A comparison of the amount of pollutant emissions from different transport modes : A first progress report

Memorandum M-814

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July 1996

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Nomenclature

A_k	part of a trip driven with the engine warming up.
A_w	part of a trip drive with a warm engine.
b	see formula (8), correlation of "durability".
C_k	correction factor for a cold start.
EI	emission index (aircraft engines), grammes of emitted species per kilogramme of consumed fuel.
EF_b	basic emission factor (road vehicles).
EF_w	emission factor of a vehicle with a warm engine
$E_{K,S,T}$	emissions [g] after a distance S in phase 1 of the US-Test-75 at ambient temperature T.
$E_{w,S}$	emissions [g] after distance S in phase 3 of US-Test-75 at an ambient temperature of 20°C.
E_w	total emission of phase 3 at 20°C.
h	interval.
$KF_{S,T}$	cold-start factor, i.e. the ratio of the extra emissions due to a cold start to the total emissions for a warm engine at ambient temperature T.
m_f	total mass of consumed fuel.
m_p	payload mass.
m_{to}	take-off mass.
MTOW	maximum take-off weight.
MZFW	maximum zero fuel weight.
NLF	load factor.
OWE	operational weight empty.
P	factor which assigns emissions and fuel consumption to passengers and freight and mail.
R	range.
S	distance (from a cold start).
SFC	specific fuel consumption, consumed fuel per tonne-km.
SFC_p	fuel consumption per passenger tonne-km.
$SFC_{c,m}$	fuel consumption per cargo and mail tonne-km.
S_w	distance wher the transition to a warm engine occurs.
T	ambient temperature.
TKT	total tonne-km transported.
TKT_p	passenger tonne-km transported.
$TKT_{c,m}$	cargo and mail tonne-km transported.
TOW	take-off weight.

1. Introduction

This progress report briefly describes the preliminary results of a master's work at the Faculty of Aerospace Engineering of Delft University of Technology. The main objective of this project is to quantify and to compare the pollutant emissions caused by different transport modes. The several transport modes will be compared with transport aircraft. Besides the main objectives there are three other objectives.
1. The different transport modes have to comply with regulations. These regulations will be reviewed.
2. The possibilities for the reduction of pollutant emissions will be discussed.
3. A brief review of possible future developments will be given.
The emphasis will be on passenger transport. The transport modes that will be reviewed are:
- regional and long distance transport aircraft;
- passenger cars;
- buses;
- classic and high-speed trains.

This progress report describes the results obtained so far. Less attention is payed to the theoretical backgrounds of these results. These backgrounds will be discussed in the final report planned to be completed in August 1996.

There are several reasons why this comparative study was initiated.
1. There are many comparative studies that have been performed earlier. The results of these show a wide variation for almost each transport mode.
2. The influence of time is considerable. The results of old studies are not necessarily valid for the vehicles that are in use at the present. Often newly published results refer to vehicles or transport systems of a few years old. Some publications use the results of other studies so that these apparently recent publications in fact refer to, sometimes, outdated information.
3. For comparison of transport modes, the emissions must be reviewed for equal travel distances. For example, it makes no sense to compare emissions from (long range) aircraft per traveller-kilometre with the emissions from a passenger car per-traveller kilometre on very short distances.
4. To draw conclusions from calculated emissions, the backgrounds of these calculations must be studied thoroughly. When this is not done, this may very easily lead to misinterpretation of the results.

For the comparison of emissions a 'system boundary' must be selected. Most transport modes in this study use fossil fuel. Electric trains themselves emit only very little pollutants (e.g. copper and dust due to braking). When the electric power generation is included, electric trains are partly responsible for emissions from power stations. In energy studies, energy consumption is often expressed in primary energy i.e. coal, crude oil natural gas, nuclear energy or several "natural" energy sources like wind energy, hydro electric energy, sun energy, thermal energy extracted from the earth, OTEC (ocean thermal energy conversion), etcetera. Transport of energy also requires energy as well as the production and destruction or recycling of the vehicles and the refinery of fossil fuels. Here the choice has been made to put the system boundary at the place where fossil fuels are burned. This means that for electric trains the

boundary is at the power station, for the other vehicles the boundary is at the vehicle itself.

In chapter 2 a review is given of the relevant emissions and their environmental impacts. Chapter 3 explains why a thorough analysis is needed. In this chapter the results of other comparative studies are analysed, these show extremely wide variations. In the chapters 4, 5, 6 and 7 the results of calculations of emissions from passenger cars, buses, trains and aircraft are presented. In chapter 8 the unfinished activities are described. At the end of this report a list of used literature is given. Not all the literature in this list has been used as a reference in this report. However, in the final report they will be used as a reference.

On 18 May 1996 a time schedule was presented. On the one hand, not all the elements in this schedule, planned to be completed by the end of June have been completed. On the other hand some work has been done on elements planned to be completed later (e.g. some literature research has been done on the regulations and on total emissions). These elements are not presented in this report. Some elements in the schedule have been changed.

2. The relevant emissions from transport and their environmental impacts

Introduction

A brief review of emissions from aircraft, trains and road traffic and their environmental impact are given. Different definitions of some emissions are used in literature. These definitions have been studied to avoid confusion. An introduction into the subject of pollution of the troposphere and the related chemistry is given by Lelieveld and Helas in [Helas, 1987]. Several aspects of air pollution are described in [Boubel 1994]. In general the environmental impact of an emission depends on time, location and concentration of this emission. The presence of other emissions also affects its environmental impact. When emissions from electric trains are considered emissions from power stations have to be taken into account. Because electricity is often partly generated by nuclear power stations, also nuclear emissions and waste have to be considered. Much information on emissions from aircraft can be obtained from [Schumann, 1990], [Schumann, 1994], [Schumann 1995], the contributions of Schumann in [AGARD-CP-536] and in [Bürgener 1993].

2.1   Carbon monoxide

Carbon monoxide (CO) is toxic due to its high affinity to red blood corpuscles. CO is involved in the chemistry with respect to ozone (O_3) production and reduction. So CO may cause the production of photochemical smog, depending on the concentration of oxides of nitrogen (NO_x). Carbon monoxide also affects the mechanism of hydroxyl (OH) radical formation and destruction.

2.2   Carbon dioxide

Carbon dioxide (CO_2) contributes to the enhanced greenhouse effect and it makes rain and snow slightly acid when CO_2 is dissolved in the falling droplets (carbonic acid pH~5.6). Furthermore CO_2 causes cooling of the lower atmosphere, more polar stratospheric clouds (PSCs), and hence more ozone depletion.

2.3   Water

Water (H_2O, water / vapour / solid) affects the environment in several ways. Water vapour is a greenhouse gas. In cloud form (condensation trails or contrails) water can contribute to the enhanced greenhouse effect, depending on several parameters. Contrails also have a cooling effect. Furthermore water plays a role in atmospheric chemistry. According to Smit in [Euroavia 1995] water vapour can be called "the engine of atmospheric dynamics".

2.4   Oxides of nitrogen

Oxides of nitrogen (NO_x) are also called nitrogen oxides [Houghton 1990] or nitric oxides [Olivier 1991]. NO_x represents nitric oxide (NO) and nitrogen dioxide (NO_2). NO_x can cause ozone (O_3) production as well as catalytic ozone depletion. Ozone is a greenhouse gas. The ozone layer is a protective shield against UV radiation. Ozone is also involved in the formation of photochemical smog. Ozone itself is harmful to human health. In general NO_x causes O_3 production at lower altitudes (troposphere and lower stratosphere) and ozone depletion at higher altitudes. NO_x causes acid rain by conversion of NO_2 to nitric acid (HNO_3, not to be confused with HNO_2 which is called nitrous acid).

2.5   Nitrogen oxides

In literature different definitions of nitrogen oxides can be found. The nitrogen oxides referred to as N_xO_y include NO_x and nitrous oxide (N_2O). N_2O is a greenhouse gas. The intergovernmental Panel on Climate Change (IPCC) defines nitrogen oxides as NO_x [Houghton 1990]. This definition can also be found in other literature.

2.6   Hydrocarbons

Hydrocarbons (HC) can be divided into several groups. Unburned hydrocarbons are denoted as UHC or C_xH_y. In [Olivier 1991] however, hydrocarbons too are denoted as C_xH_y. Commonly unburned hydrocarbons include methane (CH_4), which is a greenhouse gas. When hydrocarbons do not include methane, they are called non-methane hydrocarbons (NMHC). Methane is a chemically and radiatively active trace gas. Due to chemical reactions in the stratosphere it is a significant source of stratospheric water where it is an important greenhouse gas. Not all hydrocarbons are volatile. Hydrocarbons may be solid enough to be classified as particulate matter [Nieuwenhuis 1994]. [Olivier 1991] defines volatile organic compounds (VOC) as all unburned and formed hydrocarbons including methane, which are sometimes called "total VOC". Non-methane volatile organic compounds are denoted as NM-VOC. A group of hydrocarbons are polycyclic aromatic hydrocarbons (PAH, PAK in Dutch) some of which are known to be carcinogenic (i.e. they cause cancer).

Hydrocarbons are involved in the creation of photochemical smog. In the stratosphere hydrocarbons catalyse ozone formation, convert NO_x into a reservoir gas, and lessen O_3 destruction. Hydrocarbons also cause bad smell.

2.7   Sulphur dioxide

Sulphur dioxide (SO_2) forms sulphate particles which have several effects. Sulphate particles may be important in cloud formation and may trigger ice clouds in supersaturated regions. These particles are chemically and radiatively active. Sulphur dioxide causes acid rain due to transformation into H_2SO_4 (sulphuric acid) and it causes smog.

2.8   Soot

Soot consists of particles containing carbon (C). Carbon provides condensation nuclei (CN) for aerosols and clouds and provides surfaces for chemical processing. Furthermore soot is inconvenient and may be carcinogenic. The smoke number (SN) for aircraft engines is measured using a special filter and procedure prescribed in [ICAO 1993].

2.9   Aerosols

A description of aerosols is given in [Helas 1987]: " Mechanical suspensions of liquid or solid particles in air are called aerosols". Examples are fog, smoke, particles in exhaust gases, rain, etcetera. This will change the albedo. Aerosols can have many different environmental impacts, ranging from influence on the energy balance of the earth to health risks. Aerosols affect the radiation balance of the earth, thus they affect the climate. Aerosols also serve as condensation nuclei. So an increase in air pollution can lead to an increase in cloud formation. The surfaces of aerosols play a role in heterogeneous chemistry.

2.10   Particulates

Data of measured particulates or particulate matter (PM) are often given in literature. However, a good uniform definition of these has not been found yet in literature. Probably PM is the same as aerosols, but it may also be true that PM includes aerosols. In some literature particulate matter is denoted as (C) [Schumann 1994]. Probably only carbon particles are included here.

2.11   Lead compounds

Lead compounds are toxic, they can cause anaemia ('bloedarmoede' in Dutch) and can influence the development of the central nervous system and the conductivity of excitations of the peripheral nervous system ([Eerens 1992] page 108).

2.12   Nuclear emissions and waste

When regarding emissions from electric trains, emissions of power stations have to be taken into account. Part of these power stations are nuclear ones. Nuclear emissions are being emitted to water and air. There are several types of nuclear waste ranging from contaminated laboratory equipment to used nuclear fuel. It must be noted that also coal fired power stations emit nuclear emissions.

3. Results of some existing studies: the need for a thorough analysis

The results of some recently published emission studies have been compared to determine the upper and lower limits of emissions calculated in other studies. No selection has been made to sort out realistic values. The comparison has been made to illustrate the risk of drawing the wrong conclusions when the backgrounds are not studied thoroughly. Note that often some emissions are not referred to correctly, e.g. NO_x emissions are often measured as NO_2, in some tables NO_2 and NO_x are not referred to correctly. The same situation can be found for VOC or HC emissions (often measured as CH_4) and $SO_x(SO_2)$. The following sources have been consulted.

1. [Carpenter 1994], this book is one of the most comprehensive books on the environmental impact of railways that has been found in libraries so far. In environmental impact assessments of railways, emissions are less important than subjects like noise disturbance, disturbance of landscapes, nature reserves etcetera. This makes good information on pollutant emissions caused by rail transport rare. The information on emissions in this book is still not comprehensive enough to assess the influence of different load factors, time, the year of construction and so on. Frequently information is only given for one or several particular situations. Much information in this source has been obtained from reports of an institute called TEST (Transport and Environment STudies) in London.

2. [Whitelegg 1993], figure 3.11 and 3.12 contain information on emissions and primary energy consumption for several transport modes. The data are German (1987) and are not very detailed.

3. [Tweede Kamer 1991, 22 026, nr. 4] This source is part of the environmental impact statement of the high-speed rail connection from Amsterdam to Paris. Only very little information is provided on emissions. A comparison has been made of several transport modes. The emissions from aircraft are based on the emissions during an entire flight of 500[km] of a DC-10. SO_2 emissions from aircraft have been derived from total emissions at Schiphol airport. The emissions of trains are based on Dutch trains (1987, average load factor of 37%). The data for the high-speed train (HST) are based on very limited data of the French railway company SNCF (TGV-Sud-Est, calculations done in 1986, load factor 65%). The emissions from cars have been obtained from other literature (CBS, emissions during motorway driving conditions).

4. [Tensen 1996], a comparison of transport modes based on existing literature, mostly CBS (Netherlands Central Bureau of Statistics).

5. [Schumann 1990], in the early nineties many research projects on the environmental impact of aviation were initiated in Europe. In 1990 a congress took place in Germany of which this are the proceedings (note: this book is sold out and will not be reprinted). In this book Reichow of Lufthansa presented emission and fuel consumption data for the Lufthansa fleet in 1988 and 1989. These data will be discussed in chapter 7. On page 7 a rough estimate is made of total global emissions, the amount of passenger-kilometres and fuel consumption, from these data emissions and fuel consumption per passenger-km can be derived.

6. [Schumann 1994], many above-mentioned programmes were in progress in 1994 and a second congress was held in Germany, the proceedings of which are published in this DLR publication. On page 47 Deidewig and Lecht of DLR presented results of NO_x emission

and fuel consumption calculation for several aircraft on a flight of 1000[km].

7. [Government policy .... 1995], this source is a Dutch Governmental note on air pollution and aviation, in Dutch it is often popularly called "Nota LuLu", LuLu is an abbreviation of 'Luchtverontreiniging en Luchtvaart'. The comparative data on emissions caused by several transport modes have been obtained from CBS, ECN and NLR.

8. [Arends 1995] and [Arends 1994], these sources describe the same study by ECN (Netherlands Energy Research Foundation). In this Study a method was developed for the integral evaluation of air pollution based on weighting factors (Dutch guilders per kg) for the costs necessary to reduce emissions to a "sustainable" level. Some comparative data are given.

9. [Sjöström 1991], in this publication of Saab-Scania comparative data are given of several transport modes (page 47). Some emissions caused by electric trains are zero because nuclear or hydro electric power generation was assumed.

From these data upper and lower limits have been derived for emissions and energy consumption. For energy consumption the type of energy (primary, electric, fuel heat content etc.) was not specified in each case, this can cause large variations. The upper and lower limits are given in table 3.1. Taxis are included in the passenger cars. The very high values of CO_2, SO_2 and energy consumption for passenger cars are values of taxis.

table 3.1   **Upper and lower limits of emissions and energy consumption per passenger-kilometre for several transport modes**

		aircraft	passenger cars	"classic" trains	high-speed trains	buses
CO_2 [g/Pkm]	upper limit	346	411	117	48	114
	lower limit	130	86	38	35.8	22
CO [mg/Pkm]	upper limit	2100	24000	1700	39	1900
	lower limit	60	250	0	2	75
NO_x [mg/Pkm]	upper limit	1200	3190	4870	290	2000
	lower limit	210	50	0	87	90
HC (CH_4, VOC) [mg/Pkm]	upper limit	600	3150	1240	19	500
	lower limit	30	40	0	1	50
SO_2(SO_x) [mg/Pkm]	upper limit	112	300	1560	90	120
	lower limit	10	7	50	60	23
energy [kJ/Pkm]	upper limit	2900	5740	4131	700	1540
	lower limit	1690	1370	396	440	330

Table 3.1 shows very large differences between upper and lower values and between different transport modes. These differences can clearly be seen in fig. 3.1-3.6. From the data in the

mentioned literature it became
clear that the following factors
must be considered when
emissions from different
transport modes are compared:
-   the load factor;
-   time, or more specific, the
    year of construction or
    testing of the vehicles;
-   the travelled distance;
-   operating conditions;
-   the presence of emission
    control devices such as
    catalytic converters or
    special combustion
    chambers;
-   the used fuel type;
-   the vehicle type (long or
short range aircraft, for passenger cars: different engine swept volume, for trains: long or
short range transport or high speed trains etc.).
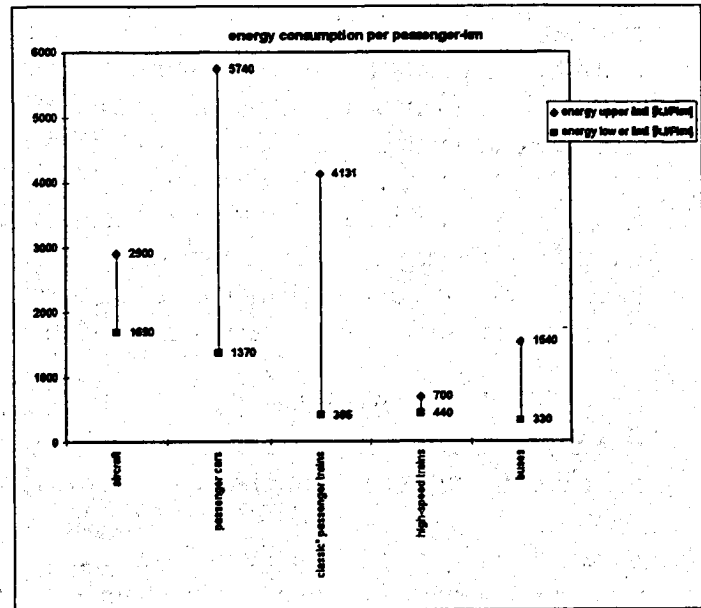

fig. 3.1

Fig. 3.1-3.6 illustrate the risk of
drawing conclusions from
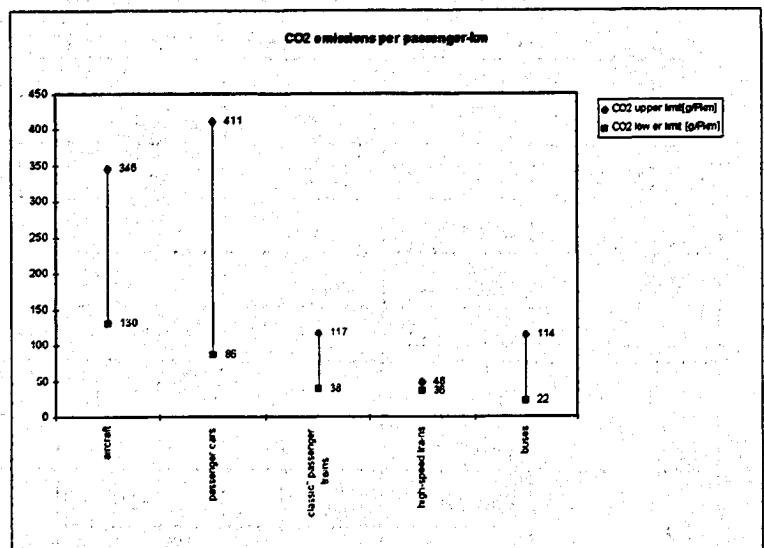published emission data without
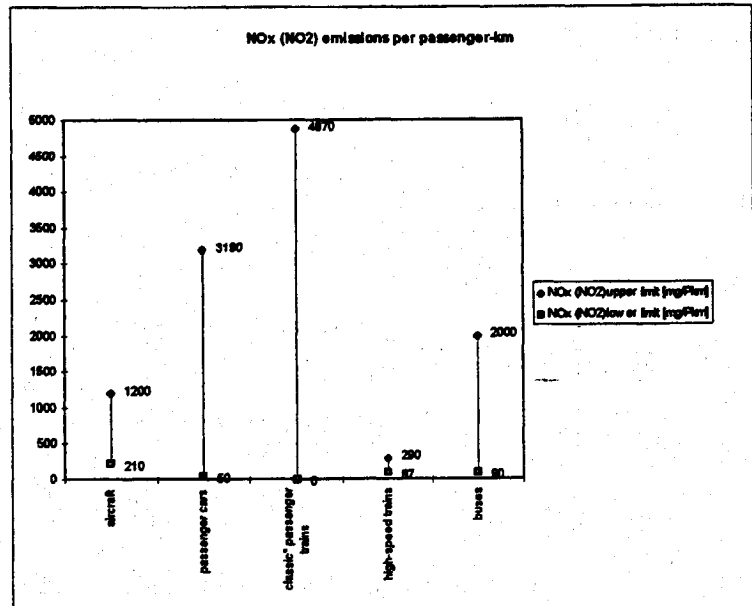thorough background
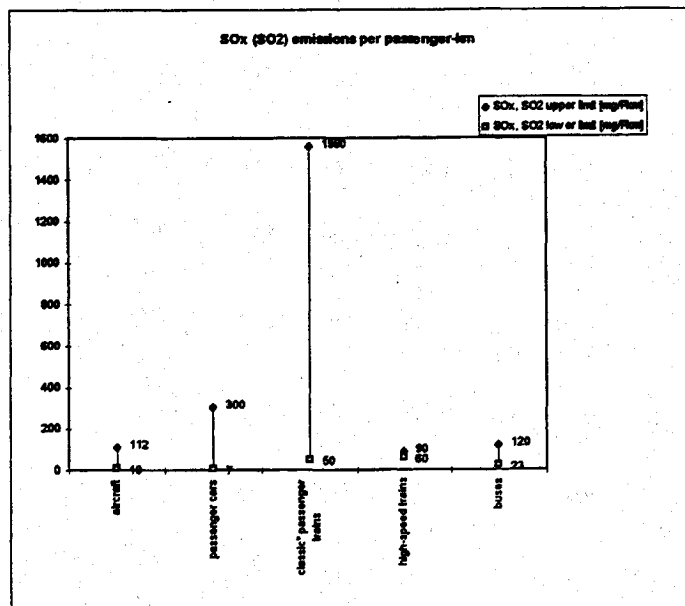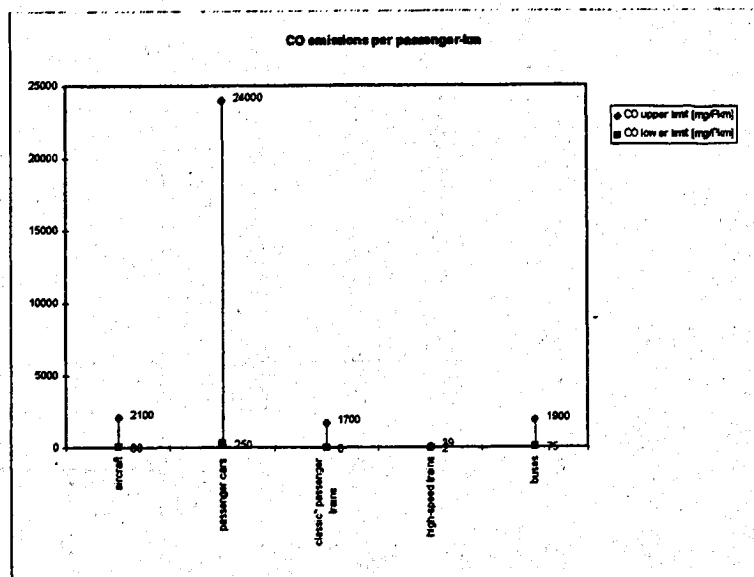knowledge.

fig. 3.2

fig. 3.3

fig. 3.4

fig. 3.5

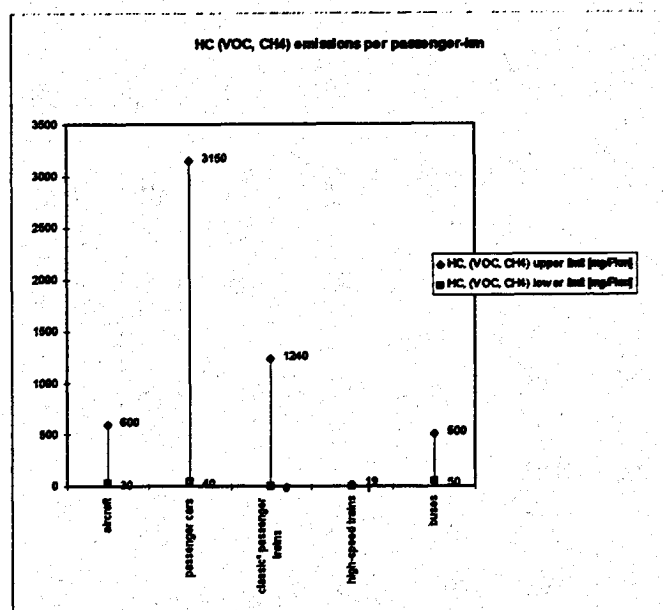fig. 3.6

4. Emissions from passenger cars

When emissions from passenger cars are considered, the word 'passenger' can cause confusion because the driver is also travelling. Therefore, the word 'traveller' is used. The driver is included in the travellers except when taxis are considered. Because there are many factors that influence the emissions per traveller-kilometre, some choices have been made.

The development of emissions as a function of time will be analysed using statistical data of the emissions and traffic performance of passenger cars in the Netherlands. The average travelled distance per trip is very short. That is why average emissions per traveller-km are certainly not typical for long distance travel. Because the emissions will be compared with emissions from aircraft, long distance travel has to be analysed. The formulas used for the calculation of emissions for long distances contain a lot of variables such as year of construction, driving condition, engine swept volume, fuel (gasoline, LPG or diesel oil) and the presence of emission control devices. Analysis of various years would be very time consuming, therefore long distance travel will be analysed for year of construction 1990 (the most recent year for which the method can be used).

Emissions from passenger cars are influenced by:
- driving conditions and the drivingg behaviour of the driver;
- fuel type;
- year of construction;
- emission control devices like catalysts, carbon canisters, exhaust gas recirculation, pulse air system, HCLB engines (high compression lean burn), etcetera;
- ambient temperature;
- a cold start;
- altitude;
- the incidence of the road;
- the age of the vehicle, the total driven vehicle-kilometres.

Most of these aspects will be discussed in this chapter. For aspects that are not described, a theoretical review will be given in the final report.

4.1   Emissions from passenger cars in the Netherlands 1980-1994

The emisions from passenger cars in the Netherlands have been studied using statistical data from CBS. The CBS publications that have used are:
- [Zakboek verkeer en vervoer 1995];
- [CBS 1994];
- [CBS 1993, statistiek van het personenvervoer 1993];
- [Luchtverontreiniging, ... 1992].

The amount of travellers per car has been determined by CBS. For some specific cases the number has been calculated from CBS data. For Dutch vehicles abroad and foreign vehicles in the Netherlands, the number of passengers remained constant at 2.5. The number of domestic travellers varied. From the traffic performance (vehicle-kilometres) and the number of travellers per vehicle, the average number of travellers per vehicle has been calculated, see fig.

4.1.

number of travellers per passenger car

Legend:
- travellers per vehicle, domestic, 'cbs, statistiek van het personenvervoer 1994'
- travellers per vehicle, abroad, 'cbs, statistiek van het personenvervoer 1994'
- travellers per vehicle, foreign vehicles in the Netherlands, 'cbs, statistiek van het personenvervoer 1994'
- average travellers per passenger car, Dutch and foreign in the Netherlands
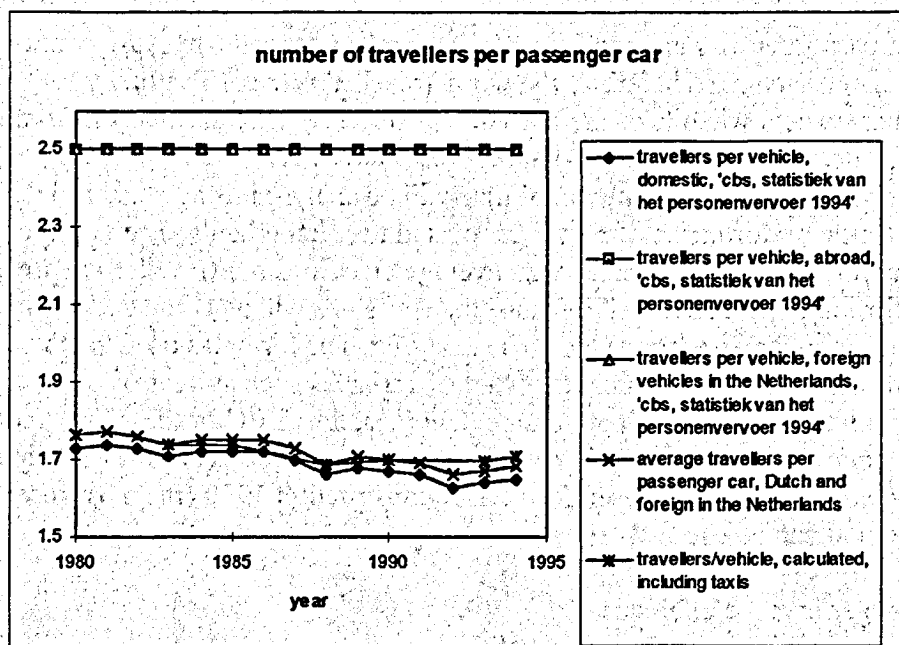- travellers/vehicle, calculated, including taxis

fig. 4.1

When the number of travellers per car is combined with the emissions per vehicle-km, the emissions per traveller-km can be calculated. The emissions of hydrocarbons per vehicle-km including emissions due to evaporation have been calculated from total emissions and vehicle-kilometres. Note that the registration of data for taxi/minibuses has changed in the 80s due to a change in legislation. The total emissions have been given by CBS, these are shown in fig. 4.2 relative to the value in 1980. This figure shows that all the mentioned total emissions except CO_2 and SO_2 are below the 1980 value.

The rapid decrease of lead compounds is due to the introduction of lead-free gasoline. The emissions per traveller-km are shown in fig. 4.3 and 4.4

annual emissions from passenger cars in the Netherlands relative to 1980 (1980=100%)

Legend:
- CO2
- CO
- NOx
- SO2
- HC incl. evaporation
- Aerosols
- lead compounds

fig. 4.2

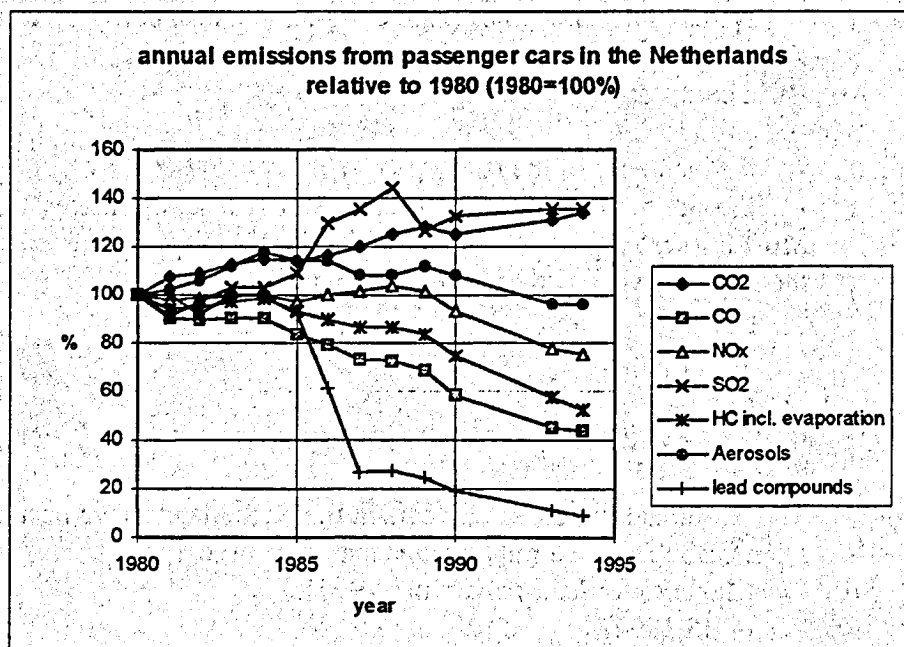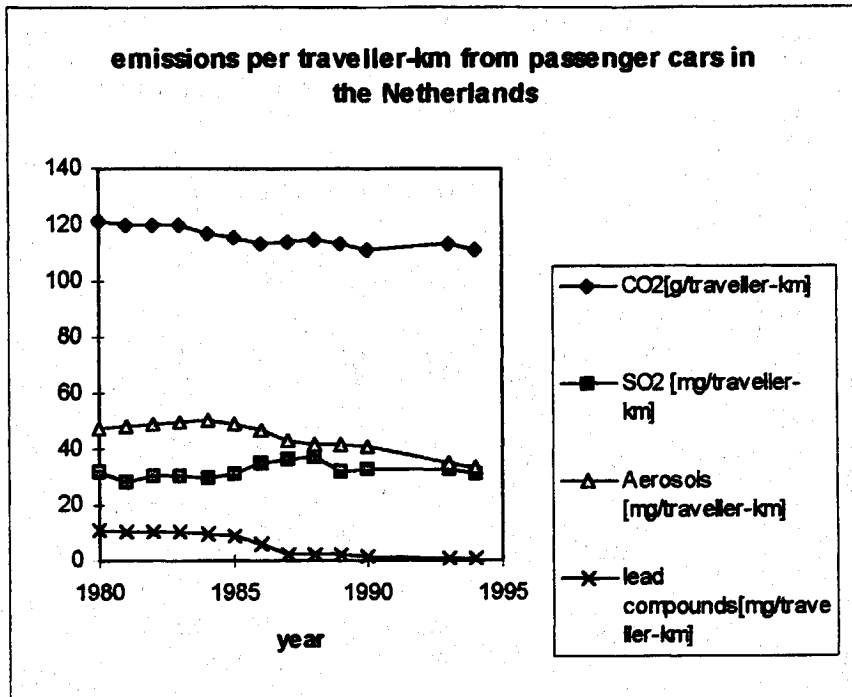**emissions per traveller-km from passenger cars in the Netherlands**

fig. 4.3

Note that all emissions per traveller-km are decreasing although SO_2 emissions had been increasing during the late 1980s. Fig. 4.5 has been compiled to show the emissions per traveller-km relative to the values in 1980.
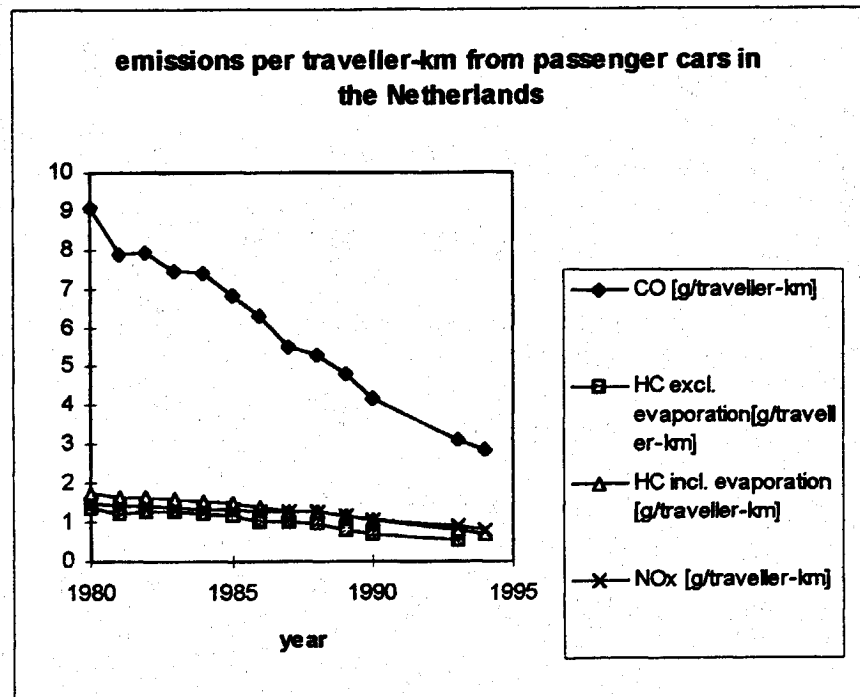
emissions per traveller-km from passenger cars in the Netherlands

fig. 4.4

emissions per traveller-km from passenger cars in the Netherlands relative to 1980

Legend:
- ◆ CO2[g/traveller-km]
- ⊠ CO [g/traveller-km]
- HC excl. evaporation[g/traveller-km]
- HC incl. evaporation [g/traveller-km]
- ✳ NOx [g/traveller-km]
- ● SO2 [g/traveller-km]
- ┼ Aerosols [g/traveller-km]
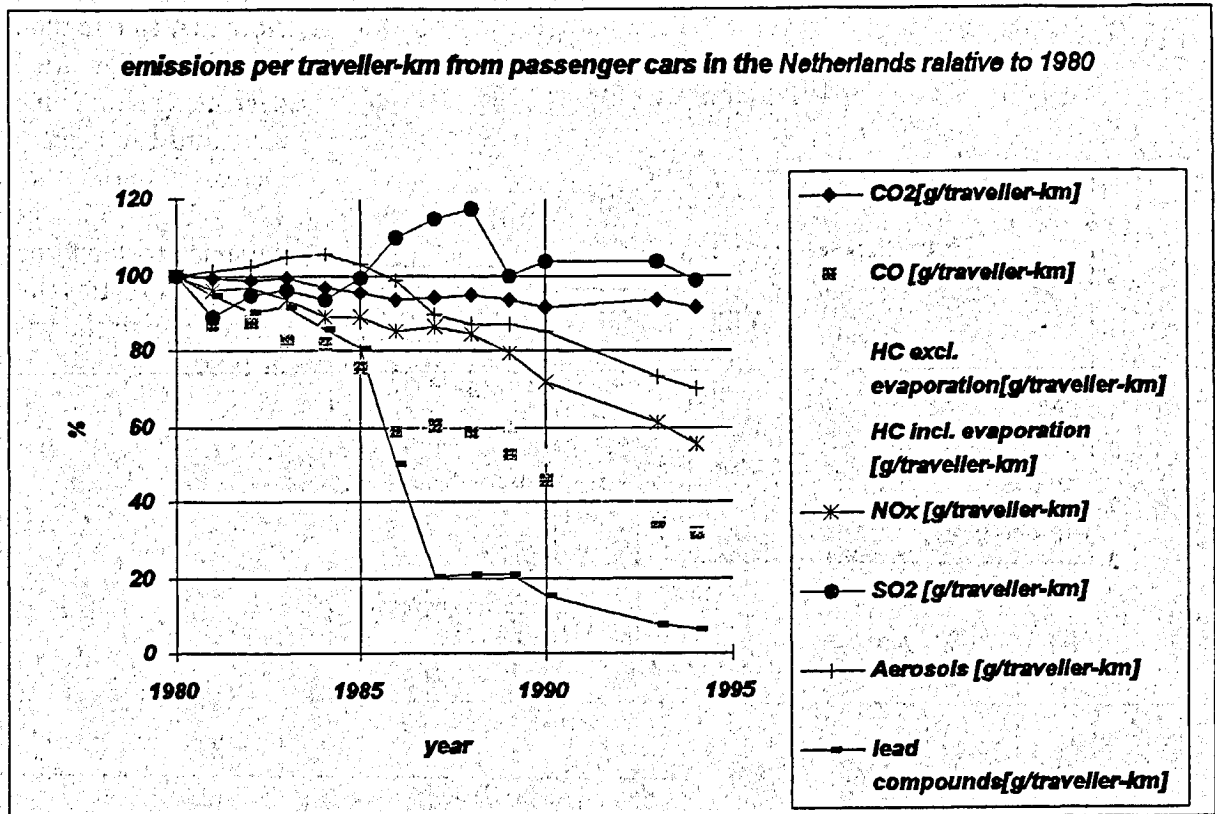- ▬■ lead compounds[g/traveller-km]

fig. 4.5

In fig. 4.5 both the HC emissions including and excluding emissions due to evaporation of fuel from the fuel system are given. In fig. 4.6 the evaporative HC emissions per traveller-km are compared to the HC emissions including evaporation.

Because of the relatively short average distances per trip, the average emissions per traveller-km cannot be used for comparison with aircraft and long distance rail transport.

This paragraph shows however that large emission reductions have been achieved since the early 1980s.

HC emissions due to evaporation per traveller-km relative to the total HC emissions from passenger cars per traveller-km in the Netherlands

fig. 4.6

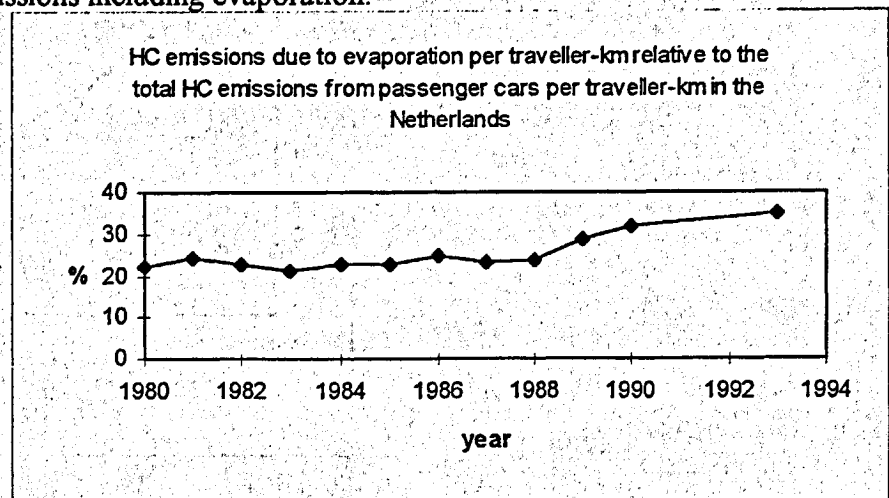This again illustrates the risk of using outdated data and stresses the need for a thorough analysis.

4.2 The influence of a cold start on the emissions from passenger cars

The emissions from passenger cars are affected by the high emissions during the time that the engine is warming up after a cold start. In [Hassel 1987] the emissions during the warming up of the engine have been investigated for cars with year of construction 1985 or earlier. Probably most of these cars do not have a catalytic converter.

The distance that a car has to drive to warm up the engine is defined as the distance driven from a cold start at the end of which the emissions and fuel consumption (per vehicle-km) have reached the levels corresponding to the warm engine. For a given car this distance depends on:
- ambient temperature;
- driving conditions.

A different method to determine the distance to warm up the engine is the measurement of the oil temperature. This method leads to the same results.

A relationship between the distance of warming-up phase and the ambient temperature has been obtained, based on the European test cycle ECE R-15. This cycle does not include the start of the engine and a succeeding phase in which the engine is idling for 40 seconds. This is why the oil temperature at the beginning of the test cycle is about 2 to 3°C higher than the ambient temperature. The results are shown in table 4.1.

table 4.1 **The distance driven during the warming-up phase as a function of ambient temperature, source: [Hassel 1987] page 125-127**

T [°C]	average distance driven during the warming-up phase of the engine [km]
5	5.1
20	4.1
-10	6.1

A straight line can be drawn exactly through these points. According to [Klein 1993] page 10 the (yearly) average ambient temperature in the Netherlands is 9°C. For this temperature the straight line relation results in an average distance of 4.8[km].

Before the average distance during the warming-up phase is determined, it is necessary to know to what extend the mentioned relation is valid for modern passenger cars. Most modern cars will be equipped with an open loop or closed loop (three-way) catalytic converters.

In [Dursbeck 1994] the effects of a cold start have been investigated. The applied method differs from the methods in [Klein 1993] and
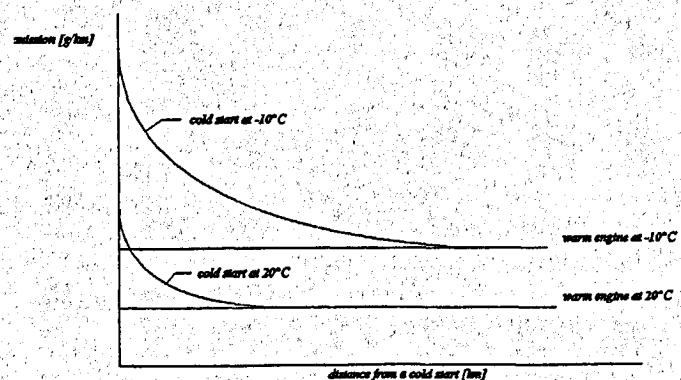
fig. 4.7   the effect of a cold start at different ambient temperatures

[Hassel 1987]. In this case the US-Test-75 has been used to determine the effects of a cold start. In general the effects are as shown in fig. 4.7, this figure is based on a figure on page 13.15 of [Dursbeck 1994].

Fig. 4.7 shows that both the emissions after a cold start and the emissions for a warm engine depend on the ambient temperature. When the higher emissions due to a cold start are not considered this may result in large errors. On pages 18.47 and 18.48 of [Dursbeck 1994] cold-start factors are given for several vehicle concepts. The cold-start factor has been defined as follows.

$KF_{S,T}$: cold-start factor, i.e. the ratio of the extra emissions due to a cold start to the total emissions for a warm engine at ambient temperature T.

$E_{K,S,T}$: emissions [g] after a distance S in phase 1 of the US-Test-75 at ambient temperature T.

$E_{w,S}$: emissions [g] after distance S in phase 3 of US-Test-75 at an ambient temperature of 20°C.

E_w: total emission of phase 3 at 20°C.

The cold start factor can be calculated from:

$$KF_{S,T} = \frac{E_{K,S,T} - E_{w,S}}{E_w} \tag{1}$$

The length of phase 3 of US-Test-75 is 5.777[km] (page 13.17). Phase 1 is equal to phase 3, except that phase 1 is driven at the beginning of the test cycle and phase 3 is driven at the end of the cycle (page 6.3-6.4). In these phases the average speed is 41[km/h], the minimum speed is 0[km/h] and the maximum speed is 91[km/h]. During 20% of the whole phase the speed is 0.

In fig. 4.8-4.10 the cold start factors are shown for several ambient temperatures and vehicle concepts. In these figures KF means cold-start factor as defined by formula (1). The vehicle concepts are:
- passenger cars with Otto engines and a closed loop catalyst (three-way catalyst);
- passenger cars with Otto engines and an open loop catalyst;
- conventional passenger cars with Otto engines, in this class also cars with special emission control devices (e.g. pulse-air system) are included;
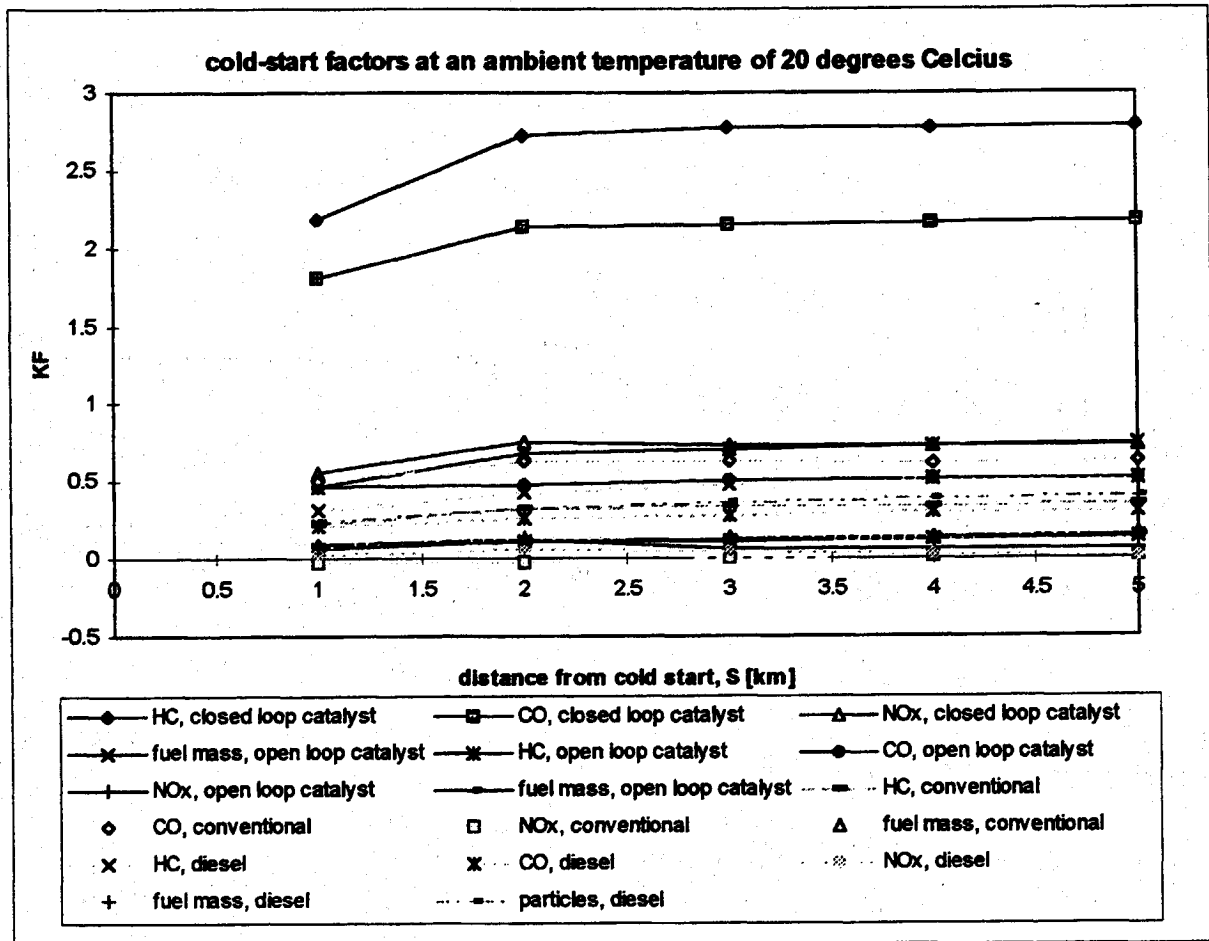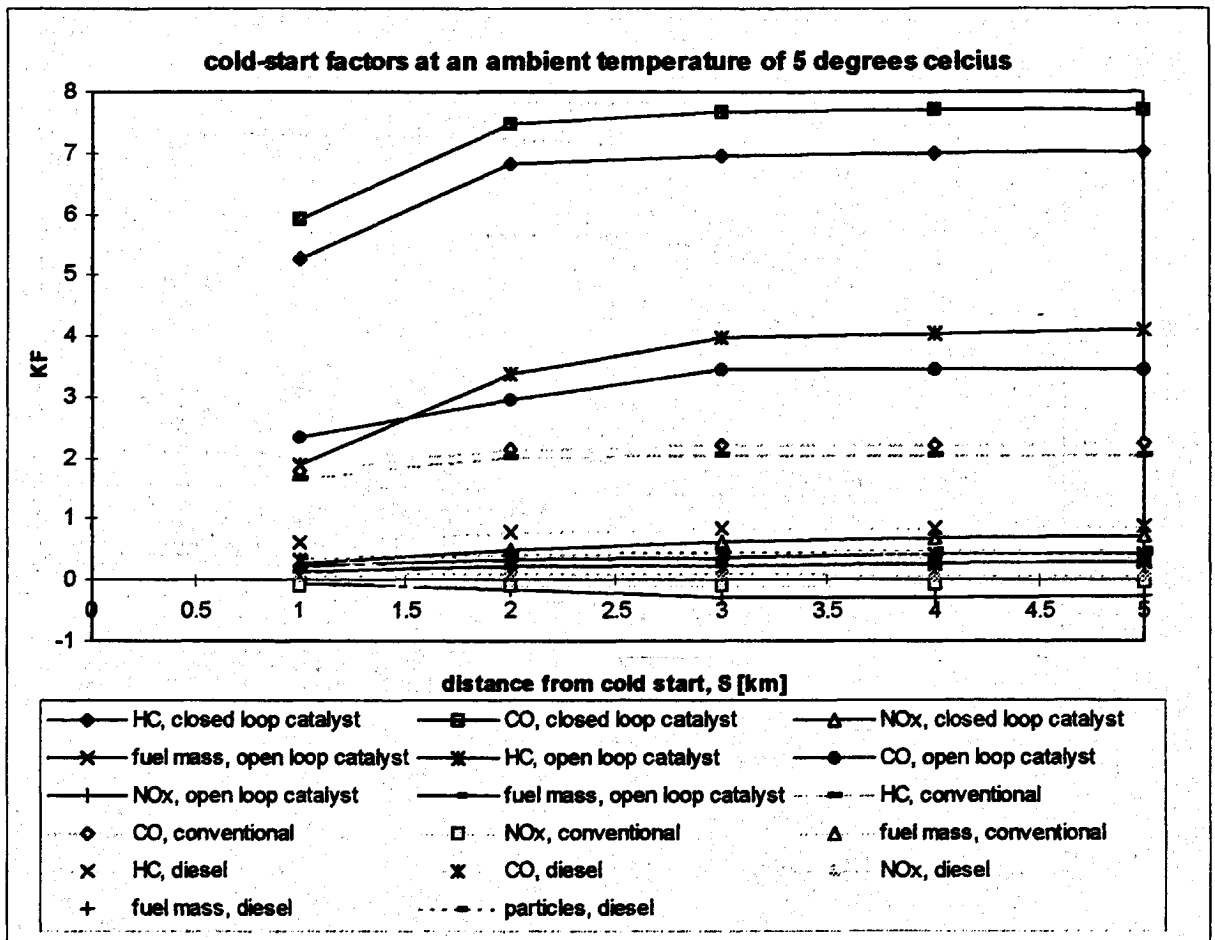- passenger cars with Diesel engines.

fig. 4.8

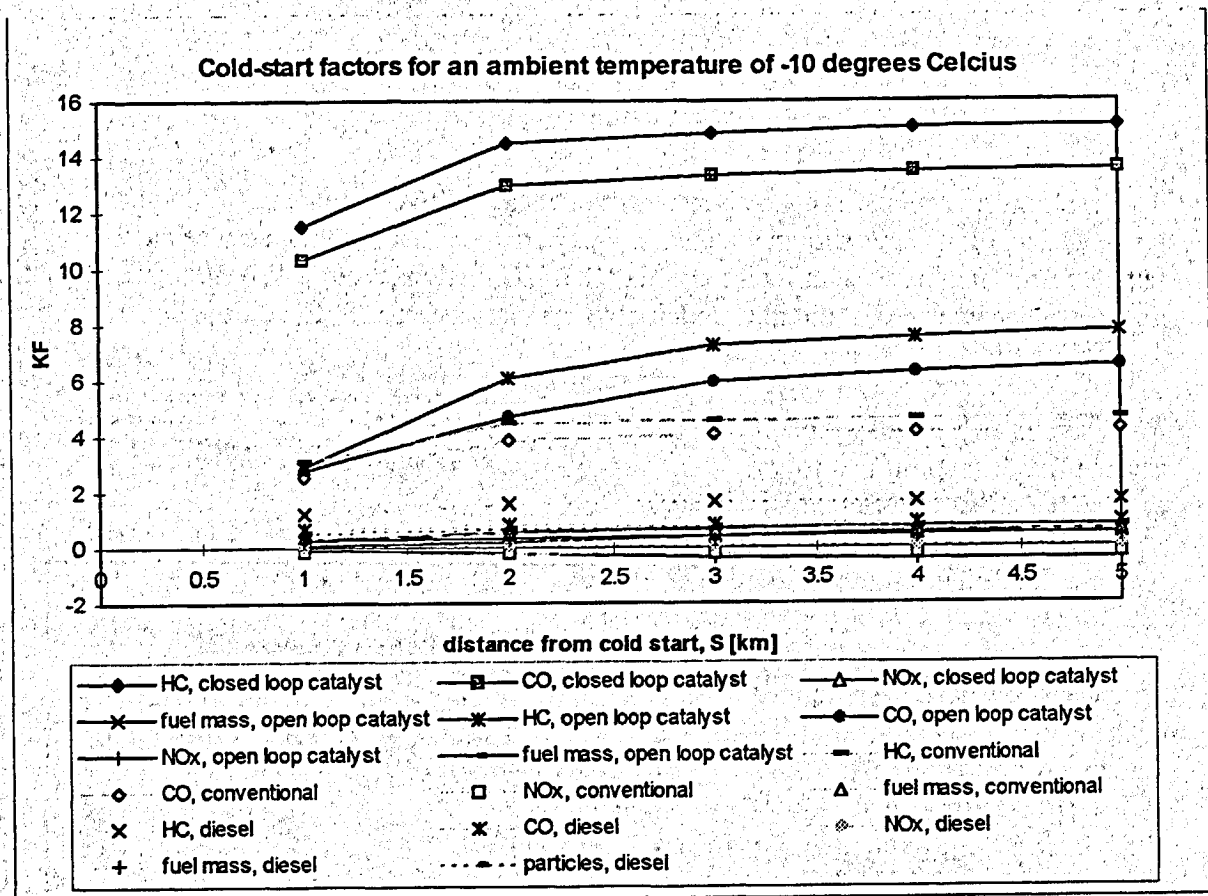cold-start factors at an ambient temperature of 5 degrees celcius

fig. 4.9

Cold-start factors for an ambient temperature of -10 degrees Celcius

fig. 4.10

Occasionally the cold-start factor can be negative (NO_x for conventional Otto engines and Otto engines with open loop catalysts, both at the two lower temperatures of 5 and -10°C)!

A method is developed that can be used to estimate the distance at which the transition to a warm engine occurs. This distance, S_w, is defined as the distance where the emissions and the fuel consumption per vehicle-km reach the levels corresponding to the warm engine. At this distance the emissions per vehicle-km reach a constant value. This means that the second partial derivative of $E_{K,S,T}$ becomes 0 and remains 0. Since E_w and $E_{w,S}/S$ are constants for a given temperature and car concept, this means that:

$$\frac{\partial^2 KF_{S,T}}{\partial S^2} = 0 \ \ for \ S \geq S_w \tag{2}$$

This derivative can be estimated using Taylor expansions of $KF_{S,T}$ with equidistant nodes. When -1, 0, and 1 correspond to three succeeding nodes with intervals, h (h=1[km] in this case) between them, the second partial derivative can be estimated with formula (3).

$$\left(\frac{\partial^2 KF_{S,T}}{\partial S^2}\right)_0 \approx \frac{1}{h^2}\left[(KF_{S,T})_{-1} -2(KF_{S,T})_0 + (KF_{S,T})_{+1}\right] \qquad (3)$$

This can only be calculated at three distances as there are five distances (1, 2, 3, 4 and 5[km]) given. Calculations have shown wide variations between car-concepts, between ambient temperatures and between different criteria (CO, HC, fuel mass etc.). When the second partial derivative became zero, it did not remain zero in most cases for S≥S$_w$. This is illustrated for T=20°C in fig. 4.11.

The choice has been made to assume that S$_w$=4[km] and to analyse the effect of different values of S$_w$ (3 and 5[km]) on the emission levels.

In the Netherlands several vehicle classes have been defined ([Klein, 1993], [Luchtverontreiniging ....., 1993], [Binkhorst, 1994], [Rijkeboer 1989]). Note: expressions like 83/351/EEC are EEC directives.

N: normal, complying with minimum requirements, [luchtverontreiniging ... 1993].

B: to a certain extend "clean", [luchtverontreiniging ... 1993].

fig. 4.11

15-04: vehicles certified according to ECE regulation 15-04 or Directive 83/351/EEC.

S6:   vehicles that complied with the conditions of the fiscal incentives of 1986 and did not use a catalyst.

S9:   vehicles that complied with the conditions of the fiscal incentives of 1989 and did not use a catalyst.

K6:   vehicles that complied with the conditions of the fiscal incentives of 1986 and used a catalyst. Before 1993/1994 this class was divided into two groups: K6-O and K6-G.

K6-O: K6 vehicles with an open-loop catalyst.

K6-G: K6 vehicles with a closed-loop catalyst

K9:   vehicles that complied with the conditions of the fiscal incentives of 1989 and used a catalyst. In most cases these vehicles us an open-loop catalyst.

U9:   originaly vehicles that made use of the fiscal incentives of 1989 and complied with the US'83 standards. Also vehicles with an engine swept volume greater than 2.0[l] that
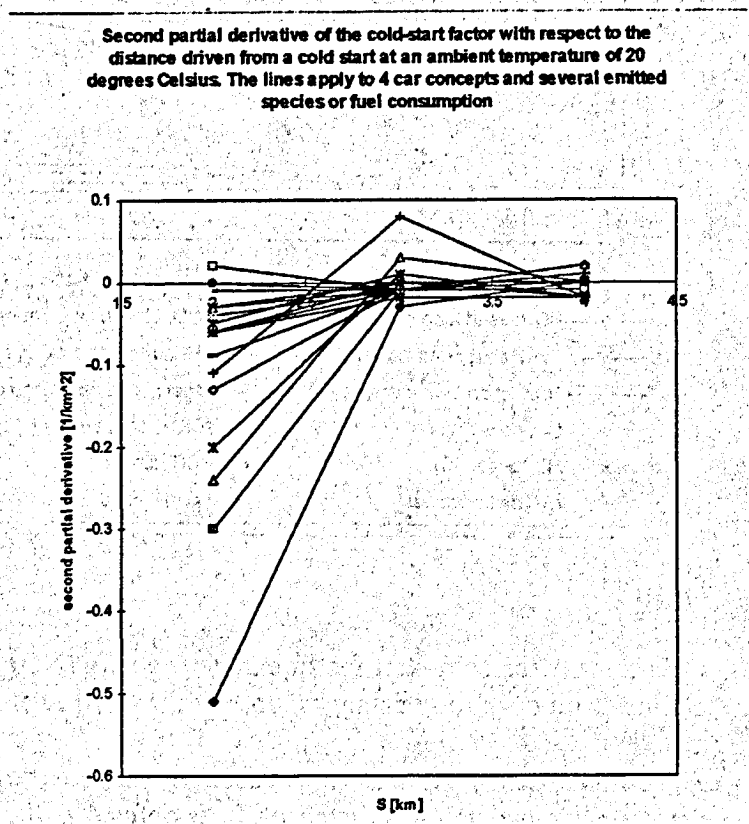
complied with 88/76/EEC fall in this category, because these two regulations were assumed equivalent. After 91/441/EEC came into force, U9 refers to vehicles with type certification according to the temporary provisions of that directive. These vehicles are besides the above mentioned vehicles also those type-certificated according to 89/458/EEC. In practice these vehicles are all the U9 vehicles with a closed-loop (three-way) catalyst. If these vehicles had an open-loop catalyst, these would have the code N9 since 1992.

E2:   vehicles that have been type-certificated according to 91/441/EEC without making use of the temporary provisions (i.e. based on the European procedure). These vehicles have a three-way catalyst. If these vehicles had an open-loop catalyst, these would have code N2.

N2:   vehicles with an open-loop catalyst, certificated according to the ordinary procedure of 91/441/EEC.

N9:   vehicles with an open-loop catalyst, certificated according to the temporary provisions of 91/441/EEC.

There are 3 types of "basic emission factors" [Klein 1993].

1.   Emission factors of VO, VOC, NO_x and aerosols (Aer) due combustion; these factors are mostly based on simulation of driving conditions in laboratory tests. These factors are expressed as grammes of emitted species per vehicle-km.

2.   Emission factors of SO_2, CO_2 and lead compounds, derived from the sulphur, carbon and lead contents of the fuels. These factors are expressed in grammes per litre of fuel.

3.   Emission factors due to evaporation of VOC, based on laboratory measurements, these factors are expressed in grammes per vehicle per day.

According to [Klein 1993] page 10, the following expression has been used to derive "basic emission factors" (EF_b) of the first type. EF_w is the emission factor for a warm engine.

$$EF_b = (A_w \cdot EF_w) + (A_k \cdot EF_w \cdot C_k) \qquad (4)$$

In this expression A_w is the part of the traffic performance driven with a warm engine, A_k is the part driven with a warming-up engine. C_k is a correction factor for driving during the warming-up phase of the engine, this factor is based on the first 4[km] after a cold start and an average yearly temperature of $9°C$. All these factors have been given in [Klein 1993]. So in the basic emission factors a correction for the influence of a cold start has been included. Expression (4) will be used to assess the influence of the cold start on the emission levels as a function of the trip distance. Define the emission factor in which the influence of a cold start is included as EF, EF is expressed in [g/vehicle-km] or just [g/km] which is the same. From (4) the ratio of the increase of EF with respect to EF_w can be calculated.

$$\frac{EF - EF_w}{EF_w} = A_w + A_k C_k - 1 \qquad (5)$$

The distance driven after a cold start is S, S_w is the distance at which the transition to a warm engine occurs. Assume:

$$A_k = \frac{S_w}{S} \quad and \quad A_w = 1 - A_k \qquad (6)$$

Substitution into (5) yields:

$$\frac{EF - EF_w}{EF_w} = \frac{S_w}{S}(C_k - 1) \qquad (7)$$

Three driving conditions have been defined, [Klein 1993].
RT1: urban driving conditions, the speed is varying and the average speed is 22[km/h].
RT2: extra-urban driving conditions, the speed is varying and the average speed is 51[km/h].
RT3: motorway driving conditions, the speed is constant and equal to 110[km/h].

Three classes of engine swept volume have been defined:
- $V_s < 1.4[l]$;
- $1.4 \leq V_s \leq 2.0[l]$;
- $V_s > 2.0[l]$.

For the several emitted species, driving conditions and vehicle classes, the ratio of the increment of the average emissions per vehicle-kilometre due to a cold start to the emissions per vehicle-kilometre of a warm engine can be calculated using values of C_k in [Klein 1993]. The calculations have been done for urban (RT1) and extra urban (RT2 and RT3) driving conditions driving conditions with the assumption that S_w=4[km], see fig. 4.12 up to 4.17. Besides these calculations the sensitivity of the results to variations of S_w will be studied.

Influence of a cold start on CO emissions per vehicle-km for extra urban driving conditions. The transition to a warm engine occurs at S=4[km]

fig. 4.12

Influence of a cold start on the VOC emissions per vehicle-km, excluding emissions due to evaporation, extra urban driving conditions. The transition to a warm engine occurs at S=4[km].

fig. 4.13

The influence of a cold start on NOx emissions per vehicle-km, extra urban driving conditions. The transition to a warm engine occurs at S=4[km]
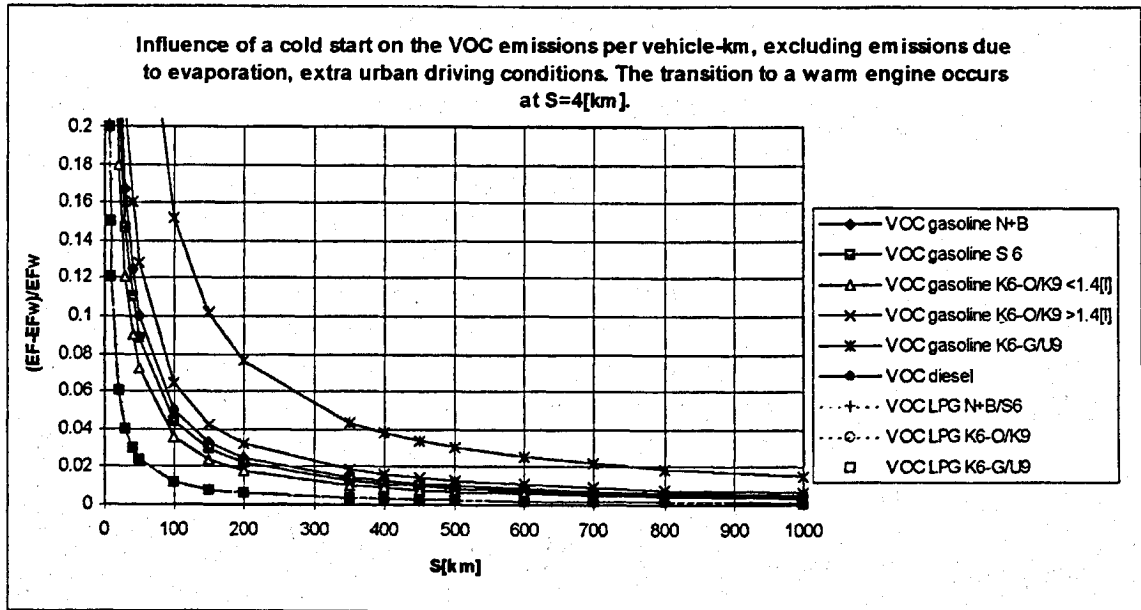
fig. 4.14

fig. 4.15

fig. 4.16

Influence of cold start on NOx emissions per vehicle-km, urban driving conditions, transition to warm engine at S=4[km]

Legend:
- NOx gasoline N+B
- NOx gasoline S 6
- NOx gasoline K6-O/K9 <1.4[l]
- NOx gasoline K6-O/K9 >1.4[l]
- NOx gasoline K6-G/U9
- NOx diesel
- NOx LPG N+B/S6
- NOx LPG K6-O/K9
- NOx LPG K6-G/U9
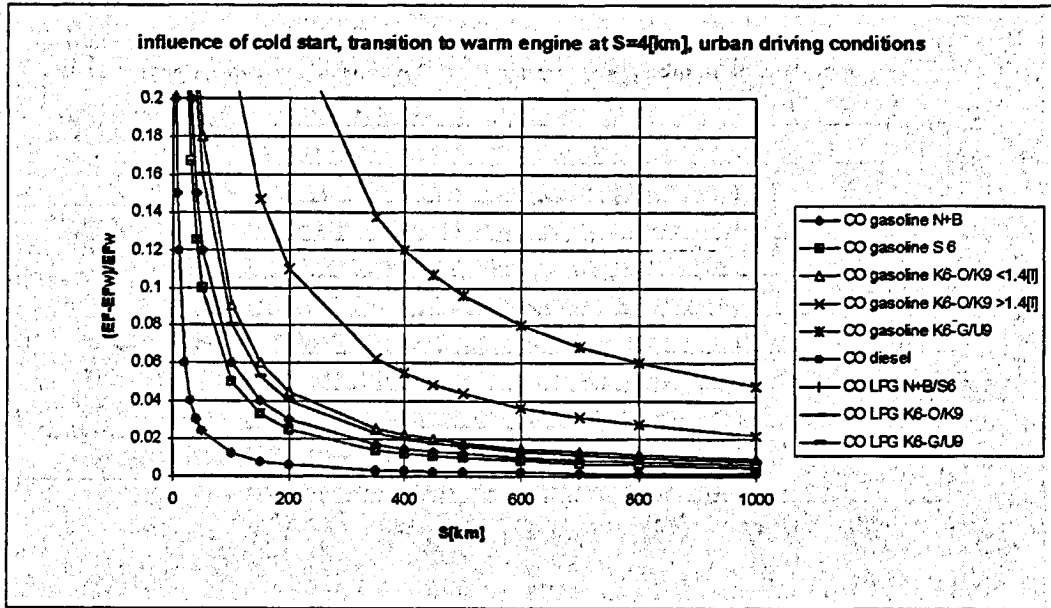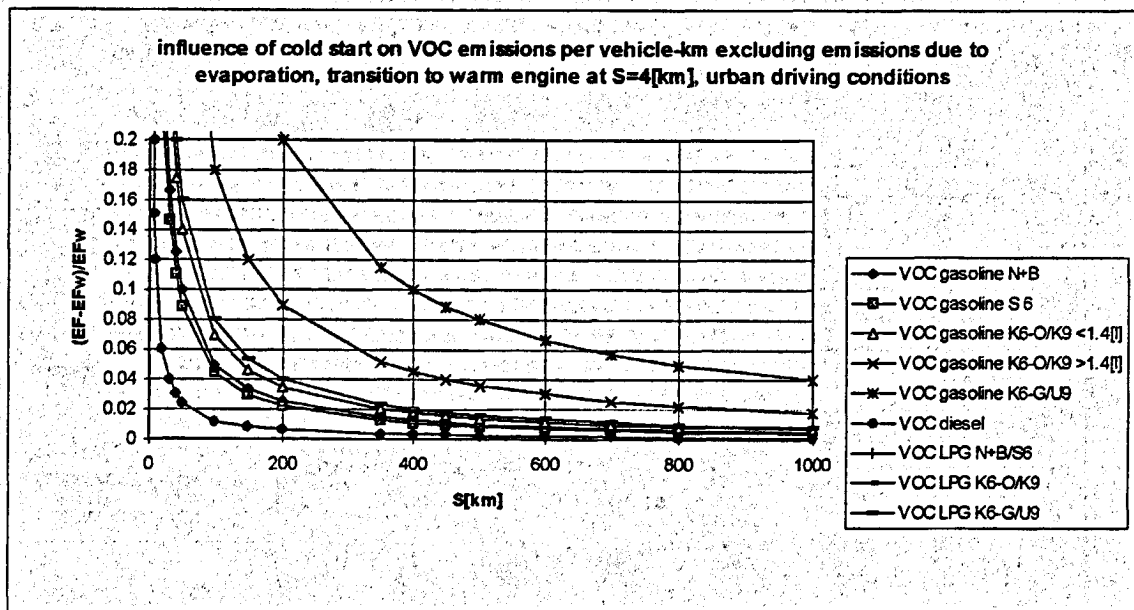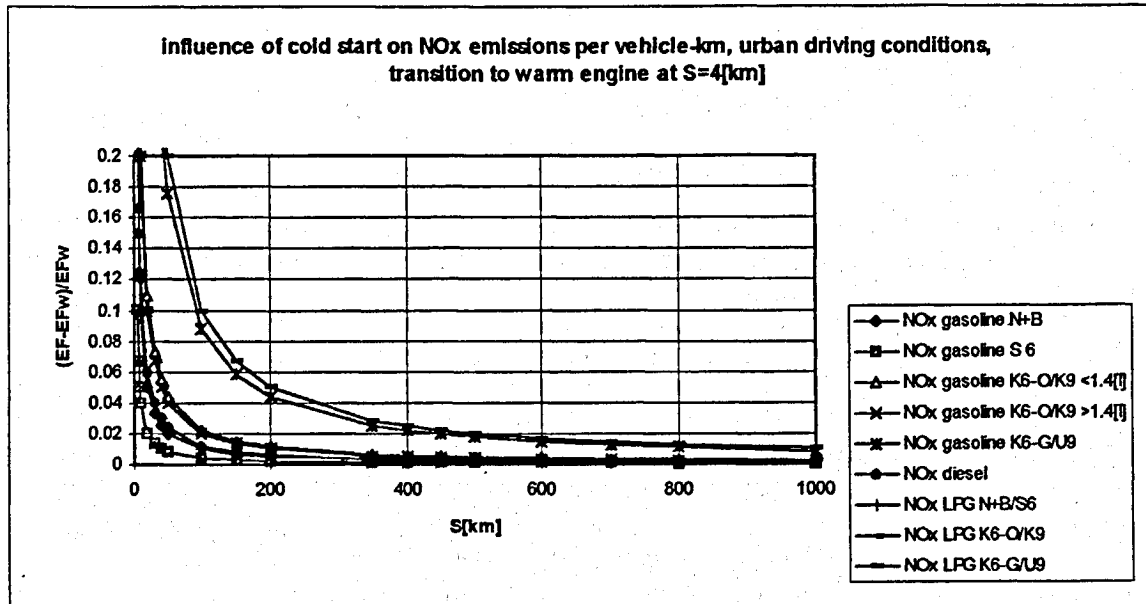
fig. 4.17

These figures have been drawn to illustrate the effects at large values of S. For small distances the increase of the average emissions per vehicle-km due to a cold start can be very high. At large distances the effects of a cold start are negligible for extra urban-driving conditions (RT2 and RT3). For urban driving conditions (RT1)the influence of a cold start is more severe than for extra-urban driving conditions (RT2 and RT3). The extra-urban driving conditions, including motorway driving conditions, are the most relevant conditions for comparison with aircraft.

The relative influence of S_w on $(EF-EF_w)/EF_w$ is independent of S and depends only on S_w/S, when C_k is given, see formula (7). The relative change of S_w/S with respect to the value of S_w/S at $S_w=4[km]$ is equal to the relative change of $(EF-EF_w)/EF_w$ with respect to the value for $S_w=4[km]$. This is illustrated in table 4.2.

table 4.2   sensitivity of the increment of the average emission factor due to a cold start variations in S_w

S_w	3	5	6
$(S_w/S-(S_w/S)_{Sw=4})/(S_w/S)_{Sw=4}$	0.25	-0.25	0.5

When S_w varies between 3 and 5[km] and the assumption of $S_w=4[km]$ is used, the value of $(EF-EF_w)/EF_w$ can easily be overestimated or underestimated by an amount of 25%. Because the values of the extra emissions per vehicle-km (average of a trip of distance S) due to a cold start are very small compared with the emissions of a warm engine for large values of S, the effect of a varying S_w at large values of S is still very small when it is compared to the emissions from a warm engine. So it is still justified to neglect the influence of a cold start on the average emissions per vehicle-km for long trips.

4.3　Emissions from passenger cars with a warm engine

Emissions per vehicle-kilometre from passenger cars with warm engines have been calculated for several vehicle concepts, engine swept volumes and driving conditions. The used method is described in [Klein 1993]. The calculations have been done for year of construction 1990. The formulas allow emissions to be calculated for S6, K6-O and K9 vehicles with engine swept volumes greater than 2.0[l] (both using gasoline and LPG fuel), these classes have probably not been produced because these cars could not comply with the regulations when an open-loop catalyst was used instead of a closed loop catalyst.

The used formulas (obtained from [Klein 1993]) are given in table 4.3. These formulas show no dependancy of emission factors and fuel consumption on ambient temperature. Assume that the emission factors and fuel consumption for warm engine do not depend on ambient temperature.

table 4.3　　Formulas for the calculation of CO, VOC excluding evaporation and NO_x, vehicle classes S, K, U, and diesel and LPG passenger cars, year of construction 1986 or later (warm engine)

	description	formula
year of construction		given
j	correction factor for year of construction	1990-year of construction
V (V_c, V_v)	speed[km/h] (constant, varying)	given in [Klein 1993]
V_s	average engine swept volume [l]	given in [Klein 1993]
M_0	mass [tonnes] gasoline, class S: 　　　classes K6, K9, U9: diesel: LPG:	$V_s/2.2+0.245$ $V_s/2.33+0.245$ $V_s/1.95+0.09$ $1.05*(V_s/2.2+0.245)$
M	mass on the road [tonnes]	$M_0+0.1$
C_x	aerodynamic drag gasoline: diesel: LPG:	$(1+j*0.02)*(7.1+(1.65+M_0))*10^{-6}$ $(1+j*0.02)8(7.1+(1.65*M_0/1.075))*10^{-6}$ $(1+j*0.02)*(7.1+(1.65*M_0/1.05))*10^{-6}$
f_{R90}	rolling friction, year of construction 1990	given in [Klein 1993]
f_R	rolling friction	$f_{R90}+j*0.05$
η_{90}	efficiency, year of construction 1990	given in [Klein 1993]
η	efficiency	$\eta_{90}-j*0.002$
b_0	gasoline, class S: gasoline, classes K6, K9, U9: diesel, indirect injection (IDI): diesel, direct injection (DI): LPG:	$190+350*V_s+j*6*V_s$ $35+400*V_s+j*6*V_s$ $100+210*V_s$ $75+160*V_s$ $175+325*V_s+j*6*V_s$

$E (E_v, E_c)$	energy consumption [g/h] varying speed, E_v: constant speed, E_c:	$(f_R+2.9)*M*V_v+0.32*C_x*10^6V_v$ $f_R*M*V_c+98*C_x*V_c^3$
B	fuel consumption [g/h]	$1/\eta*E+b_0$
b	fuel consumption [g/km]	B/V
p		given in [Klein 1993]
q		given in [Klein 1993]
CN_1		given in [Klein 1993]
CN_2		given in [Klein 1993]
C_{CO}		given in [Klein 1993]
C_{CH}		given in [Klein 1993]
EF_{CO}	emission factor CO[g/vehicle-km]	$C_{CO}*E^p*b$
EF_{VOC}	emission factor VOC[g/vehicle-km]	$C_{CH}*E^q*b$
EF_{NOx}	emission factor NO_x[g/vehicle-km]	$1/V*(CN_1*E+CN_2*E^2)$

The results for CO, VOC, and NO_x are shown in fig. 4.18-4.20. Car concepts marked with a "*" have probably not been produced!
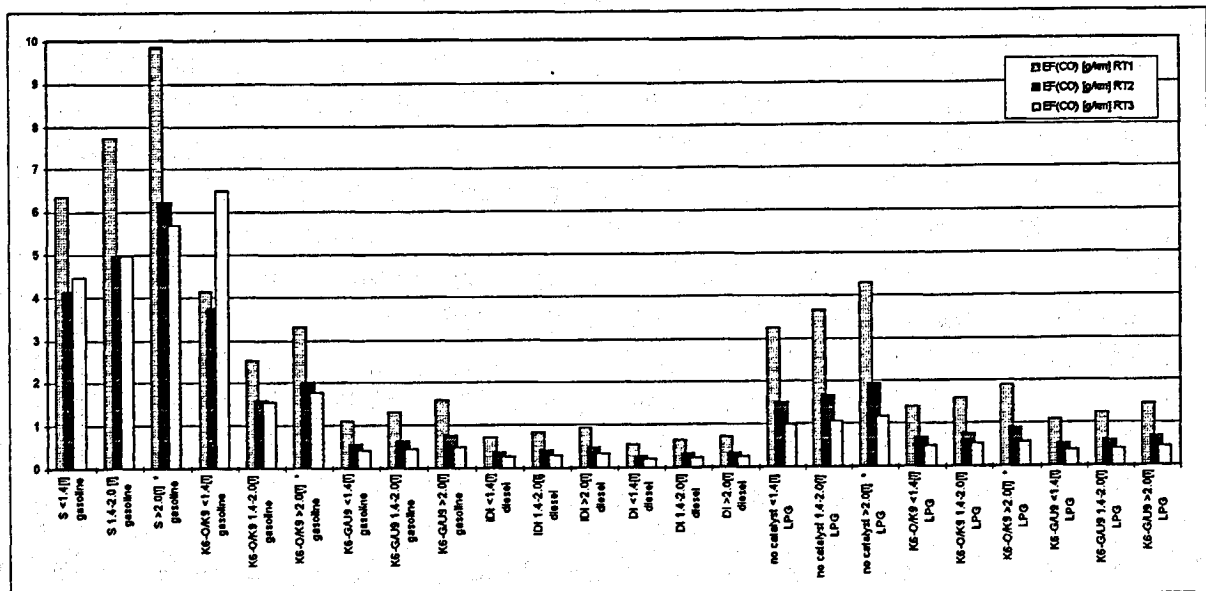

fig. 4.18   CO emissions per vehicle-km from passenger cars with a warm engine, year of production 1990, car concepts marked with a "*" have probably not been produced
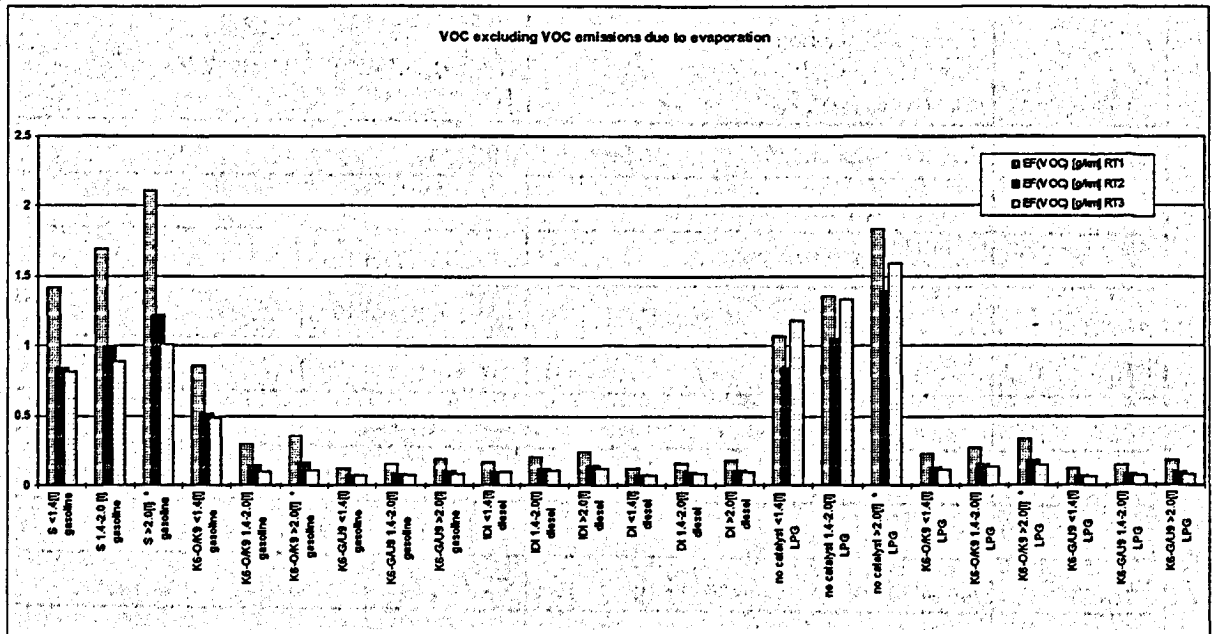
fig. 4.19   VOC emissions per vehicle-km excluding evaporation from passenger cars of year of production 1990 with a warm engine. Vehicle concepts marked with a "*" have probably not been produced.
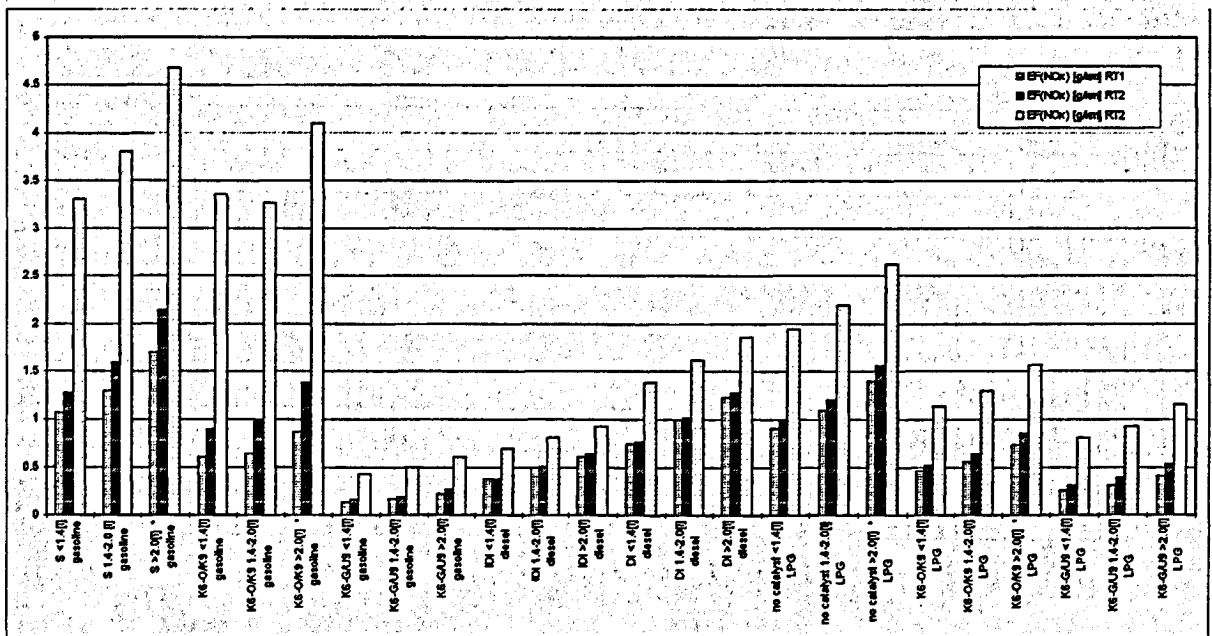
fig. 4.20   NO$_x$ emissions per vehicle-km from passenger cars with warm engines. Vehicle concepts marked with a "*" have probably not been produced.

For the calculation of CO$_2$ and SO$_2$ emissions [Klein 1993] will be used. Since the information in this source in not detailed enough to calculate emissions of lead compounds for each vehicle concept, the emissions of lead compounds will not be calculated. For LPG and Diesel cars the emissions of lead compounds are zero!

The variables and formulas, necessary to calculate CO$_2$ and SO$_2$ emissions per vehicle-km are given in table 4.4.

In [Klein 1993] the following assumptions have been made to calculate emissions of SO_2, CO_2 and lead compounds.

- 95% of the sulphur in the fuel is emitted as SO_2.
- 75% of the lead in the fuel leaves the exhaust as lead compounds, these are expressed in lead.
- All carbon in the fuel is converted to CO_2. Although the combustion is not complete, the correction for this would be negligible with respect to the amount of emitted CO_2.

table 4.4   calculation of CO_2 and SO_2 emissions from passenger cars per vehicle-kilometre

fuel characteristics sources:[Luchtverontreiniging ... 1993] page 13, 23 and[CBS, Centraal bureau voor de statistiek, Divisie handel, Transport en Dienstverlening 1995] page 38			
	gasoline	Diesel oil	LPG
GJ/l	0.033	0.036	0.024
ρ_{fuel} [kg/l]	0.748	0.84	0.53
basic emission factors of CO_2, source: [Klein 1993] page 21.			
	gasoline	Diesel oil	LPG
emission factor [g/l consumed fuel]	2370	2630	1620
basic emission factors SO_2, source: [Klein 1993], page 21			
year	gasoline	Diesel oil	LPG
1980-1989	see [Klein 1993]		
1990	0.3	2.8	0.0
formulas			
$EF_{SO2}[g/km]=EF_{SO2}[g/l]*b[g/km]/(1000\rho_{fuel}[kg/l])$			
$EF_{CO2}[g/km]=EF_{CO2}[g/l]*b[g/km]/(1000\rho_{fuel}[kg/l])$			

The energy consumption per vehicle-km has been calculated from the fuel consumption per vehicle-km [g/km] and the energy content per litre and the density of the fuel [kg/l]. The results of energy consumption, SO_2 and CO_2 per vehicle-km are shown in fig. 4.21-4.23. These have been calculated with the fuel characteristics of 1990.

fig. 4.21   energy consumption per vehicle-km of passenger cars, year of construction 1990, vehicle classes marked with a "*" have probably not been produced.

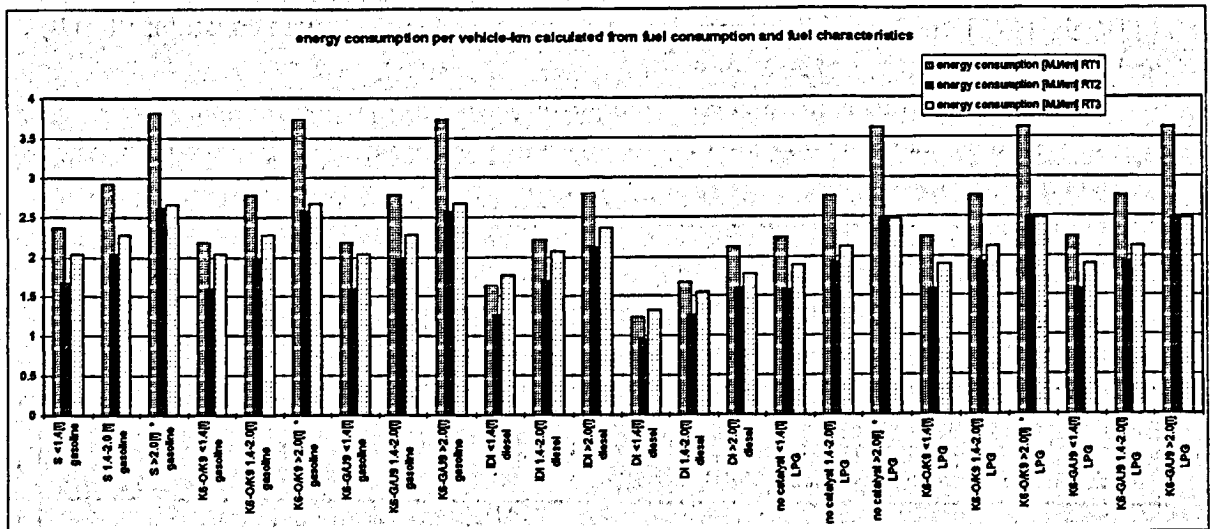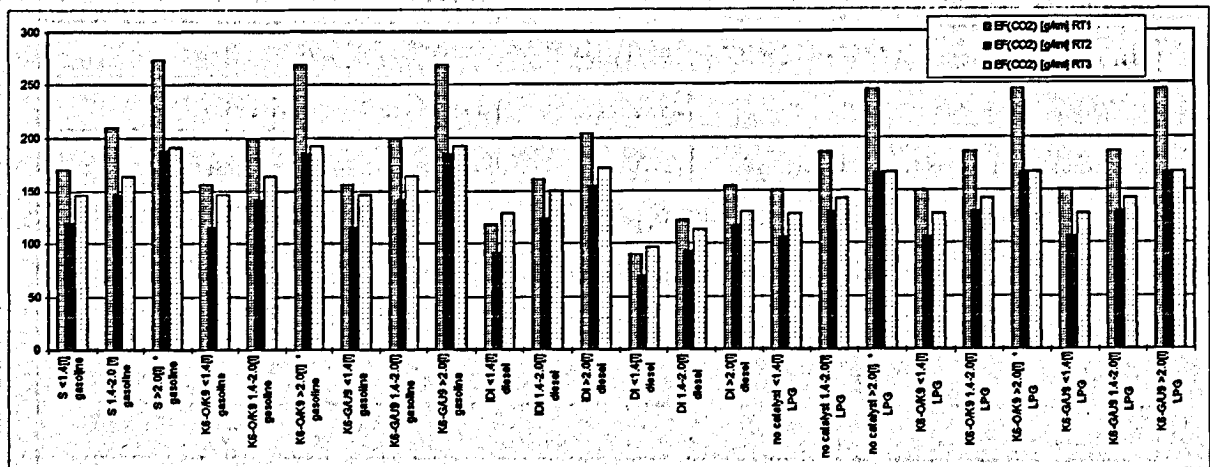fig. 4.22 CO_2 emissions per vehicle-km from passenger cars, year of construction 1990, vehicle classes marked with a "*" have probably not been produced
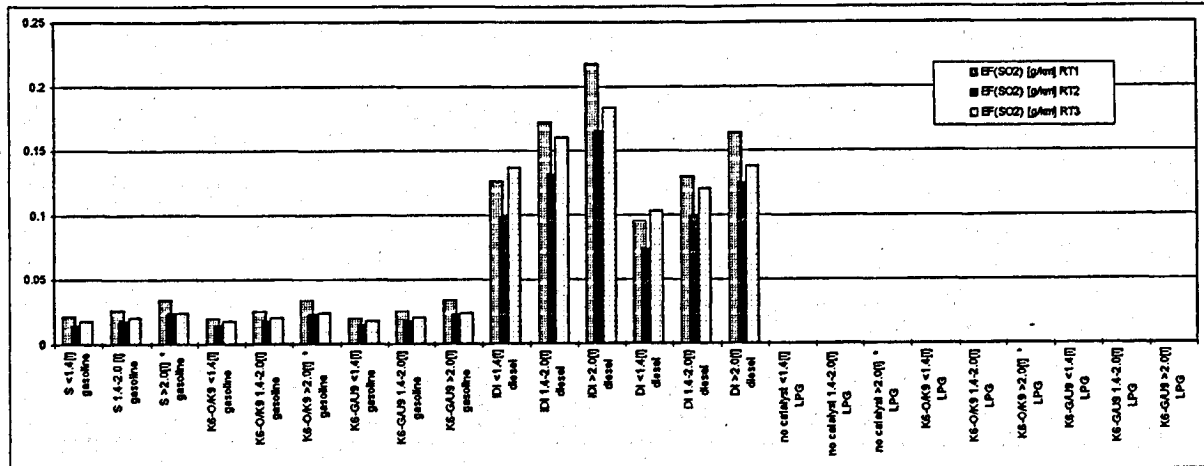
fig. 4.23   SO$_2$ emissions per vehicle-km from passenger cars, year of constuction and fuel composition 1990. Vehicle classes marked with a "*" have probably not been produced.

4.4   Evaporation of HC from the vehicle's fuel system

The evaporation of fuel from a vehicle results in emissions of HC (often called VOC, this is not necessarily the same, see chapter 2). According to page 23 of [SAE 1988] evaporative emissions can be divided into three categories:
-    running losses;
-    diurnal losses;
-    hot soak losses, these occur when a hot idling engine is stopped.

In [Klein 1993] distinction is made between warm soak losses and hot soak losses. Evaporative emissions can effectively be reduced about 80% by means of a carbon canister. In [SAE 1988] running losses have been investigated for different warmup procedures. Large differences were found for the different procedures. Evaporative emissions depend highly on fuel volatility and ambient temperature. In [Klein 1993] , page 22 and 23, a calculation procedure for evaporative emissions is described. For vehicles using LPG or Diesel fuel evaporative emissions are zero. Note that LPG vehicles can run both on LPG and gasoline and can carry both fuels simultaneously.

The method in [Klein 1993] accounts for several different fuel systems, traffic performance and the presence of a carbon canister. For all the gasoline vehicles the running losses are the same:

running losses, vehicles on gasoline: 0.25[g/vehicle-km] during driving.

Other sources of evaporative emissions depend on the number of displacements per day or the fuel system. Assume that these are given for a given car. The average part of these emissions per vehicle with respect to the total evaporative emissions decreases with the driven distance. So, for long distances the running losses can be regarded as a minimum of the total evaporative emissions per vehicle-km. From the previous paragraph the following limits have been found for VOC emissions excluding evaporation per vehicle-km, for warm engines:
-    all gasoline cars:
     -    RT1: 0.085 up to 0.123 [g/vehicle-km];
     -    RT2: 0.073 up to 1.22 [g/vehicle-km];

- RT3: 0.068 up to 1.01 [g/vehicle-km].
- K6-G/U9 cars:
  - RT1: 0.123 up to 0.193 [g/vehicle-km];
  - RT2: 0.073 up to 0.107 [g/vehicle-km];
  - RT3: 0.068 up to 0.085 [g/vehicle-km].

This means that for cars with a closed-loop catalyst, the evaporative VOC emissions can be much higher than the emissions due to combustion, see table 4.5.

table 4.5   **Running losses compared to VOC emissions due to combustion from cars with a warm engine**

vehicle concept	driving conditions	running losses/VOC emissions due to combustion
gasoline, K6-G/U9, 1990 year of construction	RT1	1.30 up to 2.03
	RT2	2.34 up to 3.42
	RT3	2.94 up to 3.68
all gasoline cars, 1990 year of construction	RT1	0.118 up to 2.03
	RT2	0.205 up to 3.42
	RT3	0.25 up to 3.68

This shows that for modern cars the evaporative emissions on long distances can be relatively large compared to VOC emissions due to combustion. However, it is not clear to what extend the running losses are influenced by the presence of a carbon canister.

For one case the evaporative emissions have been calculated more accurately, based on the method in [Klein 1993] page 22 and 23.

example
Vehicle: gasoline car with metal fuel tank, carbon canister, injection engine, 1 displacement per day, varying trip distance (S[km]).
Running losses: 0.25[g/km].
Evaporation from fuel tank: 7.2[g/day].
Hot and warm losses, injection engine: 0.7[g/day] (at1 displacement per day).
For 1 displacement per day:
average evaporative VOC emissions per vehicle-km=(7.2+0.7)/S + 0.25 [g/vehicle-km].
The results are shown in table 4.6.

table 4.6   example of VOC emissions due to evaporation

S [km]	average VOC due to evaporation per vehicle-km [g/vehicle-km]
5	1.83
10	1.04
50	0.408
100	0.329
300	0.276
500	0.266
1000	0.258

4.5   The influence of the vehicle's age on emissions

The emissions per vehicle-km are influenced by the total driven vehicle-kilometres of the vehicle (driven since production). A description of this is given by [Dursbeck 1994]. For conventional passenger cars there is a deterioration of emission levels during inspection intervals. The emission levels can be brought back to the original levels by maintenance. For older vehicles the maintenance condition is often worse. This effect is not being considered here.

For vehicles with catalytic converters the situation differs from the situation for conventional passenger cars. Due to thermal ageing and poisoning of the catalysts the conversion efficiency of these catalysts decreases with increasing total vehicle-km. This means that for passenger cars that use a catalyst, the emission levels deteriorate with age unless the catalyst is replaced.

Distinction must be made between open-loop catalysts and closed-loop catalysts. In [Dursbeck 1994] test results are given. These tests have been done for several driving cycles (definitions on page 6.3 and 6.4 of [Dursbeck 1994]):
- US-Test-75 phase1, phase 2, phase 3 and the complete cycle;
- a "highway" cycle;
- an "Autobahn" cycle, the major difference between this cycle and the highway cycle is that the speeds are much higher for the Autobahn cycle.

gasoline passenger cars with closed-loop catalysts
The results of the US-Test-75 show a very weak correlation of HC, CO and NO$_x$ emissions with the total vehicle-km. The correlation coefficient is between 0.27 and 0.29. For speeds greater than 86[km/h] the results of other cycles show almost no relation between CO and HC emissions and the total vehicle-km. For NO$_x$ there is almost no influence of the driving cycles on the correlation between NO$_x$ emissions per vehicle-km and the total vehicle-km. [Dursbeck 1994] uses the following.
- For speeds greater than 100[km/h] there is no correlation for HC and CO.
- For speeds between 80 and 100[km/h] there is a weak correlation for HC and CO.

- For speeds less than 80[km/h] use the following correlations for HC and CO.

$$\frac{emissions}{average\ emissions\ of\ a\ sample} = average\ emissions + b \cdot total\ vehicle\ -km \qquad (8)$$

For CO, $b=6.7 \cdot 10^{-6}$[l/km], for HC, $b=6.4 \cdot 10^{-6}$[l/km].
- For all speeds, NO_x emissions can be correlated with the same equation (8) with: $b=7.3 \cdot 10^{-6}$[1.km].

gasoline passenger cars with open-loop catalysts

For gasoline passenger cars with open-loop catalysts the spread off the data is much bigger than for cars with closed loop catalysts. For vehicle concepts without air/fuel control (three way catalysts need this air/fuel mixture or λ control) both rich and lean mixtures occur. Stoichiometric mixtures occur very little. This mean that either CO and HC are converted to CO_2 and H_2O with high efficiency or NO_x is reduced to nitrogen and oxygen with high efficiency. No real correlations have been found for vehicles with open-loop catalysts.

Note that the German situation differs from the Dutch (higher speeds in Germany).

For the Dutch situation the effect of vehicle's age has been investigated in [Binkhorst 1994] for U9 and K6-G passenger cars. The deterioration of emission levels at total vehecle-km equal to 80000[km] with respect to the situation at 0[vehicle-km] has been determined using the FTP cycle. The results are given as "deterioration factors", these factors are:
- CO: 1.61;
- HC: 1.32;
- NO_x: 1.36.
For the exact definition of these factors, EEC directive 88/76/EEC has to be consulted, this has been planned to happen later.

For Diesel passenger cars the emissions at high total vehicle-km (150000-195000km) have been compared with the levels of the type certification. Emissions can be both higher and lower. No dramatic deterioration between 100000 and 150000[km] was found.

4.6 Emissions per traveller-kilometre

Emissions per traveller-km will be calculated for long journeys. For long journeys the average emissions per traveller-km can be assumed equal to the emissions from cars with a warm engine since the effects of a cold start are negligibly small on journeys of several hundreds of kilometres. The evaporative HC emissions have been discussed earlier. On long journeys these can be considerable because the running losses become important. The diurnal losses and hot soak losses, both per vehicle-km decrease rapidly with increasing journey length.

With the information on the average number of travellers on a passenger car in 4.1 and the emissions per vehicle-km for warm engines, the emissions per traveller-km can be calculated for the several driving conditions. Note that for long distances the number of travellers per

vehicle is notably higher than at short distances. The average of the Netherlands is about 1.7 travellers per vehicle, this number change with time and is decreasing. For foreign vehicles in the Netherlands or Dutch vehicles abroad, CBS have used a number of 2.5 travellers per vehicle since 1980 (at least, see fig. 4.1).

> **These calculations still have to be done**

5. Emissions from buses

In this chapter, emissions from buses per traveller-kilometre will be calculated using CBS data. Many CBS publications provide information on emissions from buses and the traffic performance of busses, e.g. [CBS 1996], [Luchtverontreiniging ... 1992], [Klein 1993], [Zakboek verkeer en vervoer 1995]. Great care must be taken when using these publications since the definition of "bus" is not always given. It takes some effort to find out which definition has been used. When the "wrong" data are used, buses appear to emit lead compounds, From 1984 to 1985 these decrease rapidly to almost zero! The implications of these can be twofold.

1. Also small, gasoline fuelled minibuses are included in "buses", a decrease of gasoline lead content might have caused the decrease of 1984-1985. The average lead content of gasoline started to decrease rapidly between 1985 and 1986 [Klein 1993] page 21!
2. The changes of legislation concerning minibuses/taxis might have changed the described changes, see chapter 4.

Note that sometimes trams and metros are included in the traffic performance of "buses". The described problems related to the definition of "buses" applies mainly to the traffic performance and to a lesser extend to emissions per vehicle-km. However it is not completely clear wether minibuses have been included in "buses" or not.
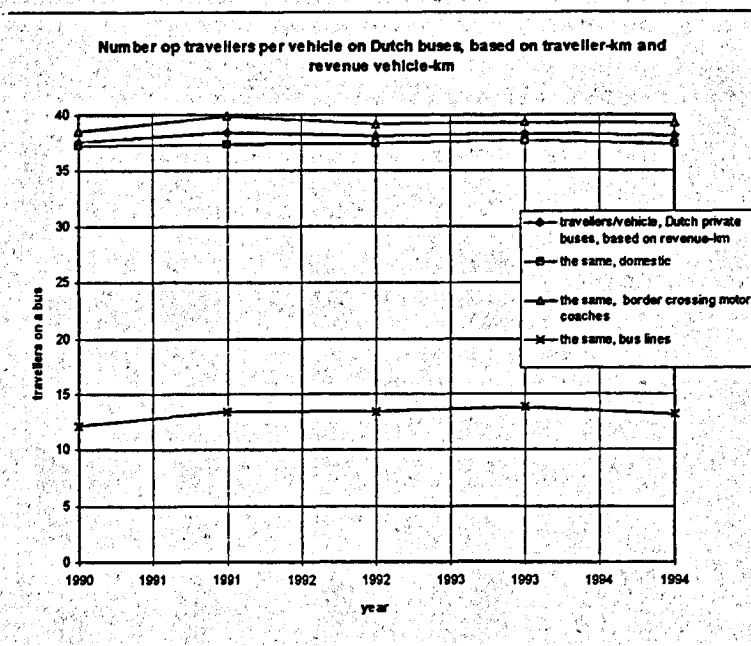
The following choice has been made. The emissions per traveller-km have been calculated from the emissions per vehicle-km from buses and the number of travellers on a bus is calculated from the traveller-kilometres and revenue vehicle-kilometres in [Zakboek verkeer en vervoer 1995]. The emissions per vehicle-km are specified per year of construction and for three driving conditions in [Klein 1993]. The effect of varying load factor on the emissions per vehicle-km is ignored.

fig. 5.1

The number of travellers on a bus is shown in fig. 5.1 for several types of bus transport. These have been calculated as mentioned above. The number of travellers per vehicle varies only very little, therefore the following constant values can be assumed.

- Dutch private busses: 38 travellers per vehicle.
- Dutch private buses, domestic: 37 travellers per vehicle.
- Dutch private buses, border crossing motor coaches: 39 travellers per vehicle.
- Dutch bus lines (including trams and metros???): 13 travellers per vehicle.

These values are the averages of 1990, 1991, 1992, 1993 and 1994, rounded of to total numbers.

Since this report is mainly concerned with a comparison of aircraft with other transport modes, it is realistic to calculate the emissions per traveller-km for border crossing motor coaches. The Number of travellers per vehicle is in this case equal to 39. The emissions per traveller-km are shown in fig. 5.2 and 5.3.
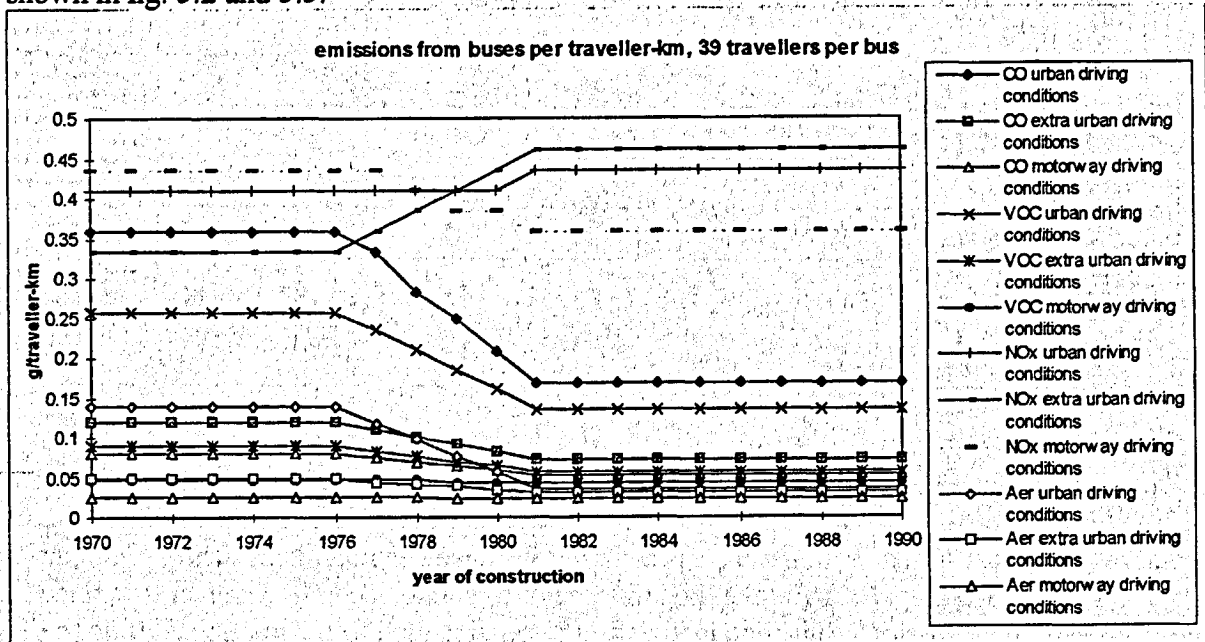

fig. 5.2

Fig. 5.2 shows almost linear changes during the late 1970s and early 1980s. Outside this period the emissions per vehicle-km appear to be constant. This might be caused by assumptions made at the calculation of these emissions.
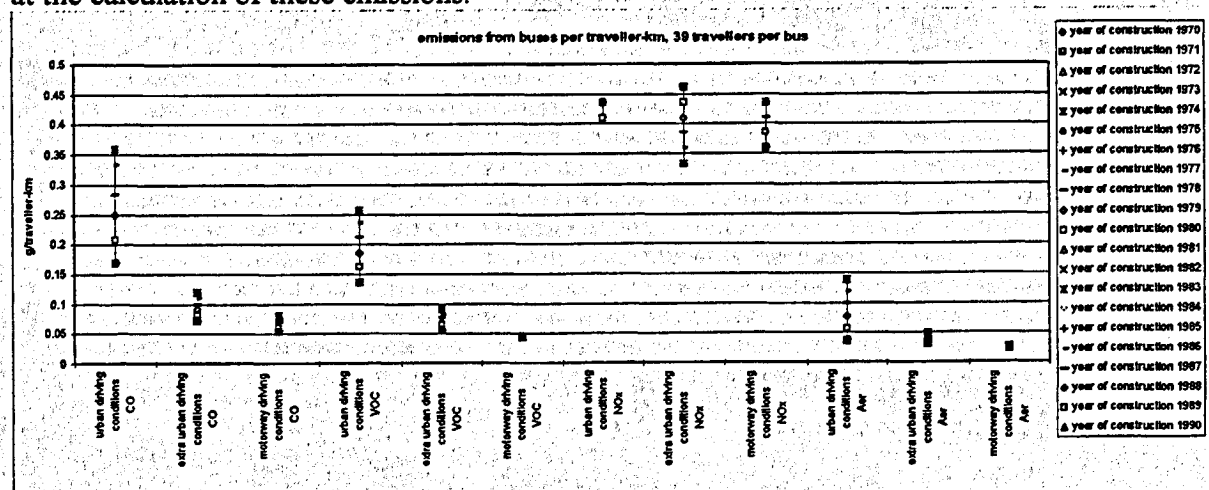

fig. 5.3

Fig. 5.3 can be used to observe differences between the driving conditions. To illustrate the changes of the emission levels for the various years of construction, fig. 5.4 has been drawn. In

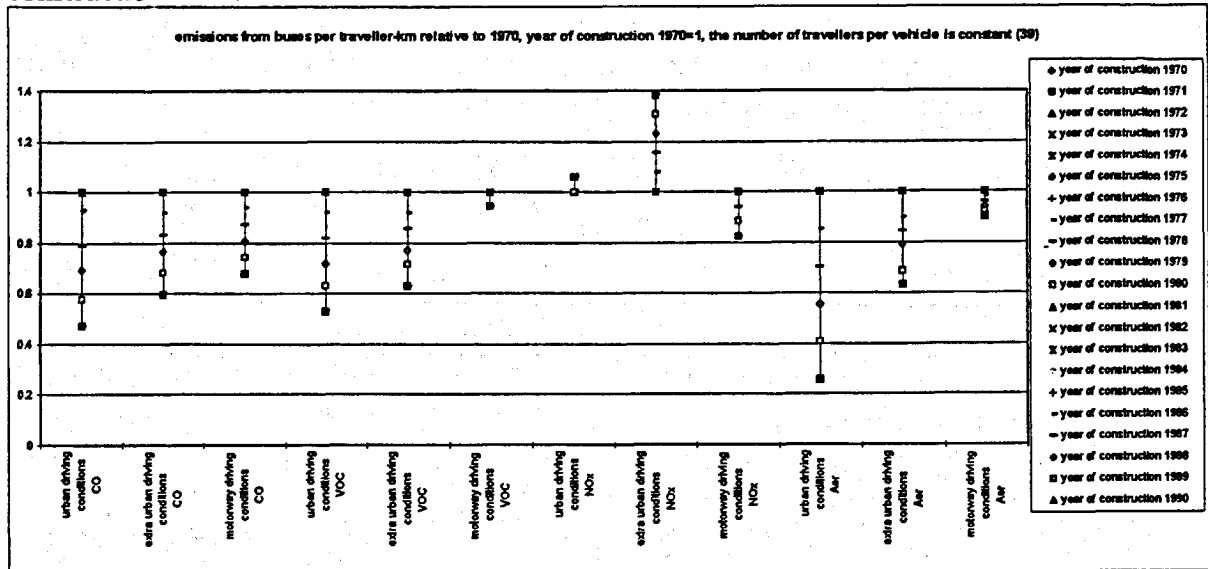this figure the emissions per traveller-km are given relative to the values of the year of construction 1970.

fig. 5.4

The figures 5.2, 5.3 and 5.4 show that all emissions per traveller-km have decreased except NO$_x$ for extra urban driving conditions and motorway driving conditions. Furthermore these figures show that for some emissions large reductions have been obtained since 1970. This illustrates that it is important to take the influence of time into account. The fact that since the early 1980's the emission levels remained constant, possibly due to assumptions during the calculations, might be an indication that these data have become outdated. More recent data have not been found yet.

6. Pollutant emissions caused by passenger trains

Several publications have been found in which information is given on pollutant emissions caused by passenger trains. All these sources have in common that little details and background information are given and that almost no attention is payed to historical developments and on differing load factors. The situation becomes even worse when the whole "energy chain" is considered from the power generation to the trains. When trains are compared with aircraft, long distance transport must be considered. A large part of the information that has been found is Dutch. Since Holland is a small country, long range rail transport on distances comparable with typical air transport distances, almost always crosses the borders. A large portion of rail transport is performed with electric trains depending on external power generation. The electric power generation differs very much between countries, This makes a reliable estimate of pollutant emissions caused by rail transport even more difficult.

To illustrate the problem, an example of the amount of supplied information in two sources is given. In a very comprehensive study on environmental impacts of the high-speed rail connection between Amsterdam and Paris, only a few pages deal with pollutant emissions ([Tweede Kamer , 22 026 nr.4, 1991] and [Tweede Kamer, 22 026 nrs. 2-3, 1991]).

Unless more detailed information is found, the data in the mentioned literature will be used. The majority of these sources have already been used in chapter 2, to determine the upper and lower levels of emissions and energy consumption per passenger-kilometre as found in several studies. The results of these studies will not be discussed in detail in this report. The results are directly available at this moment.

The literature that has been found so far is listed below.

- [Arends 1994].
- [Arends 1995].
- [Kroon].
- [Government policy.... 1995].
- [Rijkeboer 1996].
- [Sjöström 1991].
- [The vital earth 1992].
- [Boletis].
- [Tensen 1996].
- [Eerens 1992].
- [Van Doesburg 1993].
- [Whitelegg 1993].
- [Carpenter 1994].
- [Tweede Kamer, 22 026 nr.4, 1991].
- [Tweede Kamer, 22 026 nrs. 2-3, 1991].
- [CBS, Centraal Bureau voor de Statistiek, Divisie Landbouw,... 1995], page 37 and 39.
- [Zakboek Verkeer en vervoer 1995].
- [Algemene milieustatistiek 1992].
- [CBS 1996].
- [CBS, Centraal Bureau voor de Statistiek, Divisie Handel,...1995].
- [CBS, 1994].
- [Filipović 1995], in this book theoretical backgrounds are given on electric trains.

The CBS publications mentioned above contain information that can be used to calculate emissions from trains. However, these data are not detailed enough to split up the whole energy chain. The publications provide only very little information that enables attribution of emissions to passengers or freight, and to diesel or electric powered trains.

7. Pollutant emissions from aircraft: analysis of the results of existing studies

In this chapter some results are given of an analysis of pollutant emissions from aircraft in existing literature. Some calculations have been done with the published data. This chapter has not been completed yet! The following data will be analysed:
- data of the Lufthansa fleet in 1988 and 1989 described by Reichow in [Schumann 1990];
- data described by Nüßer and Schmitt (DLR) in [Schumann 1990], also see chapter3;
- the results the first version (April 1994) of global inventory of aircraft NO_x emissions of the ECAC/ANCAT & EC Working Group as published in [Schumann 1995];
- results of the NASA Atmospheric Effects of Stratospheric Aircraft program (AESA), results of this program have been published in many reports among which: [Stolarski 1993], [Stolarski 1995] and [Douglass 1992]; publications that are closely related to this programme are: [Baughcum 1996] and [Metwally 1996];
- the ICAO Engine Exhaust Emissions Data bank, [ICAO 1995].

7.1   Emissions from the Lufthansa fleet

Aircraft mostly carry payload consisting of:
- passengers;
- freight;
- mail.

These elements can be on board simultaneously. The amount of payload carried, can be limited by weight and by volume. When Specific emissions are calculated as [g/passenger-km] or [g/tonne-km][1], the problem arises of how emissions must be assigned to the several elements of the payload. Reichow in [Schumann 1990] used the following method.

A factor P=2 assigns passenger tonne-km double the fuel consumption and emissions over freight (and mail) tonne-km in a given aeroplane with a given load and consumption. This factor takes into account the additional weight involved in passenger transportation. In the case of different versions of the Boeing 747-200 (passenger, combi and freight versions) The factor P=2 provides practically equivalent specific consumption data for all versions.

This method is not correct since the only factor that determines fuel consumption and emissions for given aircraft, mission and flight conditions is the payload weight. If the operational empty weight of a passenger version is higher than the operational empty weight of a freight version (both per tonne payload), this is just a disadvantage of the specific aircraft. The only correct method to attribute emissions to the several payload classes, is on equal weight basis, i.e. with P=1. The following variables are defined:
- TKT: tonne-km transported;
- TKO: tonne-km offered;
- consumed fuel mass [tonnes] or [g]: m_f;
- NLF: load factor;

---

[1]These units are often abbreviated as [g/Pkm] and [g/tkm].

- SFC: specific consumption, fuel consumption per tonne-km: [g/tkm].

From these, the following formulas have been derived.

$$SFC = \frac{m_f}{TKT} \ ; \quad SFC_{c,m} = \frac{SFC_p}{P} \ ; \quad SFC_p = \frac{m_f}{TKT_p + TKT_{c,m}/P} \tag{9}$$

Instead of m_f, the mass of the total emitted emissions can be used to calculate emissions per passenger-km. The following data are given by Reichow in [Schumann 1990].

- The performance and fuel consumption of the Lufthansa fleet in 1989. For several aircraft types the following data are given: aircraft type, number of engines, engine type, T.O. thrust, MTOW[t], maximum payload[t], number of seats, fleet size, number of landings, TKO, NLF, TKT, TKT_p, $TKT_{c,m}$, PKT, leg length (great circle), m_f, SFC, SFC[g/tkm], $SFC_{c,m}$ [g/tkm] calculated with P=2, SFC_p[g/tkm] calculated with P=2, SFC_p[l/(100Pkm)] calculated with P=2 and a specific fuel mass of 0.8[kg/l]. Two new types of aircraft (747-400 and A-320) have been used untypically on relatively short ranges.
- The performance of the Lufthansa fleet in 1988, not specified per aircraft type. The following data are given: TKT, TKT_p, $TKT_{c,m}$, PKT, absolute emissions (total, cargo, mail, passengers) calculated with P=2 of CO_2, H_2O, C, C_xH_y, CO, NO_x and SO_2, and the same species per tkm cargo, mail and passengers and per PKM, also calculated with P=2.

The calculation of specific emissions [g/Pkm] has been repeated for P=1, the results are shown in table 7.1.

table 7.1   Emissions per passenger-km from the Lufthansa fleet in 1988

species	specific emissions [g/Pkm]		(emissions calculated with P=1)/(emissions calculated with P=2)
	calculated with P=2	calculated with P=1	
CO_2	162	119	0.73
H_2O	63	47	0.75
C	0.00	$5 \cdot 10^{-4}$	-
C_xH_y	0.08	0.06	0.71
CO	0.19	0.14	0.74
NO_x	0.78	0.57	0.73
SO_2	0.05	0.04	0.8

In table 7.1 is shown that the emissions for P=1 are considerably lower than for P=2.

Reichow has also given the "leg length" expresses as great circle distance, of each aircraft type. Probably this is the average trip length including intermediate landings. When TKO is divided by the maximum payload and the number of landings, the average distance (great circle) between takeoff and landing is obtained. This distance differs from the specified leg length, see table 7.2.

table 7.2   Distances, Lufthansa fleet 1989, compiled using [Schumann 1990]

aircraft type	leg length (great circle) [km]	TKO/(max. payload · no. of landings) [km]
B727	554	552
B737-200	533	491
B737-300	726	664
B747-200 passengers	5721	4725
B747-200 combi	4951	4106
B747-200 freighter	5324	4013
B747-400	(1609)	(1309)
A300-600	1708	1436
A310	717	621
A320	(241)	(209)
DC10-30	4159	3601

Note: B747-400 and A320 used on untypically short and medium haul routes due to introduction

In [Schumann 1990] the fuel consumption per passenger-km and tonne-km has been calculated for the aircraft in table 7.2 using the assumption P=2. These calculations have been repeated in table 7.3 with the assumption P=1. From TKT_p and TKP the average mass of a passenger can be calculated, see table 7.3, the average of the Lufthansa fleet in 1989 is 96.45[kg].

table 7.3   Fuel consumption and average passenger mass of Lufthansa fleet in 1989, compiled using [Schumann 1990].

aircraft type	average mass of 1 passenger=TKT_p/PKT [kg]	fuel consumption per passenger tonne-km [g/tkm]	
		P=1	P=2
B727	92.8	886	940
B737-200	92.1	933	970
B737-300	92.9	612	689
B747-200 passengers	97.97	401	468
B747-200 combi	97.97	345	484
B747-200 freighter	-	-	-
B747-400	97.6	(405)	(488)
A300-600	97.7	398	475
A310	94.8	512	600
A320	96.8	(667)	(667)
DC10-30	97.96	415	511

Note: B747-400 and A320 used on untypically short and medium haul routes due to introduction

The fuel consumption per passenger tonne-km, calculated with P=1, has been plotted against the leg length in fig. 7.1.

Note that the aircraft with the highest fuel consumption per passenger tonne-km are the Boeing 727-200 and 737-200. The engines of these aircraft are JT8D-15 engines. According to Reichow in [Schumann 1990], the 727-200 and the 737-200 were the only two aircraft types in the Lufthansa fleet of 1988 and 1989 that did not meet the noise requirements of ICAO Annex 16 (vol. 1) Chapter 3. The 727-200 was planned to leave the Lufthansa fleet by 1993 and the 737-200 in 1993. This shows that the phasing-out of aircraft because of noise also affects fuel consumption. Whether emission levels will improve depends on many factors like the temperatures and pressures in the combustion chamber. Some emissions like SO_2 and CO_2 depend mainly on fuel consumption. So, when fuel consumption improves, the emission levels of these species will improve too.

fig. 7.1

Fig. 7.1 shows that aircraft used on longer leg lengths do not necessarily have a lower fuel consumption per passenger tonne-km than aircraft used on shorter leg lengths. However, the data show that most aircraft, used on long leg lengths have a lower fuel consumption per passenger tonne-km than the aircraft used on short leg lengths.

Fig. 7.1 already shows that leg length and fuel consumption are related. This will be further analysed. Leg length is not the only factor that affects fuel consumption. Other factors are the takeoff mass and the payload mass. From this, the following formula can be derived.

$$\frac{m_f}{m_p R} = \frac{m_f/m_{to}}{m_p/m_{to}\,R} \tag{10}$$

This formula will be used to correlate Lufthansa data in [Schumann 1990] with the leg length. The following data are used.

- R: range[km], use the leg length of the specific aircraft, since this is more realistic than the harmonic range. By the way, the harmonic range is not given in [Schumann 1990].
- m_{to}: Takeoff mass, use the maximum takeoff mass specified in [Schumann 1990].
- m_f: the total consumed during one leg. This can be calculated from the number of landings and the ratio of the distance between takeoff and landing to the leg length (table 7.2).
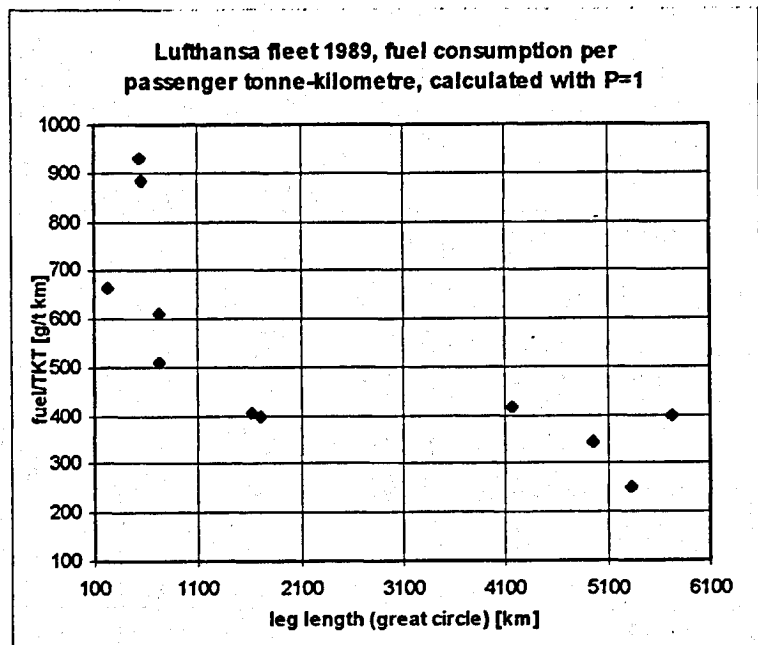
$$m_f \cdot no.\,of\,landings \cdot \frac{TKO\,/(maximum\quad payload\,\cdot no.\,of\,landings\;)}{leg\;length} \tag{11}$$

- m_p: average payload mass, calculated from the load factor and the maximum payload: average payload mass=maximum payload mass · NLF[%]/100.

The results are shown in fig. 7.2.

In this figure the values of m_f/m_{to} and m_p/m_{to} are plotted against the leg length and linear regressions are shown. The fuel fraction increases with leg length and the payload fraction increases slightly with leg length.
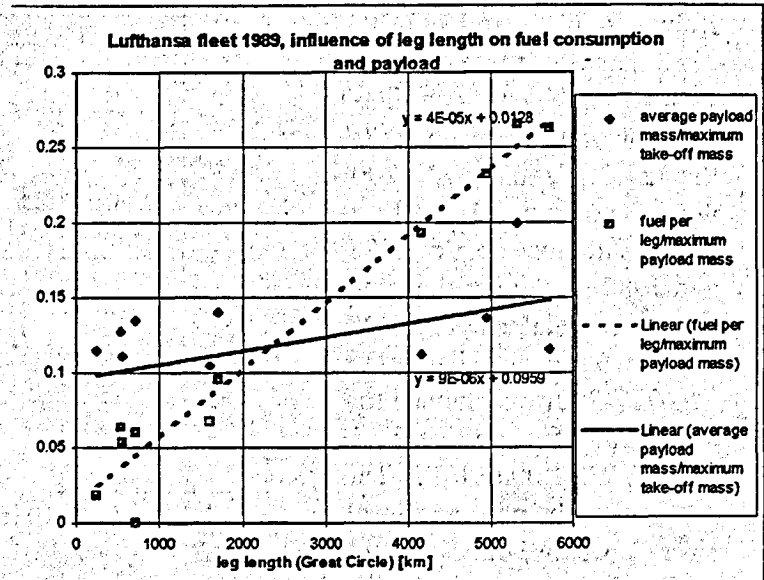

fig. 6.2

7.2 Analysis of the results the first version (April 1994) of global inventory of aircraft NO$_x$ emissions of the ECAC/ANCAT & EC Working Group as published in [Schumann 1995]

A joint working group of the European Civil Aviation Conference (ECAC) group of experts on the Abatement of Nuisance Caused by Air Transport and the European Community has been doing three dimensional global inventories of NO$_x$ emissions from aircraft. Several versions of this inventory exist:
- ANCAT 1A, the first version of April 1994;
- ANCAT 1B;
- ANCAT 2 to be completed in 1996.

Descriptions of ANCAT inventories can be found in the following literature.
1. [Schumann 1995], the final report of the AERONOX project to the Commission of the European Communities. In part III of this book (page 129-1991) the first version of ANCAT is described.
2. [Euroavia 1995], in this source the proceedings of lectures on a congress on aviation and nature are published. In lecture 5 A Schmitt of DLR presents some information on the ANCAT inventories:
   - an example of NO$_x$ emissions calculated for an Airbus A320 on a flight of 2000[km];
   - a lot of photocopies from [Schumann 1995];
   - some remarks on the second ANCAT version, including other emissions than NO$_x$;

- a revised formula for the calculation of NO_x.
3. Deidewig in [Bürgener 1992], a description of emission calculation methods used by DLR, some results for a B747-400 and an A310-300, some data of Lufthansa aircraft, used in the BMFT programme 'Schadstoffe in der Luftfahrt'.
4. [Wright, 1995], the accuracy of the AESA and ANCAT inventories is discussed.

[Schumann 1995] will be used for further analysis.

Most of the calculations of the Ancat inventory have been done by DLR. The two most important elements of the DLR method for the calculation of NO_x emissions are:
- correlation of emissions and engine performance;
- correlation of flight conditions of a given aircraft-engine combination and engine performance.

The engine/emission correlation is based on a semi-empirical method ([schumann 1995] page 120, formula A1) which calculates emissions from measured sea level values (static tests) and combustor entry conditions calculated with an engine model. For the calculation of the engine performance, thrust and drag must be matched.

In the model to calculate the engine performance the most important assumptions are:
- 2-shaft engine;
- the performance of engine/airframe is determined from fuel flow, pressure, temperature and thrust settings derived from publicly available data such as the ICAO data bank ([ICAO 1995]) and editions of Jane's all the world's aircraft;
- Takeoff mass dependant on mission, full payload, fuel for the sector, no reserves;
- Takeoff power dependant only upon MTOM (limited by maximum turbine entry temperature throughout climb 1);
- reduced power for climb 2 according to time period within segment to get to cruise;
- design maximum cruise speed in cruise with no step cruise;
- absolute humidity value held at constant sea level reference (see for example [ICAO 1993] and [ICAO 1995]).

The calculation depends on many assumptions because many necessary data have not always been published.

From the engine performance and the emission correlation methods the NO_x emissions can be calculated. As reference condition, the 100% sea level static thrust data have been used to correlate the emission index of NO_x in the ICAO data (emission index: grammes of emitted species per kg fuel) with the engine data in the performance model.

The cruise fuel was calculated by mean of the <u>Breguet formula</u> and <u>constant cruising speed and altitude</u> were assumed! Note that the Breguet formula has been derived for a <u>continuous cruise climb</u> flight at constant range factor ($V/C_T \, C_L/C_D$ for jet or turbofan engines), see for example [Ruijgrok 1990] page 357.

The assumption of constant humidity can lead to an underestimate by (perhaps) as much as 12% at higher altitudes!

Not that the flight phases included in the calculations include the whole flight profile except taxiing on the ground and landing. For each aircraft/engine combination the model was run over different sector lengths (long and short haul):
- short haul [km]: 200, 400, 500, 1000, 2000;

- long haul [km]: 200, 400, 1000, 2000, 4000, 8000.

For 200 and 400[km], cruise altitudes were assumed 3000 and 7000[m]. All other cruise altitudes were obtained from operators.

For all other sector lengths the NO_x emissions and fuel consumption were interpolated. The programme does much more than what has been described here (it calculates three dimensional global distributions of NO_x emissions and fuel consumption) This part is of less importance here.

Each flight profile has been divided into 32 steps, the distances are great circle distances (the shortest distance between two points on a sphere). All calculations have been done in standard atmosphere except humidity, which is zero in ISA.

An example is given of a Boeing 747-400 on a flight from Frankfurt to New York. This example will be used to illustrate the effect of sector length on NO_x emissions and fuel consumption.

Aircraft: Boeing 747-400.
Engines: CF6-80C2B1F.
Number of engines: 4.
Start: time= 40[s], =2[km].
Climb: 20[min], =200-300[km].
Descent: as climb.
Cruise speed: M=0.8
The emissions and fuel consumption are given in table 7.4.

table 7.4   Fuel consumption and NO_x emissions from a Boeing 747-400 with CF6-80C2B1F engines, full payload, no reserves, source: [Schumann 1995]

sector length [km]	total fuel consumption [kg]	total NO_x emissions [kg]
200	3864.04	78.87
400	6289.62	139.2
1000	12477.68	186.13
2000	22100.05	319.58
4000	41041.74	587.62
8000	81836.00	1119.13

In [Schumann 1995] the payload has not been given, therefore, the 1994-1995 edition of Jane's all the world's airlines [Lambert 1994] will be used.
Boeing 747-400, engines: CF6-80-C2B1F:
- range with 420 passengers at highest optional TOW: 13390[km];
- OWE= 181030[kg] or 181529[kg] at highest optional TOW;
- MTOW=362875[kg] or 385555[kg] or 394625[kg];
- MZFW=242670[kg].

The total NO_x emissions are shown in fig. 7.3 as a function of the sector length.

Fig. 7.3 shows that with good approximation a straight line can be drawn through the total NO$_x$ and the sector length. At short sector lengths, this results in the largest errors. The equation according to linear regression is shown on the graph.

In fig. 7.4 the relation between total fuel consumption and sector length is shown. This too, can be approximated by a straight line according to linear regression. The equation is shown on the graph.

Fig. 7.4 shows that contrary to NO$_x$ the relation between fuel consumption and sector length at short sector lengths can be approximated with the same straight line as for long sector lengths.

The same data in [Schumann 1995] can be used to calculate the total NO$_x$ emissions and the total fuel consumption per kilometre as a function of the sector length. The results are shown in fig. 7.5 and 7.6.
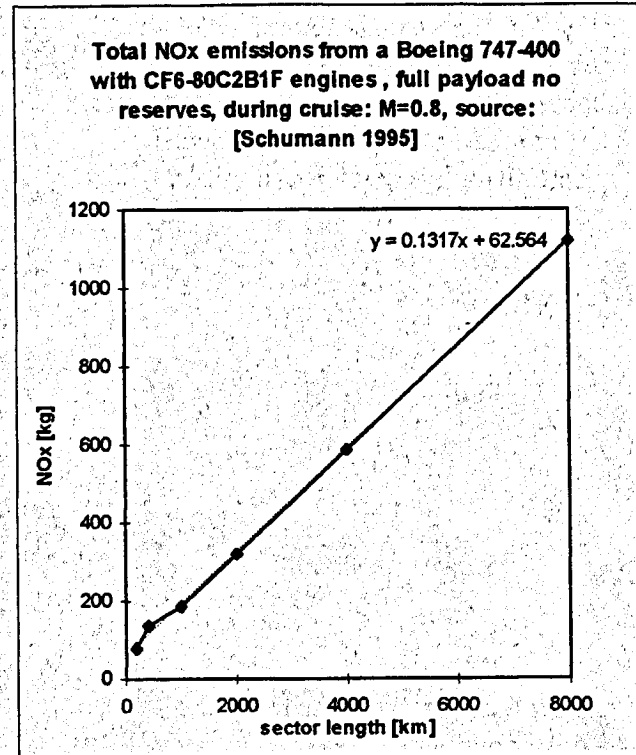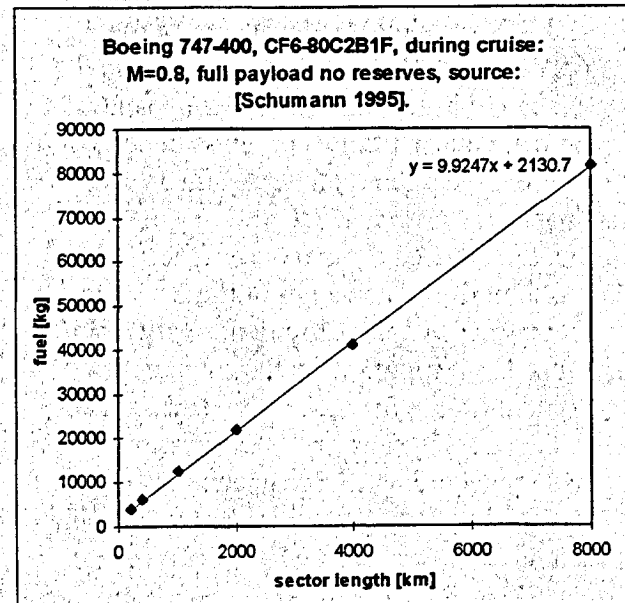

fig.7.3

fig. 7.4

Fig. 7.5 shows that the total NO_x emissions increase rapidly at short sector lengths when the sector length decreases. At long sector lengths the influence of sector length is much less dramatic.
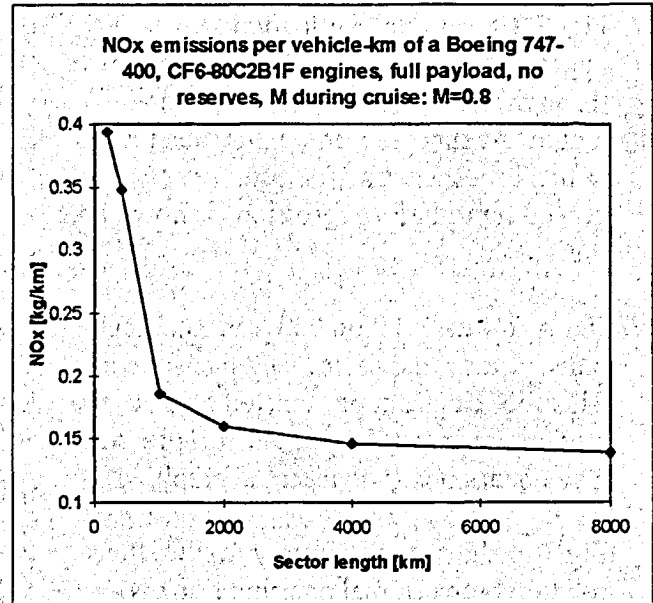

fig. 7.5

Fig. 7.6 shows the same for fuel consumption.

Some emissions like CO_2, water vapour and SO_2 are almost independent of the operating conditions of the aircraft and the engines. These emissions depend mainly on fuel consumption. The emission indices of these emissions can be assumed constant. This implies that these emissions can directly be calculated from fuel consumption. The values of the emission indices of H_2O and CO_2 do not vary much. Since large variations in the sulphur content of the fuel occur, the emission indices of SO_x can vary. The emission indices according to Schumann in [AGARD-CP-536, 1993] are given in table 7.5.
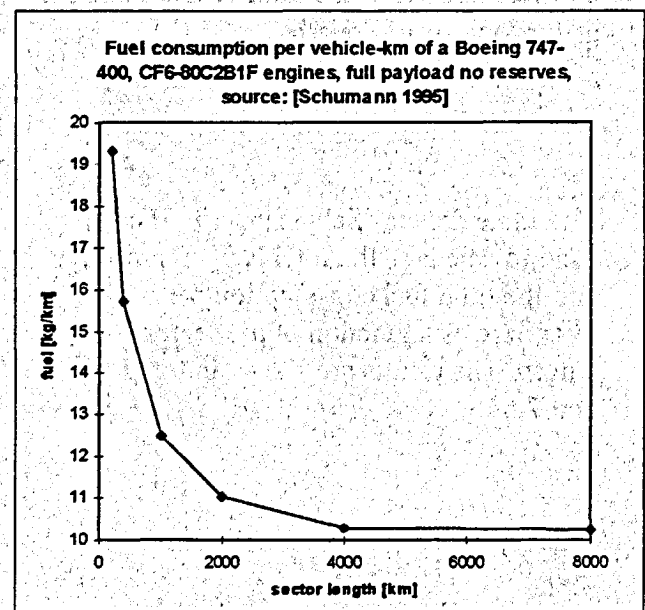
fig. 7.6

table 5 Emission indices of CO_2, H_2O and SO_2 according to Schumann in [AGARD-CP-536, 1993]

species	EI [g/kg fuel]
CO_2	3150
H_2O	1260
SO_2	1, this value can vary between 0.02 and 6

Note that some variations can occur in the EIs of CO_2 and H_2O at different operating conditions of the engine. These variations are relatively small, see for example Formica in [Euroavia 1995] (one value in this source is incorrect).

The maximum payload of the aircraft is equal to MZFW-OWE, for the standard aircraft this is 61640[kg] (not the high MTOW option). This enables the calculation of fuel consumption and emissions per tonne-km. The results are shown in fig 7.7 and 7.8.

fig. 7.7

50

The emissions per passenger-km
will be calculated with P=1, these
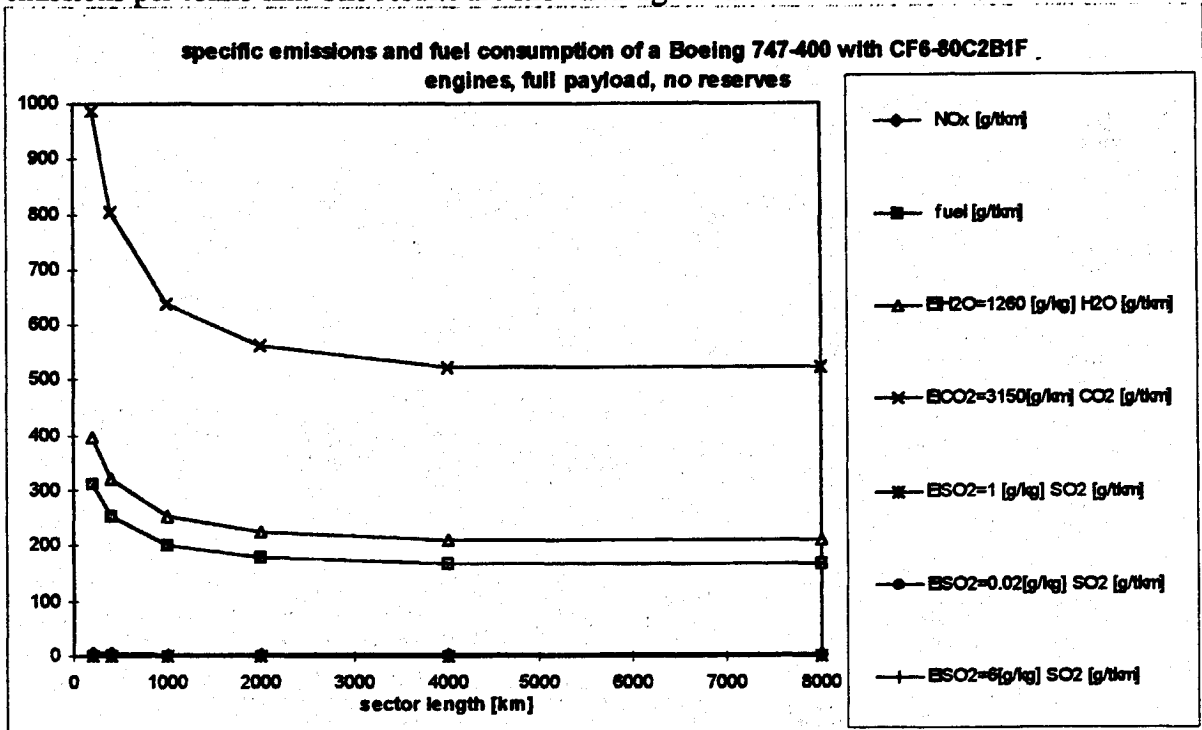can be calculated by dividing the
emissions per tkm by the amount of
passengers per tonne.

Assume that the average mass of a
passenger including baggage is
96.5[kg] which is the average of
the Lufthansa fleet in 1989. The
emissions per passenger-km are
shown in fig. 7.9.
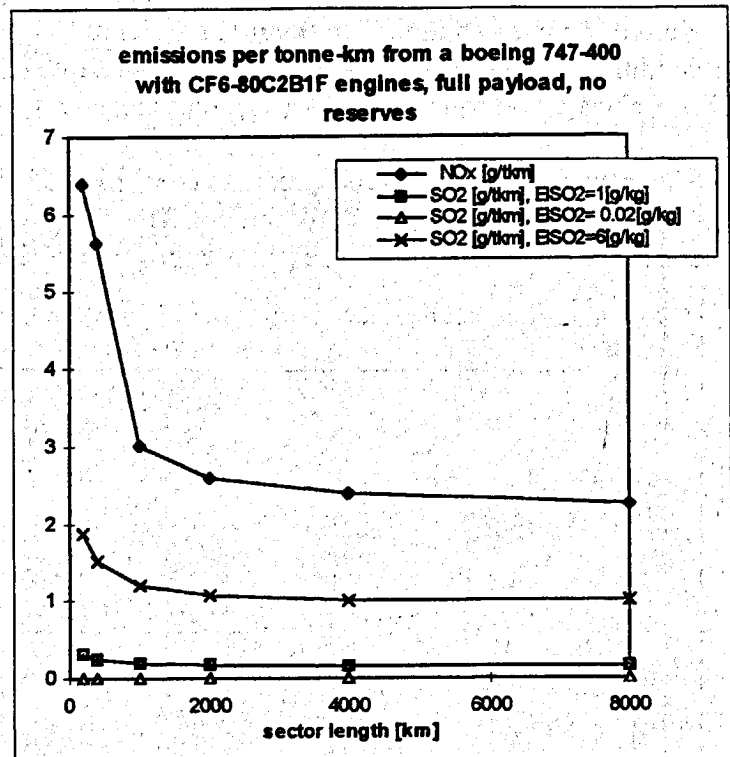
fig. 7.8
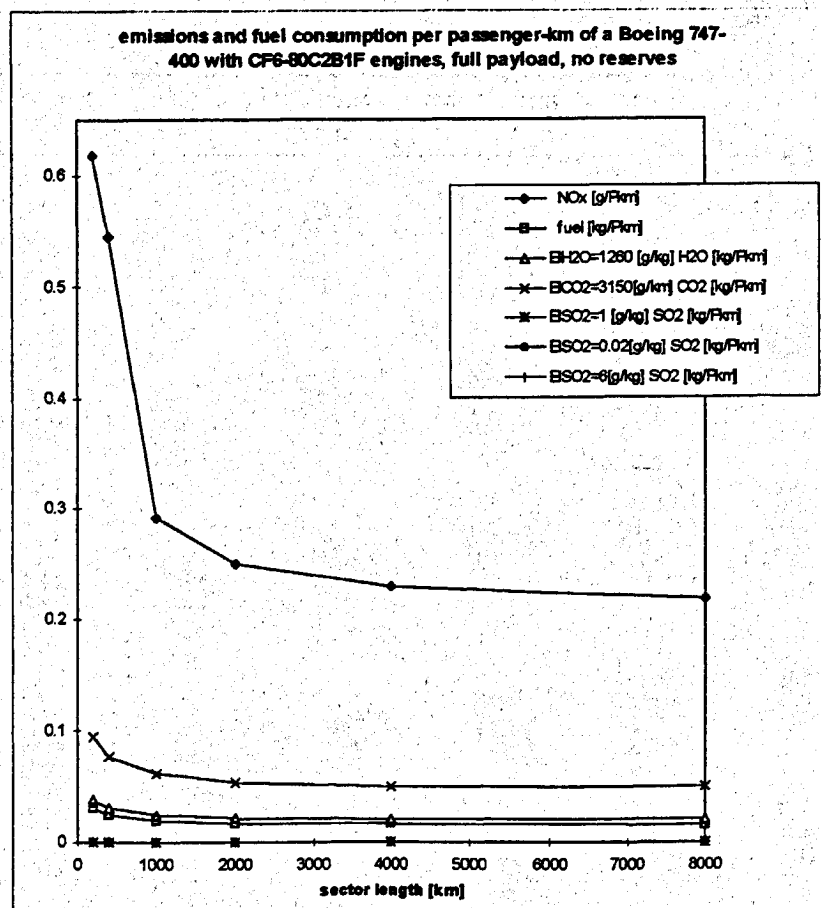
fig. 7.9

8. Planned activities

The following activities still have to be done before completion of the final report.
1. The subjects in this report will be given a more theoretical background.
2. The chapters on trains and aircraft will be completed.
3. A sensitivity study will be done. In this study the sensitivity of emissions from aircraft to variables like load factors, wind etc. will be analysed using formulas for the calculation of emissions.

   This study will be done instead of emission calculations for some typical cases!

4. The total emissions and local air pollution will be discussed.
5. The accuracy of the calculated emissions will be evaluated.
6. In a separate chapter the emissions from different transport modes will be compared.
7. A review of regulations, possible future developments and possibilities for the reduction of emissions will be given.
8. Mr. Torenbeek has to write an official instruction for this thesis.

The final report must be completed before 19 August 1996.

Used literature

The following literature has been used. Not all sources have been used as a reference in this final report. Most of these will be used as a reference in the final report, but some of these will not. However, this literature does provide valuable information. On the one hand, many sources contain comprehensive lists of literature. On the other hand many sources give information that lead to other sources used as references or can be used in further research.

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