/10 of the passenger cars, the heavy duty vehicles (trucks and buses) being about half the LDVs.

3.2.4. *Links between the mobility and emission models*

by Benoit Gilson, Vincent Favrel and Walter Hecq

See [Gilson *et al.*, 1997] for a more detailed report.

3.2.4.1. Overview of Mobility Models

Transport demand is induced by economic, demographic, political, and social factors. These factors influence transport demand with different orders of magnitude and follow complex mechanisms.

To predict transport demand, two main types of model are available. On the one hand, econometric models can be used to explain a variable related to mobility as a function of the most significant socio-economic variables. On the other hand, mobility models (often called network flow models) can be used to model traffic flow on a transport network. Mobility models are more dis-aggregated and provide more a detailed output than the econometric models.

Econometric models

Econometric models are stochastic. They explain a variable of interest (dependant variable) as a function of socio-economic variables (explanatory variable) which are time series. Times series can be either yearly, monthly or quarterly. The goal of these models is the understanding of the main determinants of the dependant variable studied over the considered time period.

There are three types of econometric model. They differ according to the dependant variable studied : either an indicator of mobility, fuel consumption, or a variable related to car fleet. In the case of modelling indicators of mobility, the dependent variable is a measure of the volume of transport, e.g. number of passenger-kilometres, vehicle miles travelled, miles travelled per car (or light trucks or lorries) etc [Greene, 1992]. For fuel consumption, the dependant variable is aggregated and can be expressed in gasoline, diesel or LPG consumption per capita, per household, or per vehicle [Epsey, 1996]. Finally, in the case of car fleet analysis, the dependant variable can be the motorization rate (the mean number of cars per adult). The methodology for the latter case is somewhat different to that of previous models as a demographic approach (longitudinal analysis) is used. This last approach is based on household expenditure surveys and panel data estimation techniques [Madre, 1995].

All of these models consider income and price/COST as main *explanatory variables*, introduced as exogenous inputs. Only a few other socio-economic variables are taken into account in these models but they are weakly significant (e.g. driven licence in the case of passenger-kilometre analysis). Data (explanatory and dependant variables) are, in general, easily available and predictable[1], but only on a broad aggregated (national) scale.

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[1] Variables can be forecast using various existing statistical techniques on the basis of the available observations.

Network flow models

"Network flow models" are, unlike econometric models, based on more dis-aggregated data. These models model transport demand by taking into account a defined transport network structure, and by means of the estimated origin-destination (O/D) matrices. The main goal is to simulate traffic on a geographic network per time period. These models consider a defined area which is split into several zones. Trips between zones are modelled. Areas covered can be local (e.g. urban level) and on a wider scale (e.g. regional or national level). The zoning system is, in general, at NUTS (Nomenclature of Territorial units of Statistics) 0,1,2 or 3 level.

The network is represented by links and nodes. Usually links are physical and logical (e.g. transfer between transport modes) connections. Two types of nodes are used : nodes representing a junction where three or more links meet or when a route changes its characteristics and the centroid nodes which represent origin zones and destination zones.

Each link of the network includes a start node, an end node, and a link type. Different parameters can be coded on the link: distance, capacity, travel time/speed, even delays for custom formalities, etc. Representations of links for road, rail, and air networks are dependent upon the level of detail covered by the model. O/D matrices represent the number of trips between each centroid node.

Classical transport models are made up of 4 main steps (sub-models): generation, distribution, modal choice and assignment steps. For a more detailed description, see Transport Research-APAS 22 studies [CEC, 1996].

The first step, which is called the *generation/attraction model*, estimates the number of trips leaving a zone (generated trips) and entering a zone (attracted trips) on the basis of socio-economic variables. Passenger and freight transportation are handled separately.

The second step is the *distribution model*, for which O/D matrices are built. These models estimate where the produced trips will go to, and where the attracted trip comes from.

The *modal choice model* constitutes the third step in transport modelling. The share of trips following the transport mode used is estimated. This results in the division of the O/D matrices built in the previous step into several sub-matrices, one for each transport mode.

The final step of the 4-step model is the *trip assignment model* where route choices are modelled. Trips, calculated in the previous steps, are assigned to a network. This results in a loaded network. The outputs are calculated for each O/D pair as path flows, junction delays, O/D travel costs. The assignment procedures can be either deterministic or stochastic. Travellers choose paths which minimise their generalised COST (or utility) functions (mainly the time parameter). In the stochastic case, a random term is added to the assignment algorithm.

Finally, a *validation* procedure is often added. Note that some models include explicitly the assignment phase by taking O/D matrices as exogenous input.

The four-step transport model scheme is used by the most well-known modelling tools. APAS 22 give an overview of the strategic or multi-national models available in the

European Economic Area. The APAS database describes 62 passenger models and 43 freight models, collected with several criteria (e.g. for passenger models) : scale (part of country, one country, part of Europe, European Union, Europe); area (in square km^2) ; scope ((part) of the home country, international); number of O/D matrices (for cars, public transport, air, sea, bicycle, pedestrian, others); number of trip purposes (0, 1, 2, $\geq$ 2); number of zones (0-200, 22-500, 55-1000, >1000); number of links in a road network (no network, 0-5 000, 5 000-10 000, 10 000-50 000, >50 000); time basis (year/month, day, morning peak, evening peak, day + peak, parts of the day average weekday); etc..

One important aspect for emission assessment is that these models can infer average speed on the links in relation to the traffic flow (number of passenger cars per hour and number of lorries per hour). The speed-flow function depends on link characteristics : capacity, number of lanes, terrain characteristics (slopes, bends).

3.2.4.2. Emission models

As a remainder, numerous emission models have been developed to assess emissions from transportation in function of explaining variables. The section 3.3 presents an extensive overview of the bottom-up emission models describing their main characteristics (e.g. time scale, traffic input, fleet description, pollutant involved, kind of output, etc.). Emission modelling focuses mainly on hot emissions but specific methodologies are proposed to take into account cold start emissions (see section 3.1.4), evaporative emissions and the influence of road gradient or load factor (see sections 3.1.5 and 3.1.6). Most of these elements are found in the COPERT II methodology [Ahlvik *et al.*, 1997] and the German-Swiss model [Hassel *et al.*, 1994; Keller *et al.*, 1995] which can be considered as references. Therefore, we have chosen these two models to consider linking between emission models and mobility models.

Concerning non road transportation, models for the calculation of non-road transport emissions have not been specifically considered in a linking perspective in this study.

3.2.4.3. Linking emission models and mobility models

Mobility models and emission models represent two components of one modelling process. These components have been largely developed independently from one to another and few studies have focussed on linking them [Hammarström, 1996]. This is one of the reasons why, currently, mobility models cannot directly provide usable data to emission models.

Data required for the road emission calculation

From a linking perspective, the main data lacking for hot emission calculations are the following: the number of vehicles per category, the kilometres driven per vehicle category on different road section types, and the average speed per road type taken into account (COPERT), or allocation of typical traffic situations to the road network with respect to different road section types (German/Swiss model).

Considering cold start emissions, apart from meteorological parameters and fuel properties, the data required that could possibly be supplied by mobility models concern : the average trip length per vehicle trip and the total annual kilometres driven by the vehicle of each category (referring to COPERT) or the distance travelled by the vehicle, the number of starts per day and per vehicle and parking duration before the trip (referring to the German/Swiss model).

COPERT II suggests a methodology for evaporative emission calculation. It requires many parameters that are, most of the time unavailable and have to be estimated. These parameters are the following : the fraction of trips finished with hot engines, the fraction of trips finished with cold engines or with the catalyst below its light-off temperature, the yearly average number of trips per vehicle per day and the total annual mileage of each vehicle category. Referring to the German/Swiss model and for the same purpose, other parameters have to be estimated : the number of times the engine is turned off, the frequency distribution of the travelled distance before the engine is turned off and the frequency distribution of the parking duration after the engine is turned off.

Linking considerations with econometric models for road transport

The ability of econometric models to predict future changes in fuel consumption, vehicle kilometres, or vehicle fleet composition can be considered for the assessment of future air pollution reduction measures. However, some major disadvantages remains from a linking point of view : the aggregated character of data (mobility is modelled as a whole) and these models do not deal intrinsically with any measure of mean speed (which is completely exogenous).

The aggregated character means that we do not have predictions of mobility per transport mode, per vehicle category, etc. Other econometric models could be built to split, for example, urban from non urban vehicles, provided statistics are available. Further investigation would be required to assess this possibility. The existing econometric models, which have been developed with goals other than emission assessment, partly satisfy the requirements of emission models provided simplifying assumptions are made.

When based on fuel consumption, models do not differentiate between different fuel types. Once again, if data on total annual fuel consumption for each type of fuel were available, models could be built on a time- series basis. These models can be linked with emission models, such as COPERT II, which calculates the total annual fuel consumption as a calibration parameter for estimating uncertain parameters (e.g. average annual mileage driven on each road class and for each vehicle category).

Furthermore, econometric models could provide information on car fleet composition or motorisation rate, which is of great interest for all types of emissions, using age cohort models. But these models provide once again only aggregated information on the car fleet as a whole. In fact, emission models require not only the total number of cars per country/region but also the structure of the car fleet, i.e. : the share of diesel, gasoline and LPG cars, or the share of different vehicle cubic capacities and the age categories of each vehicle.

Linking considerations with complex "Road network flow" models

From mobility models, it is possible to infer for each O/D trip : the number of vehicles travelling per mode and the average speed from the origin to the destination (knowing the average speed on each link type travelled). Trip distance, number of kilometres travelled per time period, number of starts can also be deduced from the input and output of the mobility models. The main matching problems between emission calculation and mobility models remain in the calculation of kilometres driven per vehicle category and of kilometres driven per road type.

In particular, concerning cold start emissions, the number of starting operations is unknown. To find it, we can make the restrictive assumption that each trip leaving a zone is considered as a start. Concerning parking duration distribution before the trip, further information has been requested from mobility model developers in order to establish if this parameter can be provided one way or another. Cold start and evaporative emissions also depend on the outside temperature which can be different following the parking location of the vehicles (indoor, outdoor). This aspect is not considered in the models and requires additional data concerning the share of vehicles parked in an indoor heated parking. Up to now, neither mobility models nor emission models consider this aspect. New developments in cold start emission modelling [Sérié & Joumard, 1997] consider the driving pattern at the beginning of the trip using the average speed as additional data. This last parameter is available from the mobility models.

Concerning evaporative emissions, the fraction of trips finished with hot engines and the fraction of trips finished with cold engines, or with the catalyst below its light-off temperature, can be determined once the trip length distribution and the ambient temperature are known. The number of trips per vehicle and per day, and the total annual mileage of the vehicle category, can also be determined by processing the output data from mobility models. The number of times the engine is turned off can be roughly estimated by assuming that it is equal to the number of trips arriving at a zone.

As mentioned previously, similar problems arise when linking emission and mobility models. Firstly, mobility models can only distinguish the share of kilometres driven by car, bus/coach and by truck. In order to reconcile them with emission models, two solutions are envisaged:

- to refine modal choice models by splitting existing modes into sub-categories, for instance, by splitting the O/D matrices for cars into sub-matrices differentiating car sub-categories (fuel types and technological concepts). This should be assessed to see the possible level of dis-aggregation that can be achieved and the COST involved;
- to use statistical data on the car fleet, and to weight the number of vehicles on each O/D pair by the share of the different vehicle categories, including annual variations. This alternative could easily be made operational but the accuracy of the method needs to be assessed.

Secondly, differences are observed in the road typologies used for mobility and emission models. A homogenisation and a standardisation will make the link easier between both models. For instance :

- The COPERT II emission model only differentiates three road types (urban, rural and highway);
- The German/Swiss emission model differentiates for three basic road types about 20 standard traffic situations for the different vehicle categories;
- Mobility models like STREAMS differentiate 9 road type links.

Attention must be paid to the fact that mobility models represent an idealised version of reality, and the accuracy of the output data is uncertain. It is perhaps negligible for the objectives for which mobility models have been initially built (analysis of congestion, economic inefficiencies, alternative development patterns, etc.) but for linking with emission models the degree of certainty needed for input data (average speed, trip distances, etc.) must also be assessed if acceptable results are to be obtained. Finally, the transportation network area studied with mobility models only partly covers the actual transport network. Therefore, no validation with fuel consumption statistics is possible at a national level.

3.3. Inventorying tools for road transport

By Zissis Samaras, Emanuele Negrenti, Mario Keller and Robert Joumard

The initial objectives of the working group included the following main research topics:

- Harmonisation of the input categories with respect to emission factors, driving behaviour, the necessary segmentation of the mobility segments.
- Harmonisation of common tools that can be used by several users; are two models (one micro and one macroscale) sufficient? How should these models be related to each other in order to produce consistent results?
- Adoption of a common methodology and a common model to forecast motor vehicle emissions at each level.
- As regards regional and local inventories, the output of the adopted models should be compared to the results of simple approaches (e.g. spatial allocation of emissions based on local fuel consumption or traffic loads) in order to investigate whether such simple models can estimate emissions with reasonable accuracy.
- Validation of the adopted methodologies at local level.

Many of the these objectives have been met. In particular [Hickman *et al.*, 1999] provided a harmonised methodology, including emission factors and driving and usage data as well future forecasts for the estimation of emissions from all modes of transport. This was achieved through an iterative process in which all subgroups were involved. This MEET model was already used, either for calculating aggregated models [Cox and Hickman, 1998] using a first version of the model [Samaras *et al.*, 1998a], or to compare transport modes as regards their pollutant emissions [Keller and de Haan, 1998].

However, many important objectives still remain unanswered, particularly in relation to the harmonisation of micro-scale and macro-scale emission models and the validation of the emission estimates. In this section a number of emission models are compared, a review of the available emission models is presented, a discussion on the classification of the models is conducted, and finally methodological aspects are discussed, in view of their application.

3.3.1. Comparison of emission models

3.3.1.1. European models

This section provides a comparison of a number of emission estimation tools that are used in Europe. The main aim was to carry out an overall comparison of the models with particular emphasis on passenger car emissions, and to provide an appraisal of their applicability and accuracy. The following models were compared:

- The 'Workbook of Emission Factors', in short HBEFA [Infras, 1995], which is the result of a Swiss/German project that was carried out from the late 80s until 1995. A main feature of the model is that hot emission factors of passenger cars are expressed as a function of instantaneous vehicle speed and acceleration, and then calculated for driving patterns which represent different distributions of speed and acceleration.
- The model derived from emission measurements conducted in the framework of the DRIVE-MODEM project, in which emission factors are again expressed as a function of instantaneous speed and acceleration [Joumard *et al.*, 1995a].
- The 'Digitised Graz Method' (DGV) [Sturm *et al.*, 1994]. As with the previous two models, this model calculates emissions from passenger cars with the aid of instantaneous emission maps, albeit based on a rather limited database.
- The COPERT 90 model [Eggleston *et al.*, 1993], developed by the European CORINAIR working group.

The emissions factors were calculated for different vehicle categories with recorded driving sequences - see [Zachariadis, 1995 and 1996; Zachariadis and Samaras, 1996] for detailed results; Figure 12 present an example. One can observe the most significant differences in CO and HC emissions of catalyst cars, in NOx emissions of catalyst and diesel cars and in HC emissions of diesel cars. At medium and high speeds, though, all four models produce fairly similar results, with NOx being sometimes an exception. However, despite these significant differences in estimates of emission factors for individual vehicle categories, the overall results of the models for a real-world vehicle mix are in most cases much less pronounced, particularly between HBEFA and COPERT, with DRIVE-MODEM generally being an exception.

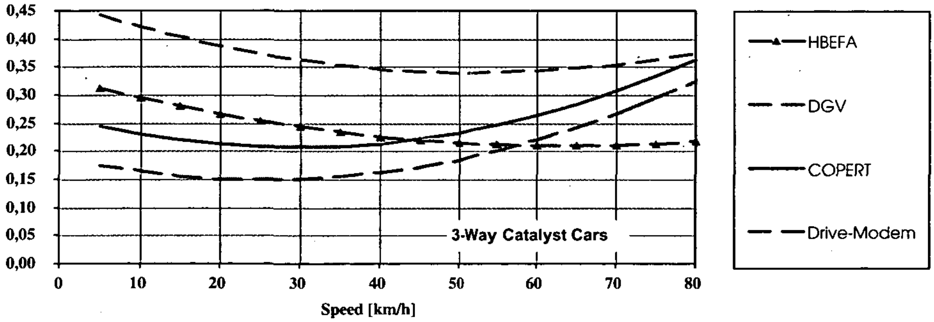

Figure 12: Comparison of hot NOx emission factors of pre-1991 3-way catalyst cars, as calculated for recorded driving sequences of Thessaloniki with the four models.

3.3.1.2. Comparison with MOBILE 5a

The structure, assumptions, and estimates of COPERT 90 were compared with those of MOBILE 5a, the latest version (at the time) of the United States Environmental Protection Agency's mobile source emission factor model [USEPA, 1992 and 1995]. The major results of this comparative analysis [Samaras & Zachariadis, 1994] are summarised below.

Federal Test Procedure (FTP) emission data provide the major background information for MOBILE's basic emission rates, deterioration rates, tampering rates and correction factors. In contrast to that, COPERT emission factors of passenger cars and light duty trucks are the product of a synthesis of emission data over various driving cycles.

MOBILE distinguishes between the three FTP operating modes: cold start, hot stabilised, and hot start, and derives the corresponding correction. COPERT assumes two operating modes: hot and cold start. A comparative assessment of the effect of ambient temperature on emissions of light-duty gasoline vehicles was performed (see an example in Figure 13). From this comparison it became clear that, with the exception of NOx emissions, there are significant differences between the two models: COPERT assumes a greater impact of low temperatures and cold start operation on non-catalyst vehicles than MOBILE, while MOBILE estimates higher emissions for catalyst vehicles in cold start operation than COPERT.

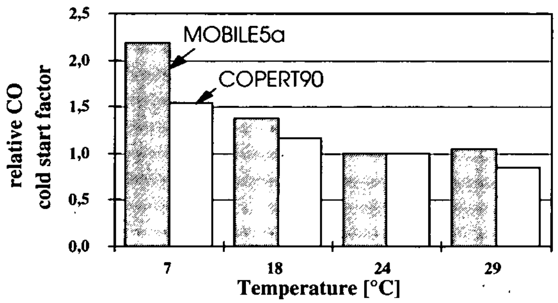

Figure 13: Extra cold start emissions of CO, as calculated by MOBILE 5a and COPERT 90 for pre-1991 3-way catalyst cars. Reference temperature is 24°C (75°F).

COPERT bases its estimates of evaporative emissions on limited information from just a few tests, whilst MOBILE has a more detailed evaporative emissions methodology. Major differences include the following:

- COPERT does not include resting losses as a separate category, and it does not estimate refuelling emissions;
- COPERT assumes zero hot soak losses for fuel injected vehicles with evaporative emission control, which is entirely different from the respective assumptions of MOBILE;
- COPERT uses average evaporative emission factors for gasoline vehicles of all types and ages, whereas the MOBILE methodology is more refined since it differentiates between vehicle types and vehicles with different emission control technology

In addition, MOBILE accounts for the influence of parameters that had not been investigated in Europe before 1990 and were therefore not included in COPERT 90. Such factors include the effects on emissions of gasoline volatility, air conditioner use, extra load, trailer towing, and altitude.

Both MOBILE 5a and COPERT 90 were used to calculation road traffic exhaust emissions in Greece in the year 1990, based on the same vehicle usage parameters. Average fuel-related emission factors were examined (Figure 14): COPERT 90 estimated higher emissions per unit of fuel consumed than MOBILE 5a. However, the total results of the calculations showed that only estimates of NOx emissions in Mobile were significantly higher (about 65%) than in COPERT. This was largely due to the higher emission factors for heavy-duty diesel vehicles in MOBILE. Exhaust NMVOC and CO emission estimates were essentially the same using both methodologies, which led to the conclusion that, even if considerable differences existed, they were almost eliminated at the level of aggregation that was investigated.

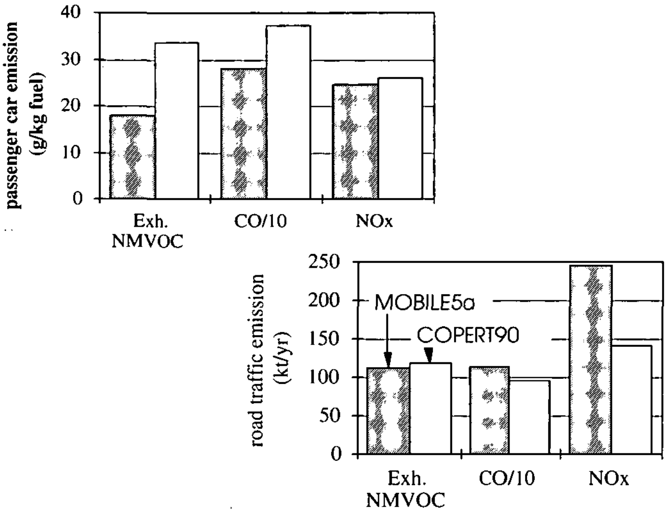

Figure 14: Average passenger car emission factors and road traffic emissions in Greece in the year 1990, as calculated by MOBILE 5a and COPERT 90.

The comparative analysis revealed that, although MOBILE 5a and COPERT 90 have the same basic structure, they also differ considerably, the differences reflecting the different stage of development of each model. MOBILE is suitable for the estimation of motor vehicle emissions in countries with an extensive FTP database and with vehicle fleet characteristics that are similar to North American ones.

3.3.2. Review of the available emission models

The level of complexity of all available models depends basically on the availability of input data. Generally three types of input data are needed: an activity or mobility indicator (e.g. vehicle-kilometres), an emission factor (e.g. g/veh-km), and a definition of the differentiation needed or desired. In general it is this latter element which determines the characteristics and the complexity of the model. This concerns in particular the pollutants covered, the categories of vehicles through their size, their technology, or their fuel, the driving conditions (average speed, or dynamics of the driving patterns), the additional factors of influence (e.g. altitude, slope, inspection/maintenance), and finally the segmentation of the activity (i.e. veh-km) according to the purpose of the model.

All models are intended to be used for a given current situation, and for future forecasts. In the latter case, the aim is usually to analyse how certain objectives can be met, or to evaluate particular measures and policies.

Thirty nine emission models have been considered. The models employ a variety of different approaches and have a number of different applications [Negrenti, 1998]. Their main parameters are presented in Annex 10.

The reported emission models belong to different families: some of them can be classified as macroscopic (city or country related models), whilst others have a more local (street level) character. Some models deal with the behaviour of a single vehicle (vehicle simulators), whilst others take into account only specific aspects (e.g. the cold start effect) of the pollutant emission process. In principle, it should therefore be possible to define a classification system for the models based on such features. In reality, the sectors of application of different types of models do not have closed boundaries, but often show a remarkable degree of overlap. To account for these limitations, we agreed to attempt a rough classification of models based on the most relevant characteristics. Two complementary ways of classifying emission models were identified. These related to either to the level of aggregation of emission factors, or to the type of application.

3.3.2.1. Classification according to the level of aggregation of emission factors

It is important to note that the differentiation of emission models according to the level of aggregation of the emission factors does not depend at all on the detail of the software, and consequently on the intended application. It is only related to the experimental data which supports the emission calculations. According to the emission factor characteristics, the emission models can generally be divided into three categories:

- The average speed based models or base models. These are the most commonly used models and account for vehicle dynamics using the concept of average speed. They work on the basis of specific emission/consumption factors for vehicle/engine technologies for particular traffic conditions. They usually form the basis of local air quality calculations, and work characteristically on the scale of a town.
- The disaggregated emission models. These take into account vehicle kinematics through detailed parameters such as speed and acceleration. They allow calculations on a local scale (down to traffic intersections), but can also be integrated for regional or national inventories. They allow vehicle characteristics to be altered individually and thereby to calculate expected future trends. They have been discussed in detail in Section 3.1.2.
- The aggregated models consist the third type of emission estimation tools. These are based on vehicle usage statistics such as annual mileage, share of road types,

- characteristic average speeds, etc. They calculate overall emissions/consumption, including cold-start effects, evaporation etc., and are used for regional or national emission/consumption inventories. These too make use of empirical average emission/consumption factors, usually produced on the basis of integrated values resulting from average speed models. An approach of this type was used by [Cox & Hickman, 1998] to develop the MEET model, in which emission factors were defined according to road type, country, and the whole European Union.

Table 11 provides an overview of the necessary and commonly used input data for these three types of model. It should also be noted that the above classification is in accordance with the distinction between the macroscale or top-down models (in practice this is just another name for average speed models) and microscale or bottom-up models (disaggregated models).

Table 11: Input data of the three categories of emission models.

	Disaggregated	Base	Aggregated
traffic volume	xxx	xxx	xxx
fleet composition	xx	xxx	xx°
average speed		xx	xx°
kinematics	xxx		
gradient	xx°	xx	x°
loading	xx°	xx	x°
ambient conditions (temp., humid.,etc.)	x°	x	x°
altitude	x°	x	x°
maintenance	x°	x	x°

x = relevant ... xxx = essential, ° = depends on the model

3.3.2.2. *Classification according to the type of application*

In order to classify the emission models according to the application, the following approach was followed:

- Systematic but aggregated definition of the expected application areas of the emission models, with the objective of defining how many types of models are needed (see Table 12). The 6 application areas were obtained by combining the 3 typical scales of calculation with the 2 usual types of calculation (absolute estimate and comparison of two situations).
- Identification of the sensitivities needed in each target model, with the objective of checking the capability of target models to take into account the relevant affecting parameters (see Table 13). The parameters have been scored in terms of relative importance for each of the 6 application areas so identified.
- Identification of the sensitivity required in each target model, with the objective of checking the ability of the models to take into account the important parameters (see Table 13). The parameters have been rated in terms of relative importance for each of the 6 application areas identified.

Table 12: Identification of the expected fundamental application areas for the emission models

	spatial scale		
type of calculation	street, route, cycle, urban area	urban network	regional, national, European
impact analysis (differential estimates)	**A**: e.g. transport telematic assess.	**C**: e.g. urban policies assessment	**E**: e.g. European network assessment
inventories (absolute estimates)	**B**: e.g. street, road, highway pollution dispersion analysis	**D**: e.g. urban inventories	**F**: e.g. national and European inventories

The following comments summarise the findings of Table 12 and Table 13:

- the split between absolute and differential analyses allowed us to determine which parameters are relevant in one case and not (or lower) in the other one.
- the defined boundaries between local, urban, and large-scale models were not absolute, but reflected the current best practice in emission modelling.
- The scheme presented in Table 12 would have apparently required 6 types of model, but in practice we can expect that the same models are used for absolute and differential calculations on the same time-space scale. Therefore, only 3 models would actually be required - one for each typical spatial (and temporal) scale.

3.3.2.3. Discussion of the two classification approaches

It is clear from the above explanation that the issue of emission inventorying has been approached from two different directions: firstly from the emissions data and secondly from the application point of view. It is evident, however, that the detail of the experimental data defines to a large extent the applicability of the emission calculations which are based on this particular data. It was made clear also (see Negrenti, 1998) that there is a great deal of overlap between the different emission models as regards the possible applications proposed by the developers. An important example here is: can average speed based emission factors support detailed calculations at very low (i.e. street) level ?

Table 13: Applications versus parameters affecting emissions

	application areas (see Table 12)						x = relevant, xx = essential
Parameters	A	B	C	D	E	F	notes
traffic volume (flow or mileage)	xx	xx	xx	xx	xx	xx	always essential
average speed	x (1)	x (1)	x	xx	xx	xx	1) less relevant than speed vs time
speed cycle	xx	xx	xx (2)	xx	-	-	2) policies impacting speed cycle (e.g. transport telematics)
gradient	x (3)	xx	-	xx	x (3)	x (4)	3) infrastructure impacts at street or corridor level 4) in very hilly countries
fleet composition	xx (5)	xx	xx (5)	xx	xx (5)	xx	5) policies changing fleet composition
Age	-	-	x (6)	-	x (6)	-	6) assess. of fleet renewal policies
maintenance	-	-	x (7)	-	x (7)	-	7) assess. of inspection maintenance policies
temperature (and trip length)	x	xx	x (8)	xx	x (8)	xx	8) policies impacting trip length
loading	-	x	x (9)	x	xx (9)	x	9) public transport or freight management
altitude	-	x (10)	-	x (10)	-	x (10)	10) relevant for CO, VOC, NOx
parking flows	xx(11)	xx	xx(11)	x	-	-	11) to assess parking policies

In view of the above, it is necessary to identify the uncertainties relating to the use of each type of model and how much can be expected from vehicle emission models.

What degree of detailed analysis is necessary for different applications?

As already mentioned, vehicle emission estimates are used for various purposes. Each one of them requires different detail and accuracy.

Emission forecasts: These are applications where fine spatial and temporal resolution is not required, and trends are generally more important than absolute emission levels. Thus, speed-dependent emission factors can adequately simulate reality. In order to come up with reliable emission factors, for each driving mode (e.g. for urban driving) the corresponding average speed should be derived using appropriate measurements and assumptions.

Air quality models: Applications for an urban region, which are comparatively detailed, require emission inventories with a spatial resolution of 500 x 500 m or 1 x 1 km. On such a scale, emissions in individual streets are not of great interest since emissions are averaged over a number of similar streets. Hence, speed-dependent emission factors seem to be sufficient. What is of particular importance in such simulations is an accurate knowledge of the distance travelled with cold engines in each part of the simulated area and for each hour of the day, as well as the impact of these cold starts on emissions. Attention should therefore focus on these issues in addition to the effect of the altitude of the region and the gradient of streets in specific parts of the area.

Small-scale applications: The calculation of emissions on the level of a single street is associated with a high degree of uncertainty. The representativity of all input data (driving profile, emissions, etc) is crucial, and the outcome for some individual streets may be considerably different from the average estimated emissions in streets of the same type. In such cases, in addition to the average speed, the vehicle kinematics on that street may have a significant influence, and simple speed-dependent emission factors may therefore be inadequate. Where driving behaviour and dynamics are of major interest (e.g. the impacts of changes in the driving behaviour have to be assessed) disaggregated approaches are recommended, as stated in chapter 3.1.2.5. However, instantaneous models do not predict consistent trends. Furthermore, the following should be noted:

- With the exception of NOx emissions, models based on modal emission measurements indicate that speed fluctuation is indeed relevant, but average speed itself is still an important influencing factor.
- The dispersion of emission results should not be overlooked. If applied to a particular case there is a wide variation of different driving profiles - even in the same individual street, creating a wide dispersion of emission results.

Table 14: Comparison of hot CO, HC and NOx emission patterns from passenger cars according to the different models in major streets of Thessaloniki.

Model	CO	HC	NOx
HBEFA built-in	118	107	71
HBEFA Thessaloniki	98	110	80
COPERT (reference point)	100	100	100
DGV	117	101	67
DRIVE-MODEM	184	141	133

The overall effect of different models on emission estimates

Hot emissions from passenger cars were studied using the 5 models presented in section 3.3.1.1 for the five streets of Thessaloniki in Greece which were used as an example earlier in this review. Two sets of HBEFA's functions were used: one derived on the basis of the Thessaloniki traffic recordings, and one based on the default traffic situations built into the model. Traffic load patterns for these streets were taken from official counts made by local authorities. A fleet composition close to that of the current Greek car fleet was assumed. Table 14 provides in relative terms the total emission estimates for all five streets. As expected, DRIVE-MODEM clearly produced higher results, particularly for some streets. The other models, in spite of considerable differences in individual vehicle categories, differed by up to ±15%. These differences were lower for CO and HC. This meant that for overall emission estimates for a country or a city, or even at street level, the differences observed, particularly between HBEFA and COPERT, were quite small.

3.3.3. Methodological aspects of emission factor application

Classical emission inventories are not the only applications for which emissions and emission factors are of relevance. In fact, many policy questions can be addressed using indicators, in particular *environmental indicators.* These are generally defined as the amount of a given pollutant released from a given process (with associated pollution control processes), normalised for a given factor (e.g. number of inhabitants, gross domestic product, etc.). Since in transport the causality between the environmental loads or pressures and the normalisation factor is not necessarily straightforward, it is more common to use *transport activity* as normalisation factor. The environmental indicators are then a measure for the "eco-efficiency" of a particular transport mode, or of a transport mode in a particular situation. These indicators can then be used to perform comparisons between different transport modes, between regions or countries, or between different points in time.

Calculation of these indicators requires quantification of the emissions as a specific term [g/veh-km], or in absolute terms [e.g. total emissions of mode m in year y]. Since environmental indicators generally only make sense in a comparative context, it is a prerequisite to consider carefully how emission factors are applied and what aspects should be considered when doing so. In the following paragraphs, several methodological aspects and important factors are addressed which have been described in studies of intermodal comparisons using the MEET methodology [Keller & de Haan, 1998].

3.3.3.1. Units of transport

In order to perform comparisons, a common unit of the transport activity has to be defined. A well established unit is the "passenger kilometer" (p-km) or "tonne kilometer" (t-km), resulting in indicators like "g/p-km" or "g/t-km". These indicators, easy to use and to communicate, are the most commonly used. However, there are shortcomings:

- Additional information or assumptions are required, in particular about load factors (passengers or tonnes transported per vehicle) since the emissions in general are calculated per veh-km. Since the information about load factors often is scarce, this introduces a substantial source of additional uncertainty into the calculation.
- What is conceptually more relevant is that these indicators are independent of the distance over which the persons travel or the goods are transported. Often transport distances vary inherently between modes. For instance, air trips are longer than car trips. In these cases, the indicator g/p-km or g/t-km does not reflect the typical usage of the mode, and hence the behavioural dimension is ignored. Therefore, it would sometimes be more meaningful to base the comparison on the activity or the product connected with a transport activity rather than the underlying activity itself. Examples: If we compare the ecological impact of wine from Europe with wine from e.g. California, the most adequate comparison is not per tonne kilometre, but on a product basis (total transport related emissions per bottle of wine).

Despite these shortcomings, the indicators g/p-km or g/t-km are well established and can be used, in general, as an indication of the (specific) environmental loads.

3.3.3.2. Operational emissions versus life cycle analysis

In COST 319 / MEET the exhaust and evaporative emissions arising during the operation of vehicles are emphasised. In addition, the production of energy is taken into account. However, if long term policy decisions are to be discussed, these areas form only part of a complete life cycle assessment, which roughly covers the following processes and activities:

- *Construction of vehicles*: Use of materials and energy, together with the corresponding emissions, used to build the vehicles
- *Maintenance of vehicles*: Use of materials (e.g. paint) and energy for maintenance
- *Operation of vehicles*: Direct emissions from the vehicle
- *Energy production*: Emissions due to the production and the delivery of the energy
- *Disposal and recycling of vehicles*
- *Construction of infrastructure*: Materials, energy and related emissions from the construction of the road, rail track or airport
- *Maintenance* (i. e. operation) *of the infrastructure*: Lightning of roads, tunnels and airports, use of salt in winter, etc.
- *Disposal of infrastructure.*

If comparisons (e.g. between different transport modes) are made on a *long term* basis, all the components should actually be taken into account, since it is likely that the additional demand will require new infrastructure, new vehicles will be constructed (and the old ones disposed), etc. Strictly speaking, restricting the assessment to the operational emissions is adequate only if *short term* decisions are being considered. In this case, the underlying assumption is that the present infrastructure is able to handle the (additional) demand. However, due to the lack of knowledge and data, and since the operational emissions are likely to cover the biggest part of the environmental load, most applications have to restrict themselves to the types of emissions which are treated in this report.

3.3.3.3. Average versus marginal approach

The *average* approach is based on emission factors which are representative for the entire fleet of vehicles (with varying construction years, and hence varying technologies). In general, emission inventories represent this situation. The total emissions divided by the total transport activity gives an indication of the average ecological performance in a particular year. This indicator therefore represents the average technology mix.

The *marginal* approach asks how much additional environmental load is created by one additional unit of transport. This requires, in general, a data set containing average emission factors. The use of average values is acceptable as long as future emissions will not differ substantially from the present ones. However, newer technologies generally have a better "eco performance", therefore the marginal approach looks particularly at the newest type of technology. For instance, a local public transport authority evaluating the engine type of new buses will use the marginal approach: Since new buses will be purchased, fleet emission factors do not apply.

3.3.3.4. Other influencing factors

Considering the influences on emissions and environmental indicators, a wide range of additional influencing factors have to be taken into account:

- *Time delay:* the time between the introduction of a new technology (modifying the emission rates), and the time where it generally affects the average emission level.
- *Differences per link type:* The fleet composition mix of various technologies may vary per route. This holds for road as well as rail and aircrafts.
- *Regional differences:* The composition of the fleet obviously differs from one country to another, mainly due to local behaviour, economic strength and financial incentives.
- *The structure of the energy production:* this holds for the fuel production (different refinery types), but in particular for the generation of electricity (see section 3.1.10).
- *Time of day:* The diurnal cycle of human activities and, hence, traffic, leads to a strong variation of features such as emission factors and load factors, which are important for the deduction of environmental indicators, particularly in the marginal approach. E.g. peak hour emission factors are likely to be different from average emissions factors (different fleet compositions, different shares of cold start effects etc.). Similarly the structure of the electricity production might vary during the day which makes precombustion factors for electricity a function of the time of the day.

3.4. Rail emissions

by Spencer C. Sorenson

This section discusses methods that can be used to estimate emissions from rail traffic. It is based on the methodology described in greater detail in [Jørgensen & Sorenson, 1997]. Emissions must be estimated on the basis of activity and unit emissions factors for that activity.

$$\dot{E} = \dot{A} \cdot E' \qquad \text{(eq. 3.4.1)}$$

Where:

$\dot{E}$ is the Emission

$\dot{A}$ is the activity

E' is the emission factor for that activity

3.4.1. Total fuel / energy consumption known

The activity is represented by the consumption of primary fuel or energy. For diesel locomotives, fuel consumed can be estimated by multiplying the fuel consumption by an energy specific emissions factor, as shown in Equation 3.4.2.

$$E_i = F \cdot FSEF_i \qquad \text{(eq. 3.4.2)}$$

Where:

E_i = total emission of pollutant, i in the time frame under consideration

F = the total fuel consumption in the time frame under consideration

$FSEF_i$ = the fuel specific emission factor, typically in gram pollutant per kg fuel

Typical factors and fuel consumption for diesel locomotive engines are given in Table 15.

Table 15: Typical emissions and fuel consumption factors for diesel railway locomotives.

Emission	Power Specific (g/kW-h)	Fuel Specific (g/kg)
CO	1 - 10	5 - 40
HC	0.5 - 4.0	3 - 25
NOx	6 - 16	30 - 70
Particulates	0.2 - 1.2	1 - 6
SO_2	0.2 - 2	1 - 10
Fuel Consumption	190- 220	-

For electric locomotives, emissions estimates can be made from of electrical power consumption. If the power consumed by trains is known the emissions must be calculated on the basis of the emissions factors for the electrical power generated in the geographical area under consideration. In this case, the calculation is as shown in Equation 3.4.3.

$$E_i = El \cdot ElSEF_i \qquad \text{(eq. 3.4.3)}$$

Where:

E_i = total emission of pollutant, i in the time frame under consideration

El = the total electricity consumption of the trains in the time frame

$ElSEF_i$ = the electrical specific emission factor, typically in gram pollutant per kWh of electricity consumed

For emissions based on electrical energy consumption, one must be careful to determine whether the electrical specific emission factors for the electrical power generation net are given on the basis of primary power plant energy consumption, or the amount of electrical energy sent out over the electrical net. The ratio between the emissions factors on these different bases is typically in the vicinity of 40 %. Since the energy consumption modelled is for train usage, it would also be appropriate to apply a suitable transmission loss in the estimation of emissions from electrical powered trains. A summary of European emissions factors for power generation can be found in [Lewis, 1997].

The emissions derived using the above approach will typically be valid for the entire mix of trains. One is not normally able to distinguish between a kWh electricity used for a passenger train or that for a freight train on the same line at the same time. Similarly, if all diesel locomotives use common fuelling facilities, it is difficult to attribute a fuel consumption to a given type of traffic.

3.4.2. Total fuel / electrical consumption not known

If the energy or fuel consumption data required for emission calculations is not known, it is then necessary to use other methods to estimate the energy consumption and, hence, emissions from this type of traffic.

The basis of the calculation procedure is the estimation of the energy consumption of a given type of train in kJ per tonne-km. This is the energy required to move the train and is essentially independent of the type of locomotion used. This enables the same methodology to be used for trains driven by either engine type. The differences in emissions arise primarily through the difference in emissions factors for diesel engines and for electrical power generation. The use of energy consumption on a mass specific basis allows for estimates in future technology based on mass reduction of trains.

Activities are in terms of passenger-km of person transport, and tonne-km of freight transport.

For **Passenger Trains**, emissions can be estimated in the following manner:

$$E_i = WSEC \cdot \frac{Pkm}{Pps} \cdot W' \cdot BSEF_i \cdot 0.0036 \qquad \text{(eq. 3.4.4)}$$

Where:

E_i is the total emission of air pollutant i in the time frame under consideration, tonnes
WSEC = weight specific energy consumption of the train in kJ/tonne-km
Pkm = the amount of passenger-km transported by the train type in the time frame
Pps = the load factor of the train, in passengers/seat
W' = train weight in tonne per seat
BSEFi = the brake specific emission factor in g/kWh of energy produced.

For **Freight Trains**, the estimation be done in the following way.

$$E_i = WSEC \cdot \frac{Tkm}{Tpt} \cdot BSEF_i \cdot 0.0036 \qquad \text{(eq. 3.4.5)}$$

Where:

E_i = total emission of air pollutant i in the time frame under consideration in tonnes
WSEC = weight specific energy consumption of the train in kJ/tonne-km
Tkm = amount of freight transported by the train type in the time frame
Tpt = tonne-freight/total train tonne or “degree of utilisation”.
BSEFi = brake specific emission factor in g/kWh of energy produced.

The activity is represented by traffic data. In [Jørgensen & Sorenson, 1997], typical values are given for representative European railway traffic. These data give an indication occupancy rates, so that it is possible to convert typical national transport statistics in units such as passenger km to actual train km. Fleet data are also given in [Jørgensen & Sorenson, 1997] for several countries, including number of power units of different types. Weight data are given for typical diesel and electric locomotives, and for different passenger cars and train sets. Train weight is important, since the train weight is the most significant parameter in the determination of the energy consumption and subsequent emission of air pollutants. The methods recommended for estimating train energy consumption are based on train work per unit mass, and therefore it is important to be able to determine the mass of a train.

3.4.2.1. Empirical energy consumption equations

Average speed also plays a major role in the determination of energy consumption and air pollutant emissions from rail traffic, typical speeds are presented for a variety of rail traffic, including high speed trains, inter city trains, interregional trains and local trains. Empirical correlations are given in [Jørgensen & Sorenson, 1997] for train energy consumption in kJ per tonne-km, as a function of average train speed and distance between stops and gives a reasonable estimate.

The correlation for trains where information was available are given in the following equations. The distances for which the equations are valid are approximate:

ICE trains:

$$\frac{\text{kJ}}{\text{tonne}\cdot\text{km}} = 0{,}0070\frac{v_{\text{average}}^2}{\ln(x)} + 74 \qquad \text{(eq. 3.4.6)}$$

$$80\text{ km} \le x \le 200\text{ km}$$

Where:

v_{average} is the average train speed over the section of the route in question

x is the distance between stops in km

TGV train:

$$\frac{\text{kJ}}{\text{tonne}\cdot\text{km}} = 0{,}0097\frac{v_{\text{average}}^2}{\ln(x)} + 70 \qquad \text{(eq. 3.4.7)}$$

$$150\text{ km} \le x \le 300\text{ km}$$

British HST Passenger train, Danish IC3:

$$\frac{\text{kJ}}{\text{tonne}\cdot\text{km}} = 0{,}012\frac{v_{\text{average}}^2}{\ln(x)} + 70 \qquad \text{(eq. 3.4.8)}$$

$$40\text{ km} \le x \le 100\text{ km}$$

Large freight train (600 tonne empty mass):

$$\frac{\text{kJ}}{\text{tonne}\cdot\text{km}} = 0{,}019\frac{v_{\text{average}}^2}{\ln(x)} + 63 \qquad \text{(eq. 3.4.9)}$$

$$80\text{ km} \le x \le 200\text{ km}$$

Swedish RC train:

$$\frac{\text{kJ}}{\text{tonne}\cdot\text{km}} = 0{,}015\frac{v^2}{\ln(x)} + 81 \qquad \text{(eq. 3.4.10)}$$

$$30\text{ km} \le x \le 800\text{ km}$$

Urban Trains:

Urban Train Energy consumption is estimated to lie between 200 and 270 kJ/tonne-km

3.4.2.2. Steady state train resistance

An alternative method for determining the energy consumption is based on the steady-state loading of the train. Steady-state train loads in kN have been converted to kJ/tonne-km for several types of trains, and have a second order dependence on train speed because of aerodynamic loading.

$$F' = B_o + B_1 v + B_2 v^2 \qquad \text{(eq. 3.4.11)}$$

Where F' is the train force in kN/tonne, and B_o, B_1, and B_2 are constants, and v is the train velocity in m/s.

Figure 15 shows the steady state loads for a variety of train types. The parameters for these equations are given in Table 16.

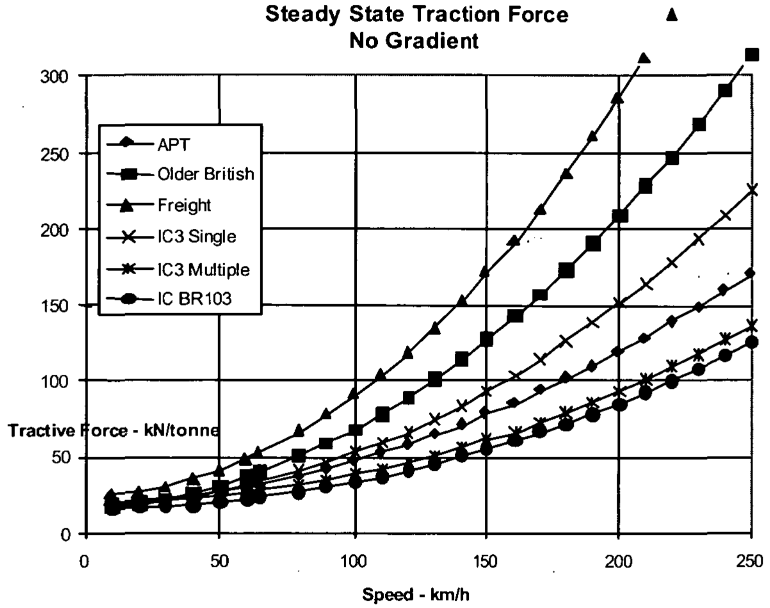

Figure 15: Traction force in kN/tonne for different types of railway trains as a function of train speed.

Table 16: Coefficients for Equation 3.4.11 for the steady state train force in kN/tonne for velocity in m/s for different train types.

Train Type	B_0	B_1	B_2
British APT	16.6	36.6×10^{-2}	26.0×10^{-3}
Older British Trains	15.5	29.2×10^{-2}	57.4×10^{-3}
Freight Trains	24.7	0	84.5×10^{-3}
Danish IC3 - Single set	19.7	0	42.5×10^{-3}
Danish IC3 - Multiple set	19.7	0	24.0×10^{-3}
German IC - BR103 Loco	16	0	22.5×10^{-3}

The steady-state load can be combined with the acceleration energy for a train, and the energy needed to move up or down a gradient, to estimate the instantaneous energy consumption of a train and therefore emissions for a more detailed route description. For emission estimations from traffic, this energy consumption must be integrated over a trip length with a representative value for the average speed. If the steady-state load is given by a second order polynomial, the integrated energy consumption for a train over a given route is given by:

$$E' \cong \frac{\left(N_{stops}+1\right)}{L}\frac{v_{\max}{}^2}{2} + B_0 + B_1 \cdot v_{ave} + B_2 \cdot v_{ave}{}^2 + g\frac{\Delta h}{L} \qquad \text{(eq. 3.4.12)}$$

Where:

B_o, B_1, and B_2	are empirical coefficients for the steady state load
N_{stops}	is the number of time the train stops along the route
Δh	is the change in elevation between the start and end of the route in m
v_{ave}	is the average train speed on the route in m/s
v_{max}	is the maximum speed to which the train accelerates in m/s

Equation 3.4.12 applies to the situation where the maximum speed of the train is approximately constant along the route. For situations on a longer route where the are significant changes in these variables, it would be best to apply equation 3.4.12 to the separate sections of the route. This method is also based on a mass specific energy consumption, and is general since most trains of a given type have very similar loading characteristics when expressed in these units. The method should be more reliable than the empirical relationships for small distances between stops. A major difficulty is determining the true number of accelerations, since road traffic limitations give rise to accelerations which are not station related, and the first term in Equation 3.4.12 underestimates acceleration energy consumption. The appropriate average velocity is also uncertain.

3.4.3. Passenger train occupancy

Occupancy of trains is dependent of the attractiveness of a route, the time of day, and the time of year. As a first approximation, one can use the following estimates for occupancy rates on a yearly average, based primarily on German and Danish data: urban: 30 %, regional: 40 %, and inter city / international trains: 50 %

3.4.4. Passenger train weight

Passenger train weights vary considerably for different types and within a given type, depending on the specific train and configuration for a special route. [Jørgensen & Sorenson, 1997] illustrates weights for several types of passenger trains. Some representative values for common train types are:

High speed:	1.1 tonnes / seat.
Inter city:	1.0 tonnes / seat for conventional trains
	0.7 tonnes / seat for modern light weight
Regional traffic:	0.8 tonnes / seat for conventional trains
	0.4 tonnes / seat for modern light weight electric
Urban transport:	0.7 tonnes / seat for conventional trains
	0.4 tonnes / seat for modern trains

3.4.5. Freight trains

For freight traffic, an input parameter is often the amount of freight shipped in ton-kilometre. In addition to the weight of the freight, one must also consider the weight of the cars used to carry the freight. The load capacity of freight cars depends to a large extent on the allowable loading per axle. Modern trains in international traffic permit axles loads of about 22.5 tons per axle. Older trains, and trains in some countries allow loading of 20 tons per axle or lower. If a larger loading per axle is permissible without significantly increasing the weight of a given freight car, then the effectiveness of the traffic is higher. This assumes, of course, that cars are fully loaded.

Typical European freight car weights are shown in Table 17, where they are given as the ratio of the tare weight of the car, to the total capacity of the car when fully loaded.

Table 17: Typical tare weight as a function of gross vehicle weight for freight cars.

Axle rating - maximum tons per axle	WR = Tare weight/Total Weight
20.0	0.33
22.5	0.27

The total weight of the train required to transport a given quantity of goods is also a function of the degree of loading of the train. Then for a given fraction of loading, X, the ratio of the total car weight to the weight of the freight carried, FR is given as:

$$FR = 1 + \frac{WR}{[1 - WR] \cdot X} \qquad \text{(eq. 3.4.13)}$$

The loading fraction is that for the entire train.

3.4.6. Locomotive weight

In addition to the weight of the cars, the locomotive must also be included in the total train weight. The following correlations may be used to estimate the weight of the locomotives:

Diesel Locomotives $\ln(M) = -0.255 + 0.658\ln(P)$ (eq. 3.4.14)

Electric Locomotives and Power Units $\ln(M) = 1.29 + 0.395\ln(P)$ (eq. 3.4.15)

Where:

M is the locomotive mass in tonnes

P is the locomotive power in kW

3.4.7. Future railway emissions

For passenger traffic in person-km, it is estimated that there will be the following annual growth rates in Europe: high speed: 8-10%, regional: 1%, and urban trains: 2%. It is estimated that freight traffic in terms of tonne-km will increase at a rate of 1% annually.

Furthermore, it is anticipated that there will be an increase in the average train speed, and that up to the year 2020 the average train speeds will have in the following annual increase: high-speeds: 1.0%, inter city and regional: 0.2%, urban: 0.1%, and freight trains: 0.5%.

Electrification of the rail net is expected to increase in countries where it is now at a low level. On a European basis, the share of traffic powered by electricity is expected to increase from its current level of 65-70% to 80% in the year 2020. Maximum values in individual countries with current high levels of electrification are expected to exceed

90% in the year 2020. Note that this is the amount of traffic and not the amount of electrified track.

Train weight plays a significant role in energy consumption and emissions from railway traffic. It is anticipated the specific weight for passenger trains in the year 2020 will be, in t/seat: high-speed and inter city: 0.4, regional and urban trains: 0.3. For freight trains it is expected that the ratio of the tare weight of the cars to the maximum total loaded weight will decrease from the current level of about 0.27 to a value of about 0.22 in the year 2020.

Improvements in the emissions from electrical power generation are expected to be significant in future years. Average European emissions levels on the basis on the amount of electrical power produced in the year 2020 are expected to be as presented in Table 18. In the same table future exhaust emissions of diesel locomotives are given: they do not include the effects of production and distribution of the fuel.

Table 18: European emissions levels in the year 2020, in g/kWh.

type of locomotive	electric	diesel
type of emission	energy production	exhaust
CO	0.04	0.5
HC	0.55	0.5
NOx	0.35	3.5
Particulates	0.07	0.08
SO_2	0.80	0.03

3.4.8. Conclusion

Methods have been presented to estimate emissions from railway traffic. Three basic methods are suggested. The first is using energy or fuel specific emissions factors in combination with known energy and/or fuel consumption. The second uses empirical correlations of weight specific energy consumption for a variety of train types as a function of speed and distance between stops. The third method is based on train rolling and aerodynamic resistance integrated over a given route. The first method should be the most accurate if consumption data are available. The second method requires a minimum of information, but is approximate and based on typical traffic. The third method is the most general, and can be applied to any type of operating condition. Estimates are presented of the changes expected to occur in the future for the factors which are used in the estimation of emissions from rail traffic. These factors can be used for any of the methods presented.

3.5 Air transport emissions

By Manfred T. Kalivoda

Air traffic contributes less than 3% to total global anthropogenic emissions of carbon dioxide and nitric oxides [Brasseur *et al.*, 1997]. However, increasing numbers of flights, and the fact that the atmospheric impact varies in a most non-linear way with altitude, have drawn more and more attention to this transport sector. In Europe many institutions are working in this area, collecting traffic and emission data, generating emission inventories, and assessing effects.

Figure 16 tries to create a rough image of who is doing what and why on the European level. It is clear that there is a lot of parallel, sometimes overlapping work done using different databases and methodologies often leading to results which cannot be matched or compared. An outline of the most important European activities is given here.

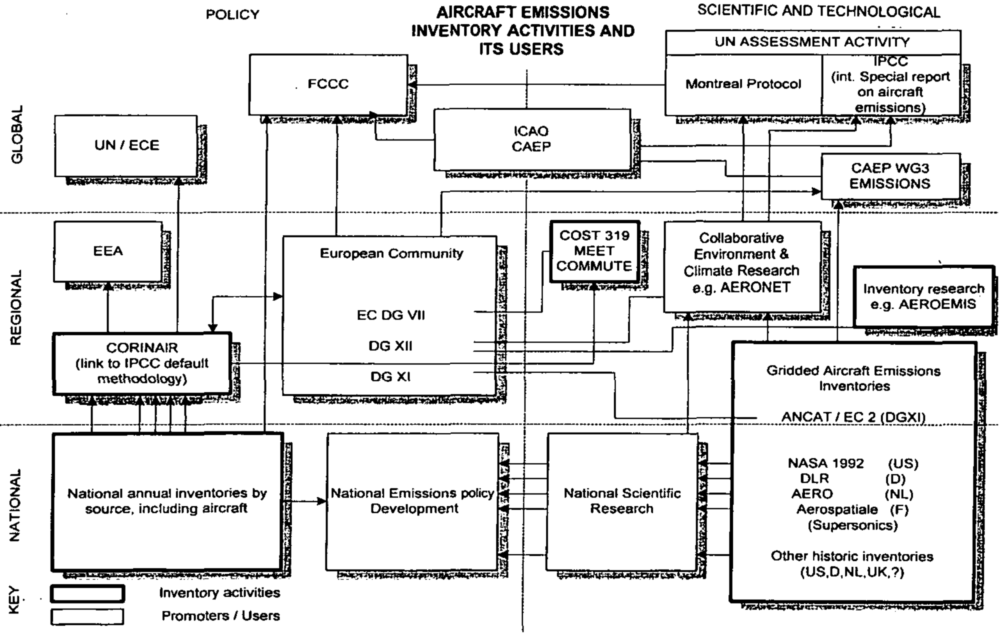

Figure 16: Rough outline of air traffic emissions related activities in Europe.

3.5.1. AERO

In 1993 the Netherlands's Department of Civil Aviation (RLD) started the national project AERO (Aviation emissions and Evaluation of Reduction Options). A consortium of four partners, RLD, Resource Analysis (RA, Delft), MVA consultancy (London, UK) and the National Aerospace Laboratory (NLR, Amsterdam) aims to determine the scope of the environmental problems related to air traffic and to find the 'best' strategy to reduce the impact on the atmosphere. A comprehensive model is being developed which makes it possible to investigate possible policy measures and to assess their impacts on the environment as well as on economies [DG of Civil Aviation, 1998].

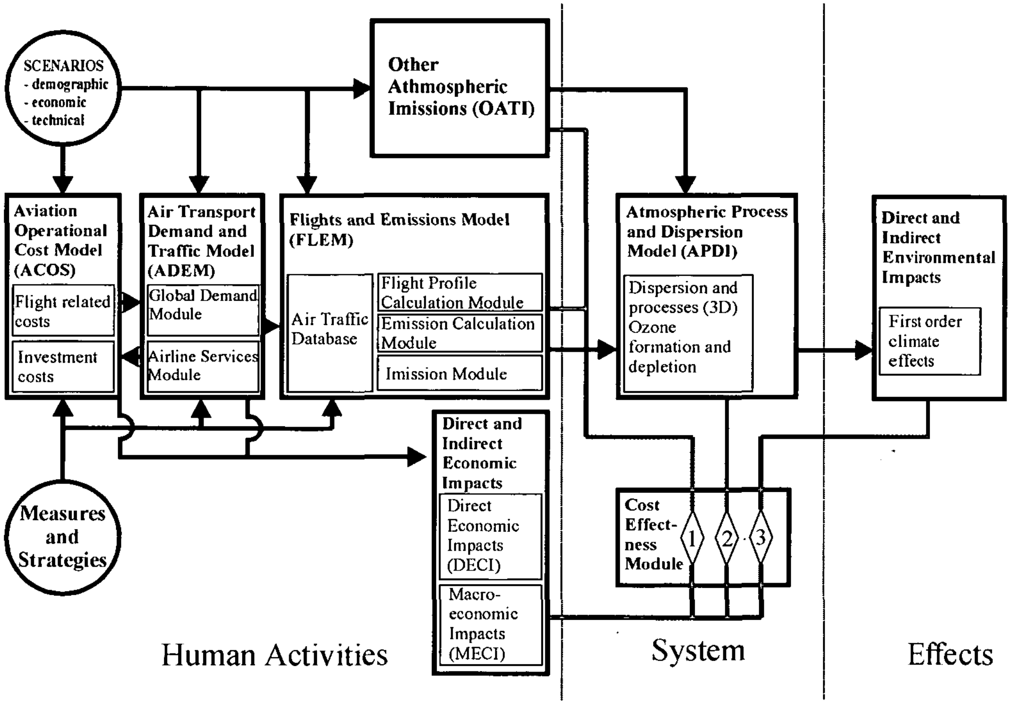

Figure 17: The AERO model [NLR, 1996].

FLEM *(Co-ordination: Paul Brok, NLR, NL)*

As an essential part of the Aero model NLR is developing the Flights and Emissions Model (FLEM). It consists of five modules:

- Flight operation modelling,
- Flight mapping,
- Emission modelling,
- Emission/immission conversion,
- Military emissions [ten Have & de Witte, 1997].

3.5.2. AERONET

AERONET is a thematic network sponsored by CEC DG XII/C Aeronautics. It started in 1997 and aims at creating an European platform

- to improve data and experience exchange,
- to establish a common view of open questions and potentials,
- to identify scientific and technological gaps,

- to support authorities in research and development politics,
- to support the generation of a common European position for international regulatory efforts.

No actual research work is performed within AERONET but there are five working groups focusing on the key issues.

HEIM *(Co-ordination: Richard Ramaroson, Onera, F and Roger Gardner, Dera, UK)*

HEIM stands for Harmonisation of Emission Inventories and Modelling. In its inventories part the project aims at:

- Current and forecast inventories for modelling, measurement programmes and policy support,
- Comparison of existing datasets and methodologies,
- Harmonisation of inventories,
- Scope and need to refine, species to be covered, new data sets including scenarios,
- Research planning.

The interface between emissions and atmospheric/climatic models in the near and far field of aircraft is the focus of the modelling activities in this group.

OTD *(Co-ordination: Gerard Bekebrede, NLR, NL)*

OTD stands for Operations & Forecast of Air Traffic Development and deals with:

- Expected development of air transportation system,
- Air traffic management (ATM) improvements and relation to emissions,
- Potential operational measures to reduce emissions,
- Operational measures to reduce the impact of aviation emissions.

MT *(Co-ordination: Andreas Petzold, DLR, D)*

MT stands for Measurement Techniques and deals with:

- availability,
- compatibility,
- accessibility,
- accuracy.

EAT *(Co-ordination: Roger Cottington, Dera, UK)*

EAT stands for Engine and Aircraft Technologies and deals with:

- present and future of fuel consumption and emissions,
- costs, time and risks of development.

SO *(Co-ordination: Lars-Gunnar Larson, FFA, S)*

SO stands for Systems Operations and deals with:

- system reactions and sensitivities to critical parameters,
- end-to-end analysis.

3.5.3. ANCAT

ANCAT stands for Abatement of Nuisance Caused by Air Transport and comprises a group of experts from within the European Civil Aviation Conference (ECAC). This group works on some specific topics.

AERONOX

AERONOX was a research project sponsored by the CEC which investigated the impact of NOx emissions from air traffic in the upper atmosphere (8 to 15km). There were three sub-projects in this programme:

- SP1 = Engine Exhaust Emission Data Base,
- SP2 = Physics and chemistry in the aircraft wake,
- SP3 = Global atmospheric model simulation.

ANCAT/EC2

The ANCAT/EC2 inventories are an extension of earlier work produced by the joint ANCAT/EC working group established by ECAC. A first base year inventory, known as ANCAT/EC1A, was published in 1995 and was used as an input for the global atmospheric models in the AERONOX project. In ANCAT/EC2 a new selection of representative aircraft types has been modelled using movement database from ANCAT/EC1A with only minor adjustments but a different profiling tool, being based on a parametric aircraft design model which also predicts fuel consumption throughout the flight cycle. Two global inventories have been produced for the base year 1991/92 and 2015 including fuel consumption and NOx emissions for global civil jet air traffic which have been plotted at a resolution of 1° x 1° x 1 km and an upper altitude of 17 km.

Future ANCAT work

In January 1998 the need for a proper database which included flight profiles for different stage lengths was found by the ANCAT expert group to be of major importance for the ECAC states. The work required to compile this database, including emission indices based on actual power settings and flight profiles, is on-going and is being co-ordinated by the Danish Civil Aviation Administration.

3.5.4. EEA activities

In 1994 the German Federal Environmental Agency (UBA) was appointed by the European Environmental Agency (EEA) as the project leader for the European topic centre on air emissions (ETC/AE). Their main objective is to establish the annual European inventory of air emissions, including total emissions and emissions by country and source sector. These activities are closely related and linked with EMEP (co-operative program for monitoring and evaluation of the long range transmission of air pollutants in Europe), IPCC (intergovernmental panel on climate change), and CORINAIR (core European inventory of air emissions): see Annex 1.

The EMEP/CORINAIR atmospheric emission inventory guidebook presents common guidelines for the estimation of emissions from traffic. The guidebook includes a section dealing with air transport [EEA, 1997]. The methodology presented includes three approaches (a very simple methodology, a simple methodology, and a detailed methodology), all based on fuel sales statistics. Four different classes of air traffic activities have to be taken into account:

- Domestic airport traffic (LTO-cycle < 1000 m altitude),
- International airport traffic (LTO-cycle < 1000 m altitude),
- Domestic cruise traffic (> 1000 m altitude),
- International cruise traffic (> 1000 m altitude).(Visual Flight Rules)

Emissions associated with domestic aviation are to be reported to UNFCCC using the IPCC source sector split. Emissions associated with the LTO-cycle are to be reported to the ECE/CLRTAP. Activities include air traffic movements of scheduled and charter passengers and freight air traffic as well as taxiing, helicopter traffic and general aviation. Military air traffic are included where possible.

3.5.5. MEET

MEET stands for Methodologies for Estimating Air Pollutant Emissions from Transport. Within the MEET project a methodology for estimating air pollutant emissions from air traffic was created. Although military operational flights and VFR (Visual Flight Rules) flights are included, the main focus was on IFR (Instrument Flight Rules) flights. Emission indices for the pollutants NOx, CO, HC, CO_2, H_2O, SO_2, and for fuel consumption have been published for 30 aircraft/engine combinations [Kalivoda & Kudrna, 1997].

In a second phase of the MEET project a study on the future development of air traffic (IFR flights only), and the expected changes and improvements in specific fuel consumption and air pollutant emissions (components NOx, CO and HC), was prepared. Three aircraft emission scenarios (a baseline, a low emission and a high emission one) for 2010 and 2020 were developed, and reduction potentials were derived, for different measures, improvements in engine design, the use of alternative fuels, etc. Finally, this led to a table of reduction rates (from the base year 1995) for fuel consumption and emission indices for components NOx, CO, and HC in the years 2010 and 2020 [Kalivoda *et al.*, 1998].

3.5.6. COMMUTE

COMMUTE stands for Common Methodology for Multimodal Transport Environmental Impact Assessment and like MEET is a DG VII research and development project. Main objectives are:

- to define a methodology for strategic assessment of the environmental impacts of transport policy options to support transport policy decision making at the European level,
- to develop computer software that embodies the main aspects of the methodology and can present the results to users,
- to demonstrate the use of the main aspects of the methodology and the computer software.

This computer software includes a module for air traffic emissions which is based on the MEET methodology and data.

3.5.7. Proposal for a harmonised approach to generate emission indices

The COST 319 working group D2 – air traffic – has worked out a proposal for a harmonised approach to generate emission indices. From the working group's point of view this harmonisation is necessary to make results from different methodologies as described in international guidebooks/guidelines (in particular EMEP/CORINAIR and IPCC) comparable and exchangeable.

Figure 18 shows a table which fulfils the minimum requirements. For each aircraft/engine combination included basic information which may have a great impact on the emission indice like origin engine type used, take off weight (influenced by seat capacity, load factor and fuel reserve policy) and average cruising altitude as well as the origin of the data have to be filled in. Fuel consumption, total amount of pollutant component and/or emission indice of pollutant are displayed for LTO cycle, climb (from > 3000 ft), cruise and descent (to > 3000 ft) on one side and standard distance classes from 250 nautical miles to 8500 nautical miles or maximum range of aircraft. If available, the LTO-cycle data should be split up into these four classes: taxi out, take off and climb out to 3000 ft, approach (from 3000 ft) and landing and finally taxi in.

*) dist.: Distance flown for climb and descent in nm= *) FL.: Flight level for cruise (incl. Step cruise)=		*CLASS OF MISSION DISTANCE*														
		250 nm					...					*8500 nm*				
Origin of data:	*Component:*	*dist./ FL *)*	*fuel [kg]*	*NOx [g]*	*EINOx [g/kg]*	*other .....*	...	...	...	...	...	*dist./ FL *)*	*fuel [kg]*	*NOx [g]*	*EINOx [g/kg]*	*other .....*
aircraft type:	*LTO Taxi out*															
engine type:	*Take off & climb out (≤ 3000ft)*															
seat capacity (class):	Approach ≤ 3000ft)															
load factor used:	Taxi in															
fuel reverse policy:	LTO TOTAL															
cruising altitude (ft)	CLIMB (>3000ft)															
	CRUISE															
	DESCENT (>3000ft)															

Figure 18: Proposed data sheet to generate emission indices from air traffic in accordance with the harmonised approach (nm: nautical mile).

3.5.8. Conclusion

The approach proposed in section 3.5.6 is a first step to make results comparable. However, it must be clear that there will be differences between fuel consumption and emission indices from different inventories and laboratories. A future research need is to compare these data and to describe the reasons for differences. This will be a hard task on the way to a European set of fuel consumption and emission indices from air traffic.

At the beginning of COST 319's work, there was a large gap, and almost no link at all, between the suppliers of methodologies and data for emission inventories and the users. On one side there was the air traffic community, which has been working on engine and combustion technology for a long time, and has a detailed knowledge of emission, whilst on the other side there were those institutions monitoring the environment which needed tools that were easy to apply.

COST 319 provided the opportunity for starting a dialogue between both sides. A very important step towards a common European methodology and data set for air traffic emission inventories was achieved by introducing a data sheet for emission indices which fulfilled the requirements of the most important users.

Nevertheless, this proposal is just a starting point, and at present only the format has been agreed. There is no commonly agreed data. The next steps will be:

- to collect all relevant emission data available,
- to explain differences between the single data sources,
- to find a European set of emission indices for air traffic emission inventories.

3.6 Maritime transport and inland navigation emissions

By Carlo Trozzi and Rita Vaccaro

In the framework of MEET project two methodologies for the estimate of maritime fuel consumption and emissions have been developed [Trozzi & Vaccaro, 1998]:

- a simplified one based on present day statistics relating to maritime traffic;
- a detailed one based on present day statistics relating to maritime traffic and port operations.

In addition specific functions for fuel consumption and days in navigation have been elaborated.

3.6.1 General background

In the simplified methodology emission factors are defined for engine types. In the detailed methodology emissions factors are defined for engine types and for the different operating modes:

- cruising
- manoeuvring
- hotelling
- tanker loading and off-loading
- auxiliary generators.

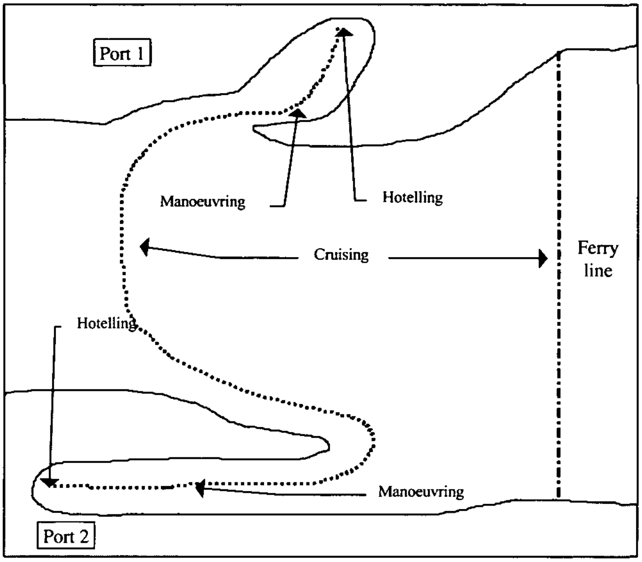

Figure 19: Ship traffic representation

Maritime traffic can be represented in the way shown in Figure 19. The Figure contains two examples:

1. typical cargo, container or similar traffic in which the ship stays in harbour up to several days;
2. ferry traffic.

In shipping activity it is customary to distinguish between (a) approaching and docking in harbours; (b) hotelling in harbours; (c) departing from the harbour, (d) cruising. Phase (a) starts when the ship's deceleration begins and ends at the moment of the docking, while phase (c) starts with departure from the berth and ends when cruising speed has been reached.

From a fuel consumption and emissions point of view, there are two manoeuvring phases (a) and (c), one hotelling phase (b) and one cruising phase (d). After its arrival in harbour a ship continues to emit at dockside (while in hotelling phase). Power must be generated in order to supply the ship's lighting, heating, refrigeration, ventilation, etc. A few steam ships use auxiliary diesel engines to supply power but they generally operate one or more main boilers under reduced load. Ships powered by internal combustion engines normally use diesel powered generators to furnish auxiliary power.

For liquid-bulk ships the power requirements of the cargo pumps for tanker off-loading, and the ballast pumps for tanker loading, must also be taken into account. In smaller tankers the pumping power requirement will add to the electrical load, whereas for larger tanks steam turbine driven pumps are generally used (even on motor tankers) with a consequent boiler load. As these power requirements can be relatively high the emissions will be estimated separately.

In ferry traffic the hotelling and manoeuvring phases are not as essential as the cruising phase. However, it would be essential to take into account manoeuvring for short passages. As the passage length increases (i.e. to over a few hours) this element will become less important and could eventually be neglected.

The following detailed methodology has been developed mainly for use in example 1, whereas the simplified methodology has been developed for use in example 2 or wherever information on harbour activity is not available. The detailed methodology must also be used, where possible, for short passages ferry traffic.

The pollutants taken into account are NO_x, SO_x (sulphur oxides), CO, VOC, PM and CO_2.

The ship types taken into account are:
- Solid Bulk
- Liquid Bulk
- General Cargo
- Container
- Passenger/Ro-Ro/Cargo
- Passenger
- High speed ferries
- Inland Cargo
- Sail ships
- Tugs
- Fishing
- Other

The engine types taken into account are:
- Steam turbines
- High speed motor engines
- Medium speed motor engines
- Slow speed motor engines
- Inboard engines - pleasure craft (only for detailed methodology)
- Outboard engines (only for detailed methodology)
- Engines for tanker loading and off-loading (only for detailed methodology)

The fuel types taken into account are:
- Residual oils
- Distillate oil
- Diesel fuel
- Gasoline fuel.

3.6.2 Simplified methodology

In order to apply a simplified methodology it is necessary to estimate the number of working days for each class of ship equipped with a particular engine types and using a particular fuel.

The emissions are obtained as:

$$E_i = \Sigma_{jkl} E_{ijkl} \qquad \text{with} \qquad E_{ijkl} = S_{jk}\,(GT) \cdot t_{jkl} \cdot F_{ijl}.$$

where:

i	pollutant
j	fuel
k	ship class for use in consumption classification
l	engine type for use in emission factors characterisation
E_i	total emissions of pollutant i
E_{ijkl}	total emissions of pollutant i from use of fuel j on ship class k with engine type l
S_{jk} (GT)	daily consumption of fuel j in ship class k as a function of gross tonnage
GT	gross tonnage
t_{jkl}	days in navigation of ships in class k with engine type l using fuel j
F_{ijl}	average emission factors of pollutant i from fuel j in engines type l (for SOx, taking into account average sulphur content of fuel)

The emission factors are selected in the framework of the MEET project. The average specific daily consumption for the different ships types is also evaluated in the framework of the MEET project. A rough estimate of pollutant emissions is possible by using this data as well as the number of navigation days of all vessels in each class.

For short-passage ferry traffic, in order to take into account hotelling and manoeuvring emissions the days in navigation must be increased, since in these modes fuel consumption is about a half of that when cruising. In this case tjkl it is equal to the sum of the days spent cruising plus half of the days spent hotelling and manoeuvring.

3.6.3 Detailed methodology

In order to apply a detailed methodology it is necessary to have:

- statistics on navigation (along a line and in ports) reporting gross and fuel use distribution of ships and average times spent in different mode;
- when the previous ones are not available:
- statistics compiled directly from the register of single ship movements to obtain detailed estimate of emissions;

or

- approximate distribution of ships and general statistics of movements to obtain gross estimate of emissions.

From such information is then possible to estimate the number of working days in the different mode for each class of ships equipped with a given engine type and using a given fuel. The emissions are obtained as:

$$E_i = \Sigma_{jklm} E_{ijklm} \qquad \text{with} \qquad E_{ijklm} = S_{jkm}(GT) \cdot t_{jklm} \cdot F_{ijlm}$$

where the new parameters are:

m	mode
E_{ijklm}	total emissions of pollutant i from use of fuel j on ship class k with engine type l in mode m
S_{jkm}(GT)	daily consumption of fuel j in ship class k in mode m as a function of gross tonnage

t_{jklm}	days in navigation of ships in class k with engine type l using fuel j in mode m
F_{ijlm}	average emission factors of pollutant i from fuel j in engine type l in mode m (for SOx, taking into account average sulphur content of fuel)

The main difference between simplified and detailed methodology is that the latter takes into account the following aspects:

- emissions during transient phases,
- emissions during hotelling phases,
- emissions deriving from auxiliary power generators,
- emissions deriving from tanker loading and off-loading,
- emissions deriving from inboard and outboard pleasure craft engines.

3.6.4 Fuel consumption

In the framework of the MEET project [Trozzi & Vaccaro, 1998] the data on fuel consumption at full power are provided. In particular, a regression analysis has been made on fuel consumption vs. gross tonnage for each ship class with the exception of inland navigation (for which data on general cargo must be used). The data are highly correlated (r > 0.68 for all cases) and all regressions are significant at a confidence level greater than 99%.

When information on ship class is not available, fuel consumption regression data for all ships in the database can be used. If information on gross tonnage is not available, the average fuel consumption can be used.

In the detailed methodology the effective fuel consumption can be obtained from:

$$S_{jkm}(GT) = C_{jk}(GT) * p_m$$

where the new parameters are:

C_{jk} (GT)	daily consumption at full power of fuel j in ship class k as a function of
gross	tonnage
p_m	fraction of maximum fuel consumption in mode m

Default fractions are reported for the different mode in the framework of MEET project. For the simplified methodology the fraction of cruising can be used.

3.6.5 Days in navigation

If days in navigation are not known, they can be estimated by service speed and distance covered as:

$$t_{jkl} = d_{jkl} / v_{jkl}$$

where the new parameters are:

d_{jkl}	distance covered (in nautical miles) by ships in class k with engine type l
using	fuel j
v_{jkl}	average service speed in knots (nautical miles/hour) of ships in class k
with	engine type l using fuel j

For the days in navigation in the framework of the MEET project [Trozzi & Vaccaro, 1998], Lloyd's maximum service speed data are used to give average values for the ship classes. The actual service speed can be well below this figure, and values can be used only as defaults.

Future work must be finalised to analyse service speed data for ship classes using the regression method, and to correlate actual service speed to maximum service speed.

3.6.6 MEET methodology for estimating future emissions from ships

The methodology is based on the MEET simplified methodology for estimating actual emissions from ships: see [Kalivoda *et al.*, 1998] for a more detailed description. Reduction scenarios are introduced only for sulphur oxides and nitrogen oxides. For the application of the methodology estimates of the number of working days for each class of ships equipped with a given engine type and using a given fuel are required.

The emissions are obtained as:

$$E_i = S_{jkl}\, E_{ijkl}$$

$$\text{with } E_{ijkl} = S_{jk}\,(GT) \cdot t_{jkl} \cdot F^*_{ijls} = S_{jk}\,(GT) \cdot t_{jkl} \cdot F_{ijl} \cdot f_{is}$$

where the new parameters are:

s	reference reduction scenario (low, medium, high)
F^*_{ijls}	average reduced emission factors of pollutant i from fuel j in engine type l (for sulphur oxides, taking into account average sulphur content of fuel) in the scenario s
f_{is}	reduction factors of pollutant i in the scenario s