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Estimation of Danish exposure factors

NERI Technical Report No. 523

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2004

Steen Solvang Jensen
Ruwim Berkowicz
Jørgen Brandt
NERI

Eva Willumsen
Niels Buus Kristensen
COWI

Data sheet

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Authors: Steen Solvang Jensen[1], Ruwim Berkowicz[1], Jørgen Brandt[1], Eva Willumsen[2] and Niels Buus Kristensen[2]

Departments: [1]Department of Atmospheric Environment, NERI
[2]COWI

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For sale at: Ministry of the Environment
Frontlinien
Rentemestervej 8
DK-2400 Copenhagen NV
Denmark
Tel. +45 70 12 02 11
frontlinien@frontlinien.dk

Contents

Foreword

External costs

COWI is leading a research project named 'Valuation of External costs of Air Pollution' under the Centre for Transport Research on Environmental and Health Impacts and Policy (TRIP). The overall objective of the project is to improve the existing Danish monetary estimates of the costs of air pollution from transport emissions. Specifically, the project will further develop the existing model for calculating unit costs per kg for emissions for CO, HC, NOx, particles, SO_2 and CO_2 and unit costs per vehicle km for all modes of transport. The project is based on the so-called ExternE Transport methodology that established damage costs for transport emissions. The ExternE Tranport project was EU funded and based on another EU funded study for the energy sector – ExternE.

Human exposure assessment

The National Environmental Research Institute (NERI) is heading another TRIP project named 'Traffic Air Pollution, Human Exposure and Health'. The overall aim of the project is to further develop the integration of traffic and environmental models to establish a strategic integrated traffic and environmental model system for impact assessment of traffic air pollution on human exposures and health under different transport and urban localisation scenarios. Part of the project is to provide new knowledge about the relation between exposure patterns and city characteristics within the Greater Copenhagen Area as a case study. A key tool in the project is further development of the so-called AirGIS that is an air quality and human exposure GIS based system.

The projects are described in greater details at the web site www.akf.dk/trip.

Purpose of report

The purpose of this report is to describe how the human exposure estimates from AirGIS can improve the Danish data used for exposure factors in the ExternE Transport methodology. Initially, a brief description of the ExternE Tranport methodology is given and it is summarised how the methodology has been applied so far in a previous Danish study. Finally, results of a case study is reported. Exposure factors have been calculated for various urban categories in the Greater Copenhagen Area.

Acknowledgement

The TRIP project is funded by the Danish Strategic Environmental Research Programme. The Ministry of Transport has co-financed the case study.

Summary in English

This report describes how human exposure estimates from NERI's human exposure modelling system (AirGIS) can improve the Danish data used for exposure factors in the European Commission ExternE Transport methodology - the so-called 'impact pathway' methodology applied for social costs estimation of air pollution. The methodology includes emissions, human exposures, dose-response relations, damages and social costs. Exposure factors are defined as the relation between emissions and population exposure (units: person µg/m^3 per tonnes per year).

Initially, a brief description of the ExternE Transport methodology is given and it is summarised how the methodology has been applied so far in a previous Danish study. This study was prepared by the Ministry of Transport and was the first attempt to apply the ExternE methodology to Danish conditions. It is outlined how data could be further improved to better reflect Danish conditions.

New Danish exposure factors have been calculated based on a case study in the greater Copenhagen Area. The case study area is a large part of Sealand including the counties of Frederiksborg, Roskilde and Copenhagen and the municipalities of Frederiksberg and Copenhagen. The area includes the capital of Copenhagen and a large number of cities of varying sizes. A large part of the area is also rural areas. This area serves as the case study area for estimation of emission and exposure factors. Exposure factors have been calculated on the regional scale (Europe) and the local scale (Greater Copenhagen Area). Hence, impacts on the European scale due to emission changes in the Greater Copenhagen Area are also taking into account. Furthermore, Danish exposure factors have been calculated for various urban categories in the Greater Copenhagen Area.

Regional and local scale air quality models developed at NERI have been applied to estimate the revised Danish exposure factors based on scenarios of emission changes in the Greater Copenhagen Area and the subsequent concentration fields and population exposures. Exposure factors are estimated for rural and urban areas where urban areas are further grouped in different city size categories.

Summary in Danish

Rapporten beskriver, hvordan eksponeringsestimater fra DMU's humane eksponeringsystem (AIRGIS) kan forbedre danske data for eksponeringsfaktorer, som beregnes efter den såkaldte "impact pathway" metode, der er anvendt af EU Kommissionen i forbindelse med "ExternE Transport" projektet. Metoden anvendes til estimering af de samfundsøkonomiske omkostninger ved luftforurening. Metoden inkluderer emission, befolkningseksponering, dosis-respons sammenhænge, effekter og samfundsøkonomiske omkostninger.

Indledningsvis gives en kort beskrivelse af metoden i "ExternE Transport", og det opsummeres, hvordan metoden har være anvendt i et tidligere dansk studie. Trafikministeriet forestod dette studie, som var det første forsøg på at anvende metoden på danske forhold. Det er beskrevet, hvordan data yderligere kan forbedres for bedre at reflektere danske forhold.

Nye danske eksponeringsfaktorer er blevet beregnet med udgangspunkt i et casestudie, som omfatter Hovedstadsområdet (Frederiksborg Amt, Roskilde Amt og Københavns Amt samt Frederiksberg og København kommuner). Området omfatter byer af forskellig størrelse men også større landområder, og er derfor velegnet til at beregne eksponeringsfaktorer. Eksponeringsfaktorer er beregnet for det regionale niveau (Europa) og det lokale niveau (Hovedstadsområdet).

Regional- og lokalskala luftkvalitetsmodeller udviklet af DMU er anvendt til at beregne reviderede danske eksponeringsfaktorer baseret på ændringer i emissioner i Hovedstadsområdet og de afledte koncentrationer af luftforurening og befolkningseksponering. Eksponeringsfaktorer er således estimeret for land- og byområder, hvor byområderne tillige er underopdelt i forskellige bystørrelser.

1 ExternE Transport Methodology

1.1 Methodology

The relation between transport and damage costs is illustrated by COWI in Figure 1.1 where COWI has made the ExternE methodology operational (Trafikministeriet 2000; Friedrich and Bichel 2001). The idea is that it is possible to calculate the change in damage cost based on changes in transport activities and to estimate unit damage cost in relation to km travelled for different mode of transport. From an economic point of view the cost of transport should reflect the marginal external costs. Information about unit damage costs for the different mode of transport may be used to adjust the cost of transport through taxes and subsidies.

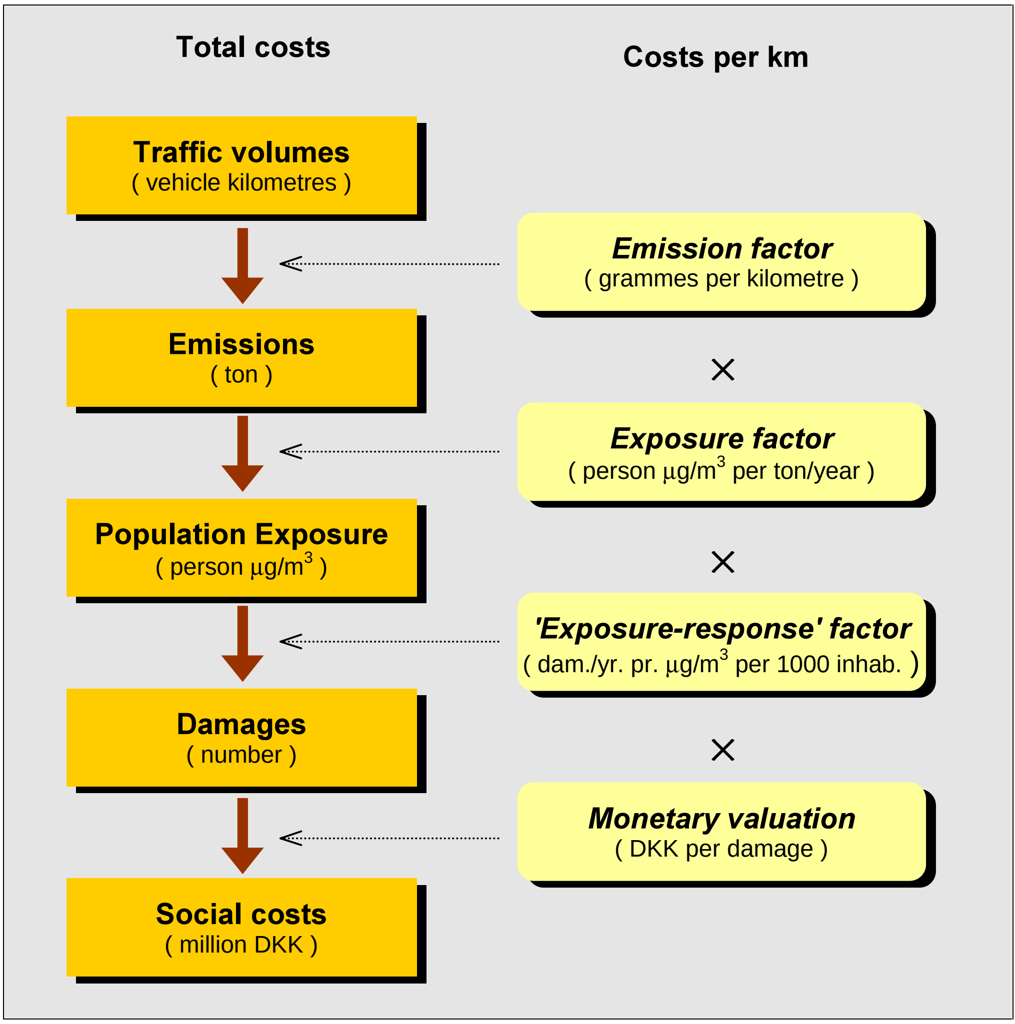
The left side of the figure illustrates the procedure for calculating total costs. The right side of the figure illustrates the operational approach for calculating marginal costs, which are the costs to be calculated in the project.

The marginal costs reflect the costs that a change in emissions in a certain location imposes. This means that each factor in the chain has to represent the effect of a marginal change in the previous link. For instance:

- The exposure factor represents the marginal change in e.g. population exposure to NO_2 due to a marginal change in NO_x emissions
- The exposure-response factor represents the marginal change in e.g. morbidity due to a marginal change in exposure to particles.

Technically, a marginal change is equal to the average change, if there is linearity between the two factors.

Figure 1.1 Illustration of operational approach of the ExternE Transport methodology



Emission factors

The relation between km travelled of different modes of transport and emissions is described by emission factors (gram per km) e.g. subdivided into urban and rural emission factors.

Exposure factors

The relation between emissions and population exposure is described by exposure factors (person µg/m^3 per tonnes per year).

Exposure-response factors

The relation between population exposure and damage is described by exposure-response factors (annual damage per µg/m^3 per 1000 inhabitants).

Damage factor

The relation between damage and damage costs is described by the damage factor (DKK per damage).

1.2 Previous Danish Experience with the Extern E Methodology

A Danish study prepared for the Ministry of Transport (Trafikministeriet 2000) is the first attempt to apply the Extern E methodology to Danish conditions. In the following a brief description of the data and methods applied will be summaries and evaluated with focus on the emission and exposure factors.

Methodology

The operational approach of the ExternE methodology presented in *Trafikministeriet* (2000) is based on the assumption that there is a linear relationship between emissions, exposures and social costs. However, as we shall see later this is not always the case for pollutants that are transformed in the atmosphere.

Emission factors

The relation between km travelled of different modes of transport and emissions is described by emission factors (gram per km) subdivided into urban and rural emission factors based on the so-called TEMA emission tool established by the Danish Ministry of Transport.

The TEMA emission factors have never been validated against air quality data from tunnels or street canyons to check if they represent real world conditions.

Exposure factors

The relation between emissions and population exposure is described by exposure factors (person µg/m^3 per tonnes per year).

To be able to estimate human exposure (a person's contact to a pollutant) it is necessary to describe the population's contact to the concentration levels that the emissions cause, as illustrated in

Figure 1.2.

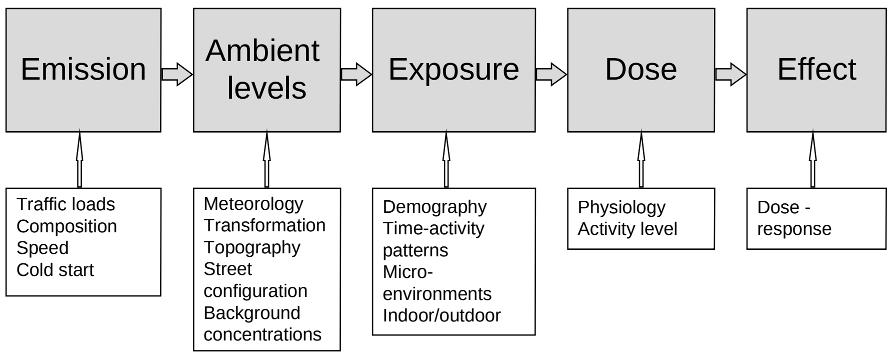


Figure 1.2 The source-effect chain applied to traffic air pollution (Jensen 1999).

To estimate the simultaneous spatial and temporal variation in concentrations and populations is a very complex undertaken as further described in Jensen (1999).

In the ExternE project a simple approach was applied. The ambient annual average concentrations within a grid cell is used as a proxy for the air quality together with the population in the grid.

Regional scale

For the regional scale the Danish study was based on *Eyre et al.* (1997, Appendix 1). For regional scale (rural areas) a simple formula for dispersion and transformation was defined. The formula can be viewed as a single layer trajectory 'model'. It is assumed that a pollutant disperses uniformly in all directions from the source at average wind speed and mixing height, and average deposition and transformation rates are applied. The average population density within the pollutant range is used to estimate the exposure factor in relation to one tonne of emissions annually.

The method is not validated, it does not take into account the non-uniform circulation of air at a regional scale, topography, land cover, differences in emission and population densities etc. The formula does not describe the spatial and temporal variation in concentrations. At best it can give a very rough index for average exposure at a large scale. All in all, the model approach is not state-of-the-art within long-range modelling.

The Danish study (Trafikministeriet 2000) uses the same exposure factors.

Local scale

For short ranges the single layer trajectory model used at regional scale is not applicable. Instead, data from an existing study was used. Modelled urban background levels by Gaussian dispersion modelling and validated against measurements was used to derive average exposure factors for local scale based on average modelled concentrations, emission and population data from Greater London. Data are from 1990. Smaller cities were not considered (Eyre et al. 1997, Appendix 2).

The approach is scientifically sound but it still reduces the exposure factor to one figure that is based on the average urban background concentrations and average population density in just one city. The exposure factors are also empirically specific to London conditions.

The Danish study applies the exposure factors from London based on average population density in Copenhagen. However, the approach is not entirely correct since the observed concentrations in London are correlated with the population density and also the emission density. The correlation is also specific for 1990 and is likely to change in time. The Danish study does not consider smaller cities.

Exposure-response factors

The relation between population exposure and damage is described by exposure-response factors (annual damage per $\mu g/m^3$ per 1000 inhabitants).

The exposure-response factors in the ExternE study have been based on the international literature for health and environmental impacts published during the late 80'ies and mid 90'ties.

The Danish study is also based on the ExternE exposure-response factors.

The exposure factor is related to long-term average exposure using the urban background or rural background as concentration field. The exposure-response factors should therefore also be related to these concentration fields which are usually the case in health studies. Concerning health, the impact can be divided into mortality and morbidity in relation to high short-term exposure and long-term exposure. Since the ExternE methodology is related to long-term exposure it should only be able to estimate the effects attributed to long-term exposure. It is unclear how this issue is treated in the methodology.

Damage factor

The relation between damage and damage costs is described by the damage factor (DKK per damage).

The Danish study is also based on the ExternE damage factors.

The value of a life is very important for damage estimates. The impact of assuming the value of a life using a statistical life or number of years lost has been assessed in the Danish study.

2 Methodology for Estimation of Danish Emission and Exposure Factors

This chapter will outline the methodology applied for an improvement of the Danish emission and exposure factors in the Extern E method. The methodology is applied for Greater Copen-hagen Area as a case study area.

Case study Area

The case study area of the TRIP project is a large part of Sealand including the counties of Frederiksborg, Roskilde and Copenhagen and the municipalities of Frederiksberg and Copenhagen. This area is also called the HT area (Area of the Greater Copenhagen Bus Company). The area includes the capital and a large number of cities of varying sizes. A large part of the area is also rural areas. In the following the area is called the Greater Copenhagen Area (GCA). This area also serves as the case study area for estimation of emission and exposure factors. Impacts on the European scale due to emission changes in the GCH are also taking into account.

2.1 Emission factors

Emission factors (gram per km) for the different modes of transport is subdivided into urban and rural emission factors based on the so-called TEMA emission tool established by the Ministry of Transport. The tool is based on a collection of existing Danish and international emission data.

The purpose of the model is to provide a tool for assessment of the emission from alternative trips e.g. comparison of a trip by passenger car or bus, or a trip by ferry or plane. The tool has a Windows interface, it is free of charge and intended to give the public, professionals and decisions-makers an impression of the emission impact of alternative trips.

The TEMA emission tool draws heavily on results from the EU MEET project and EU COPERT emission models.

The emissions are based on laboratory measurements. However, real world on-the-road emissions may be different.

Validation of emissions against street concentrations

One way to validate emission factors is in tunnel studies where measured concentrations are compared to modelled concentrations based on the emission model. These studies usually show that emission factors are underestimated.

In a Danish study using a street canyon as a 'tunnel', NERI has also shown that COPERT emission factors underestimate when comparing modelled concentrations with measured concentrations for NO_x and CO (Jensen et al. 2002). These invert calculations using the Danish street canyon model OSPM (Operational Street Pollution Model) and measured street concentrations have also shown that benzene and PM10 emissions are underestimated (Palmgren et al. 1999) and (Palmgren et al. 2001).

Therefore, NERI has estimated 'NERI' vehicle emission factors that have obtained good results when applied in the street canyon model and compared to measured air quality data. These emission factors are applied in the case study.

Emission database

The TRIP project has also established a large GIS based database on km travelled in the Greater Copenhagen Area based on a GIS road network with a resolution down to individual road sections.

Accuracy

The accuracy of the absolute level of vehicle and other emissions may not be very crucial for the Extern E methodology because it considers the marginal change in emissions, that is, a relative change. However, it is important that there is a correct relation between emissions and estimated concentrations.

2.2 Exposure factors

Marginal changes

The approach for calculating the marginal effect of a change in exposure due to a marginal change in emission implies calculating the effect on the exposure of (in principle) all persons of a change in emission at a certain location. This means that the following distinction has to be made geographically to calculate the exposure factors:

- The location of the emission
- The location of the receptors.

In the existing calculations based on Eyre et. al. (1997), the location of the emission is either "rural area" or "urban area", the latter represented by Copenhagen. The location of the receptors is (in principle) all Europe.

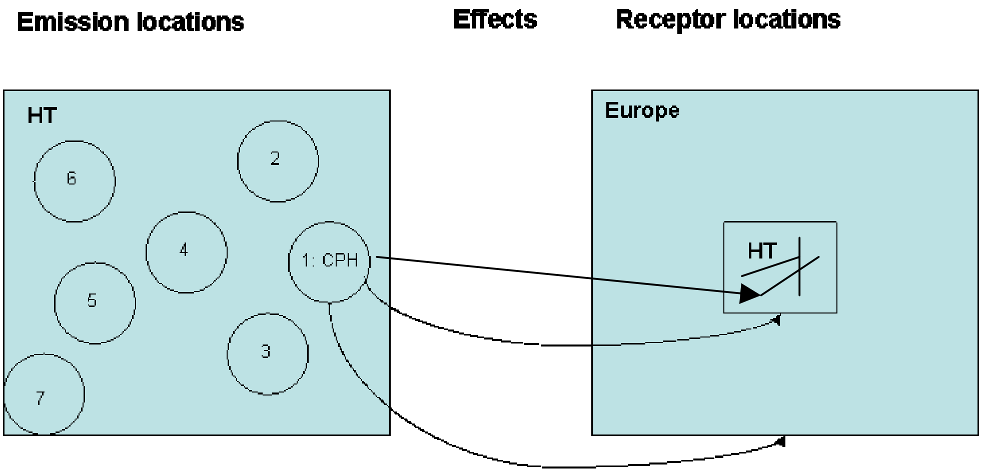
Emission locations

In the case study seven locations in Greater Copenhagen Area were considered for the location of the emissions based on the TU urbanisation categories. TU is a national Danish transport survey that is performed on a regular basis. Based on the TU urbanisation categories it should be possible to generalise the results to a national level. To limit the number of calculations the TU categories of 1, 4, 5 and 7 were encompassed in the case study.

Table 2.1 Locations of emission change

TU urbanisation category	Examples	Included in case study
TU1. Capital	Copenhagen centre	X
TU2. Suburbs to the capital	Gladsaxe (or Herlev)	
TU3. Cities with more than 100.000 inhabitants	n.a. in case area	
TU4. Cities with 10.000-99.999 inhabitants	Hillerød (or Roskilde)	X
TU5. Cities with 2.000-9.9999 inhabitants	Stenløse	X
TU6. Cities with 200-2.000 inhabitants	Skævinge	
TU7. Rural areas (<200 inhabitants)	All rural locations	X

The idea is to calculate the change in concentrations (and hence exposure) for receptor locations within the HT area and Europe due to a change in emissions in a TU urbanisation category.



Receptor location

The location of receptors is subdivided into the case study area (HT area) and Europe. The HT area is subdivided into different TU categories.

Urban background receptor in case study area

For the case study area, the receptors are cells in a grid. The grid cells can be of varying size. Emissions and population data were established on a 1x1 km^2 grid, and a 2x2 km^2 grid for concentrations to limit computer calculation time.

European receptor

For Europe (except GCA) the receptor grid is based on the 50x50 km^2 grid used in the DEOM model. Population data are based on EuroStat (county level data representing 1995-98 data).

Calculation procedure

The formula for calculating the exposure factor, $\exp_{l^e}$, for the TRIP project is as follows:

$$\exp_{l^e} = \frac{\sum_{l^r} \Delta \exp_{l^r}}{\Delta emis_{l^e}} = \frac{\sum_{l^r} \sum_i \Delta conc_i \cdot pop_i^{l^r}}{\Delta emis_{l^e}}$$

$$= \frac{\sum_{i \in Europe/HT} \Delta conc_i \cdot pop_i^{l^r}}{\Delta emis_{l^e}} + \frac{\sum_{i \in HT} \Delta conc_i \cdot pop_i^{l^r}}{\Delta emis_{l^e}}$$

$$= (1) + (2)$$

where

l^e is the location of the emissions, $l^e = 1, 2, \ldots, 7$ TU urbanisation categories

l^r is the location of the receptor, l^r = HT, streets in HT, Europe excl. HT

$\Delta \exp_{l^r}$ is the change in population exposure in location l^r

$\Delta emis_{l^e}$ is the change in emission in location l^e

$\Delta conc_i$ is the change in concentration ($\mu g / m^3$) for the population in cell i, i = 1, 2, …, ?

$pop_i^{l^r}$ is the number of people in cell i in location l^r

The exposure modelling is divided on two types:

- Urban background (local scale)
- Regional background (European scale).

The following approach is applied:

The European regional background exposure is the relevant measure for calculating (1) in the formula and the urban background for calculating (2).

UBM for urban scale

The Danish Gaussian Urban Background Model (UBM) has been used to model the urban background concentrations in GCA (Berkowicz 2000). The time resolution is one hour. The pollutants considered are listed in Table 2.2.

Table 2.2 Exposure factor modelling using the UBM model

Urban scale	Exposure factor
OK	Person µg/m^3 PM_{10} per tonne PM_{10} per year
Not relevant	Person µg/m^3 nitrates per tonne NO_x per year
Not relevant	Person µg/m^3 sulphates per tonne SO_2 per year
OK	Person µg/m^3 NO_2 per tonne NO_x per year
n.a.	Person µg/m^3 SO_2 per tonne SO_2 per year
OK	Person µg/m^3 O_3 per tonne NO_x per year
Not relevant	Person µg/m^3 O_3 per tonne NMVOC per year
OK	Person µg/m^3 benzene per tonne benzene per year
OK	Person µg/m^3 benzene per tonne NMVOC per year
OK	Person µg/m^3 CO per tonne CO per year

It is not relevant to model nitrates, sulphates, and ozone formation in relation to NMVOC on the urban scale since these processes do not take place on the local scale but only on a regional scale.

Vehicle emissions are only considered since it is the dominant source compared to other sources like space heating and industrial processes.

The emissions are based on the emission factors of the OSPM model. At the moment SO_2 emission factors are not implemented in the model and hence not available. However, SO_2 emissions from vehicles is very limited compared to other sources.

Annual average levels have been calculated based on hourly time-series.

DEOM for the European regional scale

The Danish Eulerian Operational Model (DEOM) will be used to model European regional background concentrations (Brandt et al. 2001; 2003). DEOM is based on the EMEP emissions for Europe. The time step is 15 minutes with output of one hour time-series. Calculations are done on a 50x50 km^2 spatial resolution.

Emission and population data are established on the same grid as the 50x50 km^2 grid used in the DEOM model. Emission data originates from EMEP (European Monitoring and Evaluation Programme) from 1998 and population data are based on EuroStat (county level data representing 1995-98 data). Meteorological data from 1999 is based on modelled data from the Danish NERI THOR system.

To be able to model marginal changes in the rest of Europe due to emission changes in Denmark it is necessary to consider large marginal emission changes to be able to model even small changes in exposure. Therefore, the exposure factors have been calculated based on emission changes in the entire area of GCA and not just in a small area within GCA. This approach is justified since the exact location of emissions within GCA is of little relevance when considering the impact to receptors in Europe.

In Table 2.3 the pollutants considered are listed.

Table 2.3 Exposure factor modelling using the DEOM model

Regional scale	Exposure factor
n.a.	Person µg/m^3 PM_{10} per tonne PM_{10} per year
OK	Person µg/m^3 nitrates per tonne NO_x per year
OK	Person µg/m^3 sulphates per tonne SO_2 per year
OK	Person µg/m^3 NO_2 per tonne NO_x per year
OK	Person µg/m^3 SO_2 per tonne SO_2 per year
OK	Person µg/m^3 O_3 per tonne NO_x per year
OK	Person µg/m^3 O_3 per tonne NMVOC per year
n.a.	Person µg/m^3 benzene per tonne NMVOC per year
OK	Person µg/m^3 CO per tonne NMVOC per year

The particle module in DEOM presently only include secondary particles formed in the atmosphere based on emission of gasses. Secondary particles included are nitrate, sulphate and ammonium. Primary particle emissions are not included (directly emitted particles, soil dust, etc.). Therefore, it is not possible to calculate an exposure factor for PM10 at present. However, work is in progress to establish PM10 emission data and to describe physical and chemical processes for calculation of PM10 concentrations (together with PM2.5 and TSP).

The DEOM model also calculates NH_4^+ (ammonium).

DEOM emissions include NOx, SO_2, NMVOC and NH_3.

The hourly time-series from the DEOM model is also an input to the UBM model and accounts for the regional contribution to the urban background. The reference DEOM scenario is used for all UBM scenarios.

Accuracy of marginal changes

Annual average levels are calculated based on the hourly time-series. It is important not to attempt to model the impact of too small emission changes since the change in concentration may have the same order of magnitude as the numerical error in the calculations due to oscillations in the numerical solutions inherited in an Eulerian model. This is why the emission change considered on the European scale will be based on larger emission changes. It is also important not to consider a tiny modelled change as a real change due to the uncertainty in the numerical solutions.

Validation

The DEOM and UBM models have been comprehensively validated against monitoring stations.

Scenarios

The following scenarios have been encompassed so far for the European regional scale (DEOM model) and the local scale (UBM model).

Scenario (DEOM)	Emission reduction in GCA
Sc_R100	Reference (no reduction)
Sc_R75	75% of Ref. (25% reduction)
Sc_R50	50% of Ref. (50% reduction)
Sc_R25	25% of Ref. (75% reduction)
Sc_R00	0% of Ref. (100% reduction)

Scenario (UMB)	Description	Emission reduction in relation to GCA (%)
Sc_75_TU1	25% reduction in Copenhagen incl. Frederiksberg	2.7
Sc_25_TU1	75% reduction in Copenhagen incl. Frederiksberg	8.0
Sc_75_TU4	25% reduction in cities with 10.000-99.999 inh.	5.4
Sc_75_TU5	25% reduction in cities with 2.000-9.999 inh.	0.7
Sc_25_TU5	75% reduction in cities with 2.000-9.999 inh.	2.2
Sc_75_TU7	25% reduction in rural areas	13.2

3 Case Study Results

As outlined in chapter 2 the exposure factor consists of two contributions: one on European scale (1) and one on local scale (2). A change in exposure (change in concentration times population in a grid cell) is related to the emission change of a specific location. In the following the input data applied is briefly presented and the final results are shown and discussed.

3.1 Exposure factor for the European scale based on DEOM

Emission data

GCA only takes up parts of the corresponding 50x50 km^2 resolution emission and calculation grid cells, see Figure 3.1.

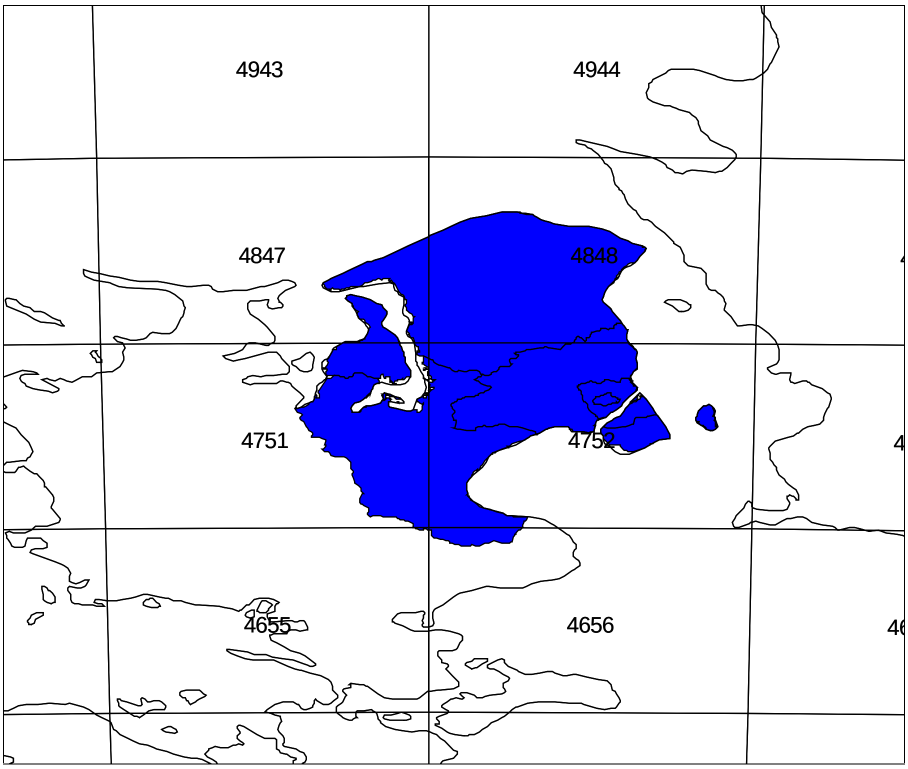


Figure 3.1 The fraction of the Greater Copenhagen Area (GCA) included in corresponding DEOM grid cells.

The emission fraction of the GCA of the individual DEOM grid cells have been determined to be able to reduce the emission in GCA correctly in the different scenarios. It is assumed that the emissions are evenly distributed within the land area of a grid cell.

Table 3.1 Percentage of GCA in corresponding DEOM grid cell

DEOM grid cell ID	% GCA of DEOM grid cell
4656	9
4751	27
4752	97
4847	44
4848	62

The emission of GCA in the different scenarios is given in the table below.

Table 3.2 Emissions of GCA in the different scenarios

Scenario	NMVOC (1000tonne/ year)	SO_2 (1000tonne/ year)	NOx (1000tonne/ year)	NH_3 (1000tonne/ year)
Sc_R100	19.8	29.7	49.5	5.3
Sc_R75	14.9	22.3	37.2	4.0
Sc_R50	9.9	14.9	24.8	2.6
Sc_R25	5.0	7.4	12.4	1.3
Sc_R00	0	0	0	0
Reference emissions in GCA as per cent of all emissions in DEOM domain	1.5	2.6	3.4	1.1

Impact area of concentration changes

The DEOM model was run for the different scenarios. The maximum impact area of a significant change in concentrations between the reference and the 100% emission reduction scenarios was analysed for all pollutants to select an impact area to serve for exposure calculations. An example is shown in Figure 3.3. The maximum change in concentrations are typical within a few per cent with the largest changes close to the Greater Copenhagen Area.

Computing time

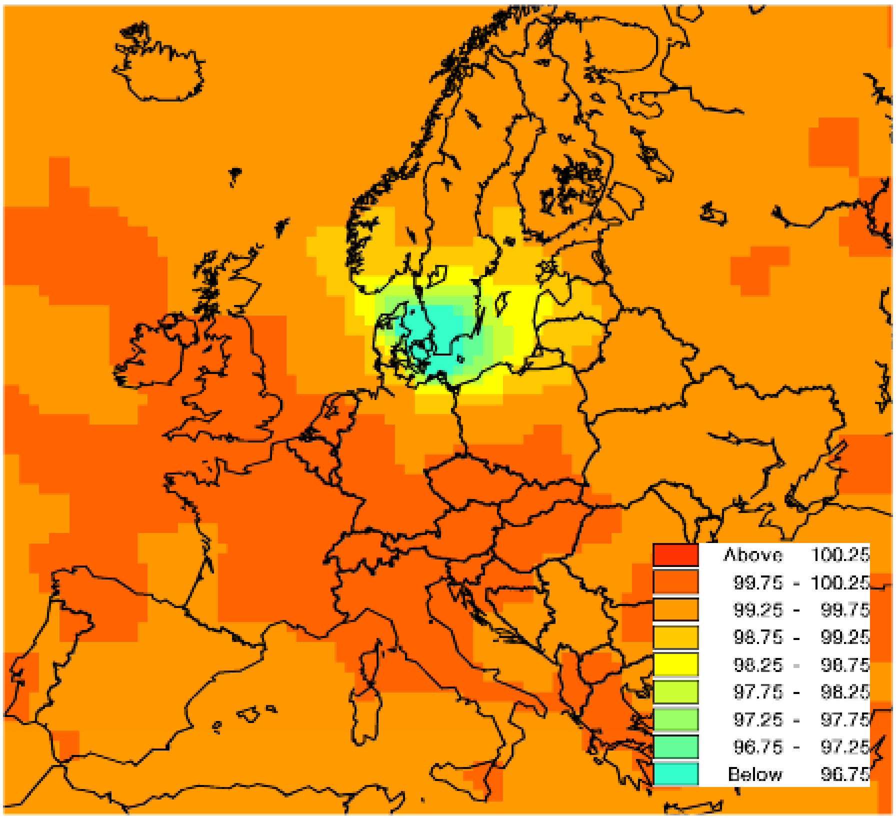


Figure 3.2 The difference for NO_2 concentrations between the reference and the 100% emission reduction scenario given in per cent of the reference scenario. A per cent less than 100 refers to a reduction in concentrations. Data from 1999.

The computing time per scenario on a workstation is 12 hour.

Numerical noise

Changes in concentrations in Denmark, Southern Sweden and Norway, Northern Germany and the Baltic countries are significant. The tiny changes outside this area are numerical "noise" and are excluded. Such numerical noise is an inherit part of the numerical solutions in an Eulerian model and are due to the Gibbs phenomenon. The numerical noise may generate a scenario concentration that is higher than the reference concentration despite an emission reduction since two "large" concentration figures are subtracted that both have a small uncertainty.

To avoid this numerical noise (and not to amplify it by multiplying it with the population data) only grid cells with lower concentrations in all scenarios compared to the reference have been included. A different case is O_3 where only higher concentrations in all scenarios compared to the reference are included since O_3 increases when NOx and NMVOC are reduced.

Output accuracy

Modelled concentrations have an output format of three significant figures. This means that a change in concentrations are only registered if there is a minimum change of 0.1-1% between two scenario values for a grid cell.

Impact area

The impact area is illustrated in Figure 3.3.

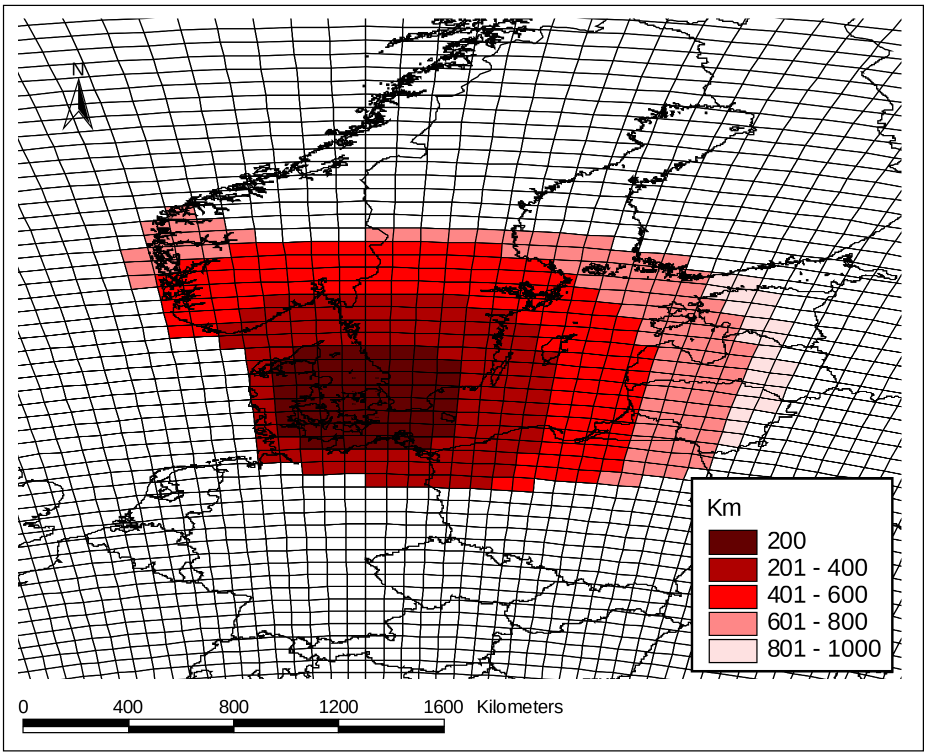


Figure 3.3 Impact area of the DEOM model for exposure factor calculations due to emission reductions in GCA. The shape of the impact areas is influenced by the dominant western, south-western winds. Distances from the Greater Copenhagen Area (GCA) is also shown. Grid cells in different circular distances from GCA were selected in an UTM co-ordinate system that preserves distances. Here visualised in a geographic projection that is not preserving distances.

Evaluation of concentration distribution within impact area

An evaluation of the concentration multiplied by population distribution within the impact area was carried out to assess the dependence on distances from the Greater Copenhagen Area under the various scenarios. The analysis was carried out for a worst case situation taking nitrate as an example. Nitrate is formed relatively slowly in the atmosphere. NO_2 is chemically transformed to nitrate with 5% per hour. With an average wind speed of 5 m/s about 57% of NO_2 is left after 11 hours (200 km), about 18% of NO_2 is left after 33 hours (600 km) and about 6% of NO_2 is left after 55 hours (1000 km). Additionally, NO_2 will also be removed by wet and dry deposition but these processes are of less importance in relation to the chemical transformation. We wanted to assess if the transformation and removal processes for nitrate were taking place within the demarcation of the impact area.

The results are shown in Table 3.3. It is seen that up to 40% of nitrate concentrations multiplied by population is within 200 km from GCA, about 70% within 400 km, about 90% within 600 km and about 98% within 800 km. Therefore, the majority of the concentration changes (multiplied by population) takes place within the defined impact area for a slowly reacting species as nitrate.

Table 3.3 The percentage of changes in nitrate concentrations times population summarised over grid cells in the impact area in different distances from the Greater Copenhagen Area given for the different scenarios

Scenario	0-200 km (%)	0-400 km (%)	0-600 km (%)	0-800 km (%)	0-1000 km (%)
Sc_R75	34	65	89	98	100
Sc_R50	38	71	89	98	100
Sc_R25	39	72	91	98	100
Sc_R00	40	73	91	98	100

Comparison between measured and modelled data

The DEOM model has been validated against all EMEP monitor station in Europe by comparison between measured and modelled data. The model performance should be assessed on such a scale. However, to give an indication of how well the DEOM model perform for the Greater Copenhagen Area a comparison was carried out between modelled data and regional background station in or close to the Greater Copenhagen Area. In Figure 3.5 for the location of regional background monitor stations and DEOM grid cells in the Greater Copenhagen Area are shown.

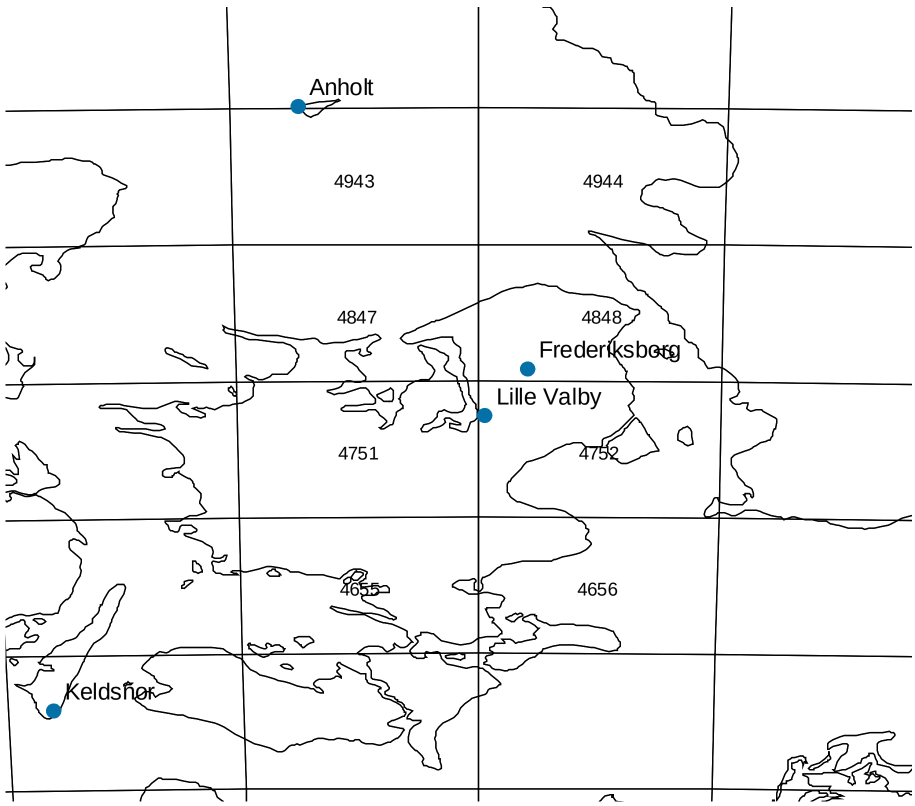


Figure 3.4 Location of regional background monitor stations and DEOM grid cells in the Greater Copenhagen Area

Table 3.4 Comparison between measured and modelled regional data ($\mu g/m^3$). DEOM modelled data from 1999 (emissions from 1998). NOx as NO_2-units.

DEOM grid cell	NO_3^-	SO_4^{--}	SO_2	NO_2	NO	NOx	O_3	CO
4943	1.4	2.2	3.2	9.1	0.90	10	65	235
4944	1.3	2.2	3.2	8.8	0.93	10	65	238
4847	1.4	2.6	3.2	9.3	0.94	10	65	236
4848	1.4	2.6	3.2	9.5	0.94	10	65	242
4751	1.5	2.6	3.2	9.2	0.95	10	65	238
4752	1.4	2.6	3.2	9.5	0.94	10	64	242
4655	1.5	2.6	3.2	9.1	0.95	10	64	240
4656	1.5	2.6	3.2	9.1	0.94	10	64	242
Monitor stations	NO_3^-	SO_4^{--}	SO_2	NO_2	NO	NOx	O_3	CO
Anholt	3.5	2,7	1,4	7,4	n.a.	n.a.	n.a.	n.a.
Kelsnor	5,4	3.5	1.7	9.0	1.0	10	67	n.a.
Frederiksborg	3,3	2.8	1.1	10	2.0	12	-	n.a.
Lille Valby	n.a.	n.a.	n.a.	12	3.2	15	60	n.a.

The monitor station that best represent the regional background conditions in the Greater Copenhagen Area is probably 'Frederiksborg'. 'Lille Valby' is relatively close to the city of Roskilde (40.000 inh.) and slightly influenced by emissions from Roskilde. Measurement data are from the monitor database of NERI and *Elleman et al.* (2000).

About 15% of measured nitrate is nitric acid. Nitric acid has been subtracted to give the figures presented in Table 3.4.

CO is not measured in the regional background. Measurements from the urban background station of H.C. Ørsted Institute in Copenhagen is 318 $\mu g/m^3$ and it is estimated that regional levels will be about half based on Dutch monitor data (Jensen 1997), that is, about 160 $\mu g/m^3$.

Modelled data are from 1999 based on meteorological data from 1999 but emissions are from 1998. The impact of using 1998 emissions is marginal since emission trends changes slowly.

It is seen that the model reproduces well the measured concentrations of sulphate, NO_2, NOx, O_3 and CO. It underestimates nitrate by a factor of 2 and SO_2 by a factor of 2-3. However, the absolute levels are less critical since the exposure factors represent a change in concentrations times population divided by a change in emissions of the Greater Copenhagen area. Therefore, it is important that the DEOM model is able to relative changes of concentrations due to changes in emissions.

Population data

The population within the impact area is visualised in Figure 3.5

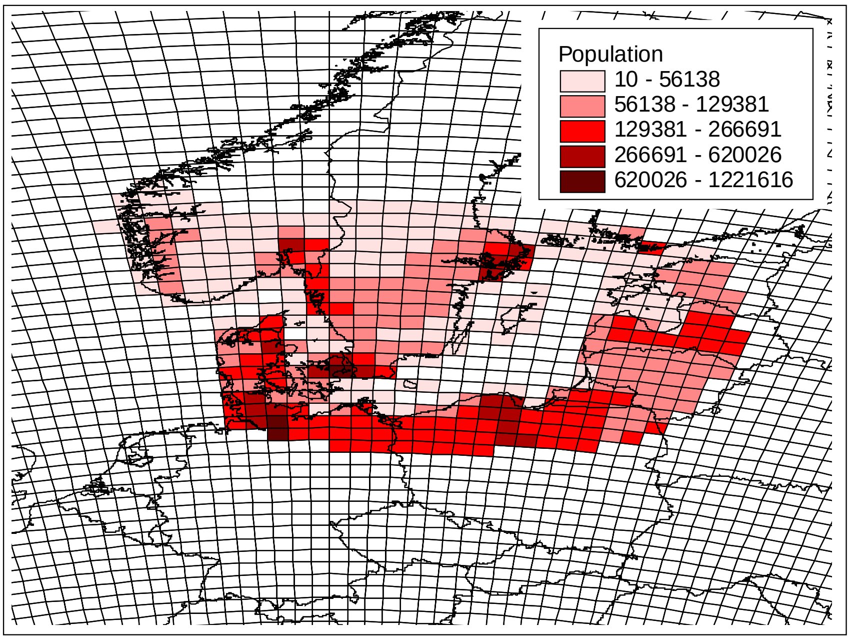


Figure 3.5 The population within the impact area of the DEOM model due to emission reductions in GCA.

The entire population in the impact area is 38.9 million people. There are 2.0 million people in the five grid cells covering the GCA and 1,5 in the GCA based on the distribution given in Table 3.1. The actual population is 1,8 million in GCA which means that the population outside the GCA in the five DEOM grid cells are slightly overestimated leading to slightly overestimation of the exposure of theses cells.

Exposure factors for regional contribution

The exposure factor for contribution to the European receptors of an emission change in GCA is shown in Table 3.6.

Table 3.5 Exposure factors for regional contribution based on the DEOM model

Scenario	NO_3 (Person µg/m³/ tonne NOx)	SO_4 (Person µg/m³/ tonne SO2)	NO_x (Person µg/m³/ tonne NOx)	NO_2 (Person µg/m³/ tonne NOx)	SO_2 (Person µg/m³/ tonne SO_2)	O_3 (Person µg/m³/ tonne NOx)	O_3 (Person µg/m³/ tonne NOx)[1]	O_3 (Person µg/m³/ tonne NMVOC)	O_3 (Person µg/m³/ tonne NMVOC)[2]	CO (Person µg/m³/ tonne NMVOC)
Sc_R75 (75% of Ref. or 25% reduction)	13,1	36	137	123	52	-95	-83	-237	33	1310
Sc_R50 (50% of Ref. or 50% reduction)	11,6	24	108	90	44	-94		-234		1234
Sc_R25 (25% of Ref. or 75% reduction)	11,6	23	99	85	42	-93		-232		1102
Sc_R00 (0% of Ref. or 100% reduction)	11,6	23	97	82	40	-91		-226		1062

Note 1: Unequal emission reduction. Only NOx reduced.
Note 2: Unequal emission reduction. Only NMVOC reduced.

Equal emission reductions

Discussion of results

All exposure factor calculations are based upon equal emission reductions for NOx, NH_3, SO_2 and NMVOC. For example, in the 25% reduction scenario all emissions are reduced 25% at the same time.

Unequal emission reductions

However, if emissions are reduced individually the exposure factors are different. To illustrate this phenomenon scenario calculations were carried out where emissions were reduced individually for NOx and NMVOC (25%) to assess the impact on the exposure factor for O_3. The results showed little change in the exposure factor for O_3 versus NOx indicating that NOx is the main precursor for O_3 instead for NMVOC for conditions in the impact area. That is, we get a similar exposure factor when we reduce NOx and NMVOC with 25% at the same time or if we only reduce NOx with 25%. The exposure factor for O_3 versus NMVOC changes significantly indicating that that there is a large different between a scenario where NOx and NMVOC are reduced simultaneously or only NMVOC is reduced. A 25% reduction of NMVOC leads to small but positive exposure factor indicating that a small overall reduction in O_3 due to reduction in NMVOC emissions.

Similar analysis were made for the other pollutants and revealed that under conditions in the impact area NMVOC is the main source to CO, SO_2 is the main source to SO_2 and sulphate, and NOx to nitrate.

This illustrates that the combination of emission scenarios influence the exposure factor e.g. equal or unequal emission reductions of NOx, NH_3, SO_2 and NMVOC.

Non-linearity on the European scale

One of the assumptions of the operational approach of the ExternE methodology is that there is a linear relation between emissions and concentrations. This assumption implies that the values of the exposure factors would be the same for different emission reductions. It follows from Table 3,5 that this is not he case as the exposure factors differ up to about 40% between scenarios. This is due to the non-linear relation between emissions and concentrations. This implies that the exposure factor will be different depending on the initial concentration levels, the magnitude of the emission change and the geographic region considered.

Link between emission and concentration

The main linkages between emissions and concentrations concerning chemical transformation are illustrated in Figure 3.6. Wet and dry deposition processes are also important and different for the different pollutants. There is a complex relationship between emissions and concentrations where one type of emissions influences several pollutants and several emissions influence the same pollutants.

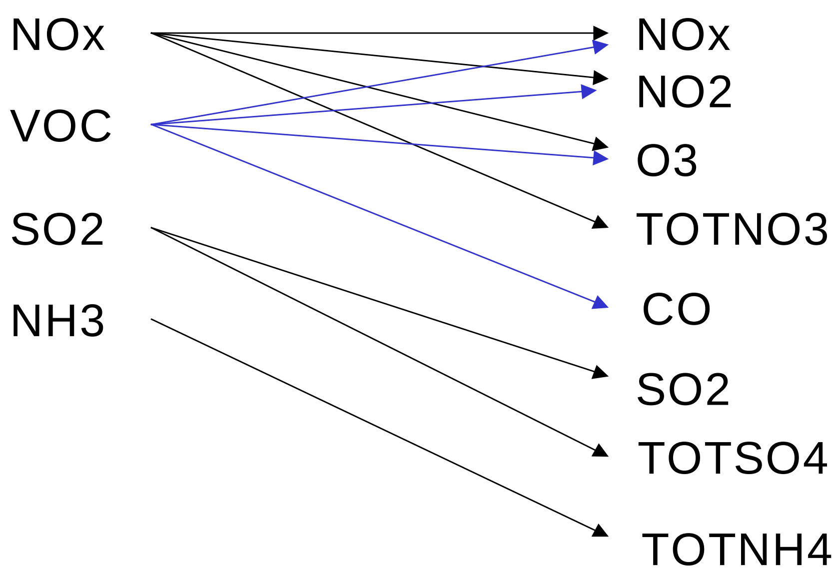


Figure 3.6 Main linkages between emissions (left) and concentrations (right) in the DEOM model

Exposure factors for the various pollutants

The exposure factor for O_3 is negative because the change in concentrations is positive (O_3 increases when NOx and NMVOC emissions decrease). The exposure factors are almost the same for all scenarios indicating that the emission reductions in the Greater Copenhagen Area has little influence on the average ozone levels within the influence area since ozone formation is a large-scale phenomena determined by NOx and NMVOC emission in all of Europe.

NO_2 exhibits one of the largest non-linearity due to its dependence on e.g. O_3. SO_2 and sulphate are also non-linear but to a lesser degree. Nitrate exhibits the least non-linearity since NOx is the main source.

One might expect that the exposure factor for CO would be the same for all scenarios because CO is directly emitted (a fraction of NMVOC in the DEOM model) and it is relatively stable. However, this not the case since CO is part of photo-chemistry.

Match between emission reduction for European and local contribution to exposure factor

As we shall see in section 3.2, the total emission reductions within GCA is in the range of 0.7% and 13.2% in the different emission reduction scenarios for various urbanisation classes. Ideally, exposure factors for all these scenarios should have been calculated to be able to match exposure factors at the European and local level for these urban scenarios. The exposure factor that best matches these reductions is the Sc_R75 scenario (25% reduction) which should be used when one wants to compare the European and local exposure factors. Model runs with emission reductions of 5% and 10% were also carried out. However, the differences between the reference situation and these two scenarios were very small and hence no at-tempt was made to calculate the exposure factors for these scenarios.

Exposure factors are geographically dependent

The estimated exposure factors reflect that the emission change takes place under Danish emission source and atmospheric conditions and in this respect they are geographical specific and specific to Danish conditions.

To illustrate that the same emission reduction in Europe may lead to very different concentration reductions in different parts of Europe we will demonstrate some results from a previous study of ozone (Bastrup-Birk et al. 1997). The relationship between ozone concentrations and NOx and NMVOC emission reductions were studied for 12 sites in Europe. Reductions in NOx and NMVOC separately and in combination were studied. Ozone was studied as AOT40 (Accumulated over threshold, 40 ppb). See Figure 3.7, Figure 3.8 and Figure 3.9.

It is seen that the relation between emissions and ozone is highly non-linear especially in the highly polluted parts of Europe (e.g. Germany, France and the Netherlands) for sites far away from the big sources the relationship seems to be close to linear (e.g. Finland, Algeria). It is also seen that the results are different depending on separate reductions of NOx and NMVOC or a combined reduction.

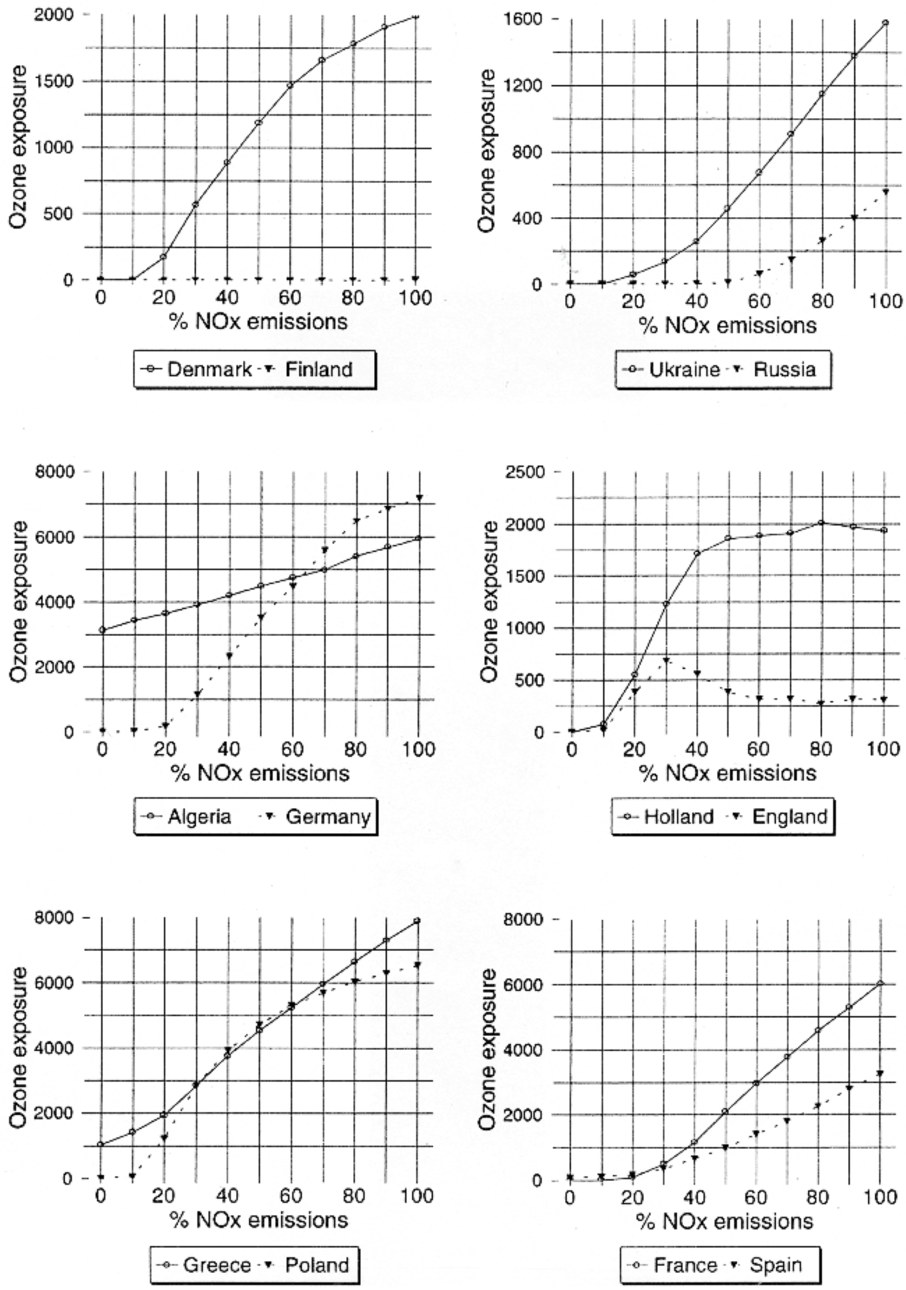


Figure 3.7 Relationship between the NOx emissions and the AOT40 values for August 1993 at 12 sties in Europe. From *Bastrup-Birk et al.* (1997).

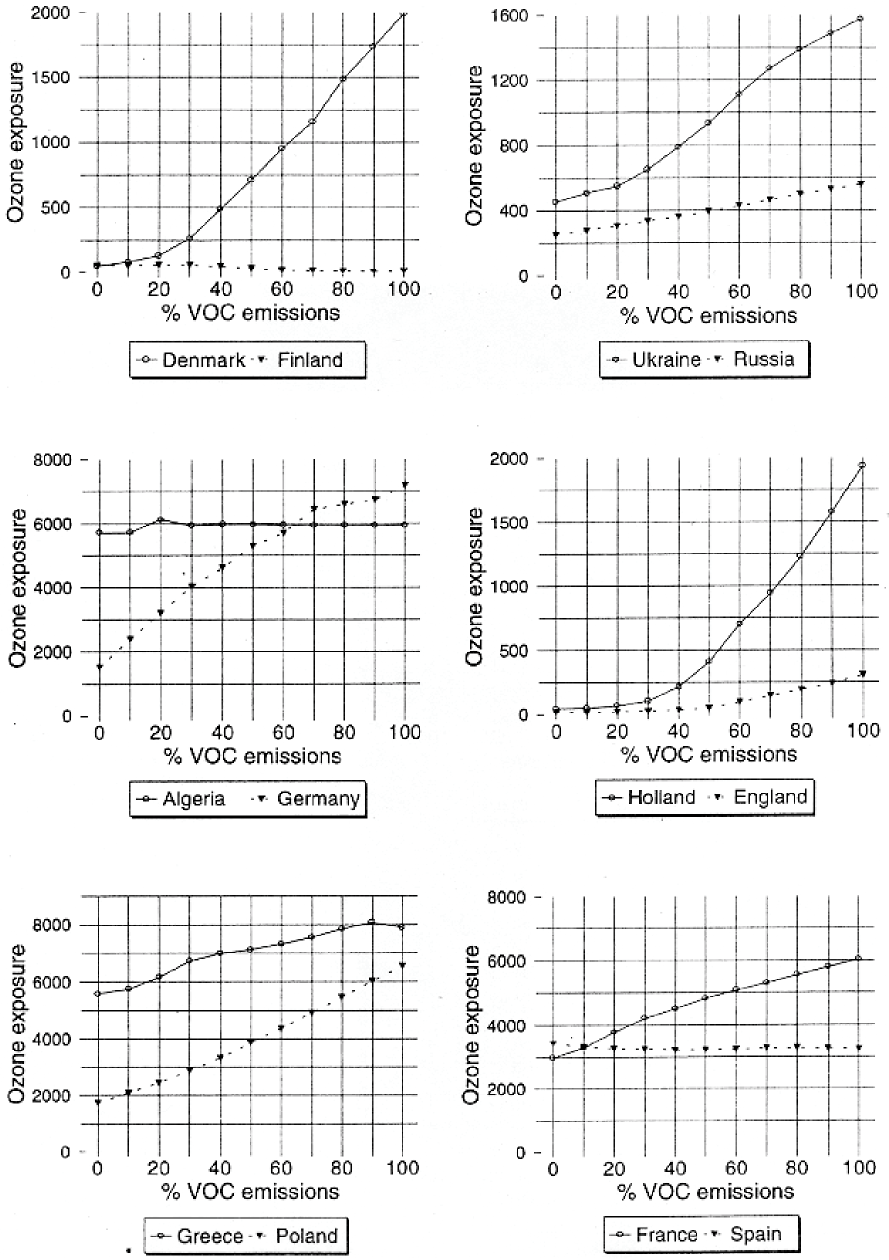


Figure 3.8 Relationship between the human-made NMVOC emissions and the AOT40 values for August 1993 at 12 sties in Europe. From *Bastrup-Birk et al.* (1997).

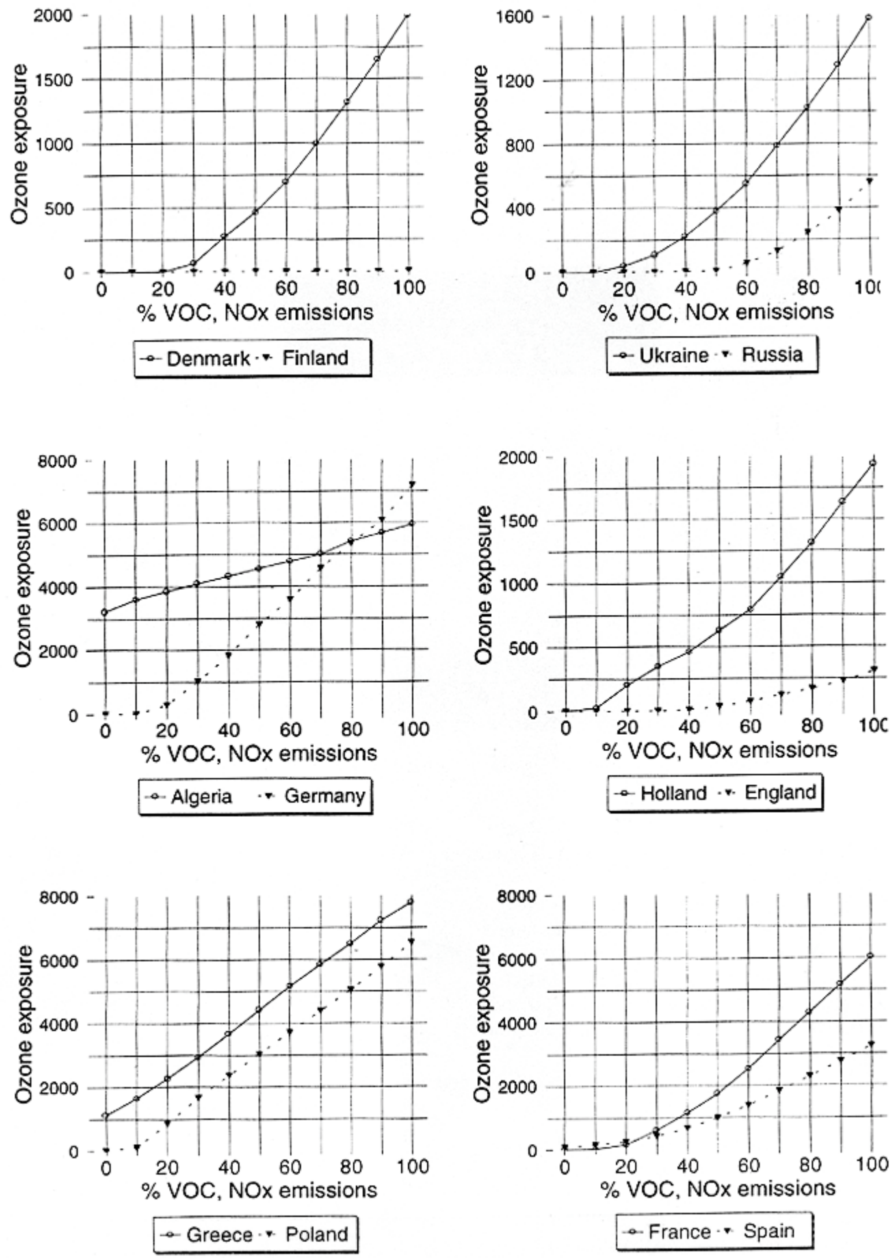


Figure 3.9 Relationship between the NOx and human-made NMVOC emissions and the AOT40 values for August 1993 at 12 sties in Europe. From *Bastrup-Birk et al.* (1997).

3.2 Exposure factors for the GCA based on UBM

Urban and rural categories

The GCA has been subdivided into the seven urban and rural categories defined in TU (see previous **Table 2.1**) based on a city built-up theme combined with urban data on number of inhabitants, see Figure 3.10.

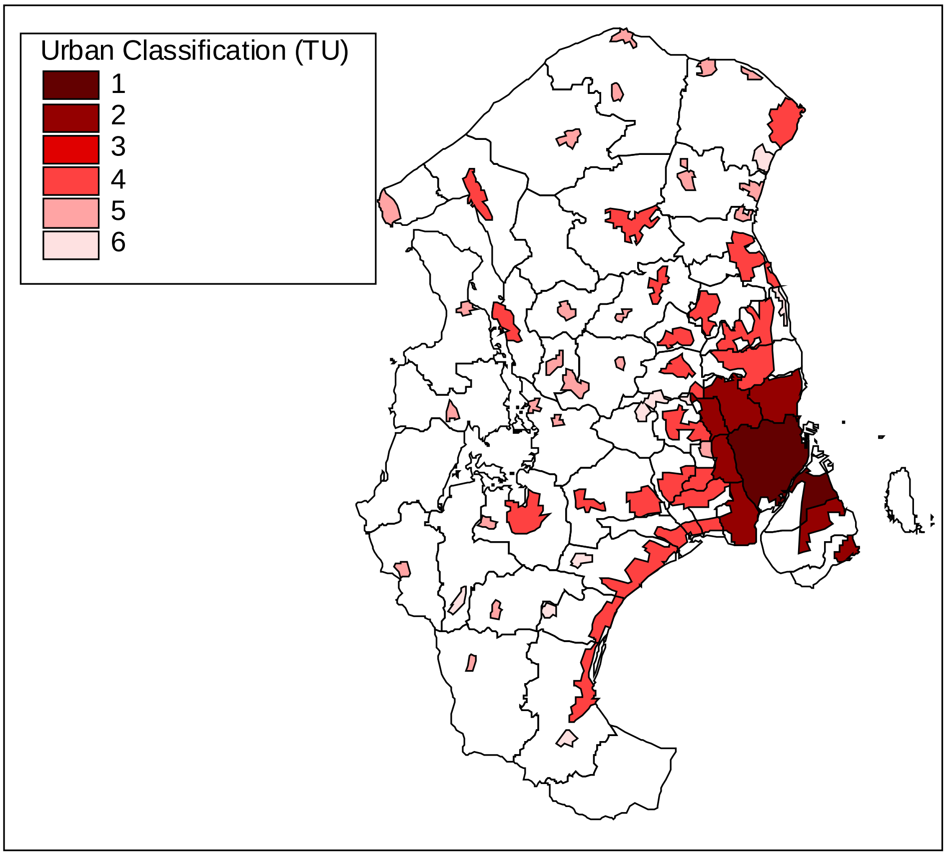


Figure 3.10 Urban and rural categories (TU classes). Category 7 is the white area. There is no category 3 in the analysis. See Table 2.1 for description of the different TU classes.

The data is incomplete for cities with 200-2000 inhabitants (TU6) where some fall into the rural areas (TU7).

Emission data

A large GIS based dataset on km travelled in the Greater Copenhagen Area has been established based on a GIS road network with a resolution down to individual road sections. The database includes approx. 180,000 road segments. It is based on the TOP10DK road theme that includes all roads (state, county and municipality). TOP10Dk is a national dataset maintained by the National Survey & Cadastre. Various methods have been developed to assign traffic from the Copenhagen – Ringsted Traffic Model to the TOP10DK road theme. The traffic model included traffic for most main streets. Based on GIS methods the remaining roads were classified in dead-end roads and smaller roads and assigned standard traffic levels. Traffic levels correspond to 1995-97.

Km travelled and its distribution on four road classes have been summarised on a 1x1 km^2 grid (Danish standard grid). Vehicle emissions on the same grid is generated by the urban background emission preprocessor that is based on 'NERI' emission factors for input to the UBM model. The emissions are proportional to the km travelled and only marginally influenced by the distribution of the four road classes. The spatial distribution of km travelled is illustrated in Figure 3.11.

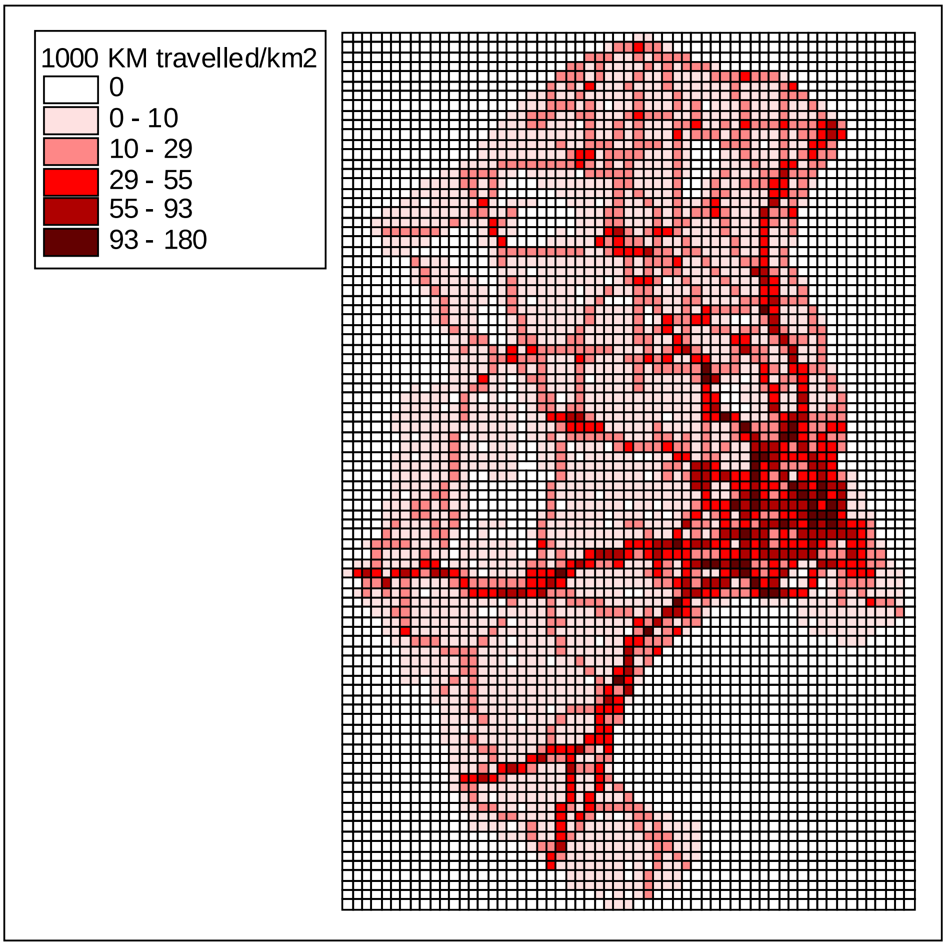


Figure 3.11 Km travelled in GCA on a 1x1 km^2 grid

Comparison of different datasets

Km travelled for GCA in the data set is 15,551 million km per year with 85% on roads with more than 1,000 Average Daily Traffic (ADT). The Danish Road Directorate has estimated km travelled to 13,700 million km per year (1995) for GCA. It seems that the dataset slightly overestimate km travelled.

The spatial distribution of km travelled was also compared to a detailed traffic survey for Copenhagen carried out by the Danish Road Directorate (around 1995). The correlation on a grid cell basis was good but the dataset had higher levels compared to that of the Danish Road Directorate. However, the survey underestimated km travelled since roads with low traffic levels were not included.

The spatial distribution of the km travelled obviously reflects the different scenarios because the emission reduction has a different spatial distribution, see Figure 3.12.

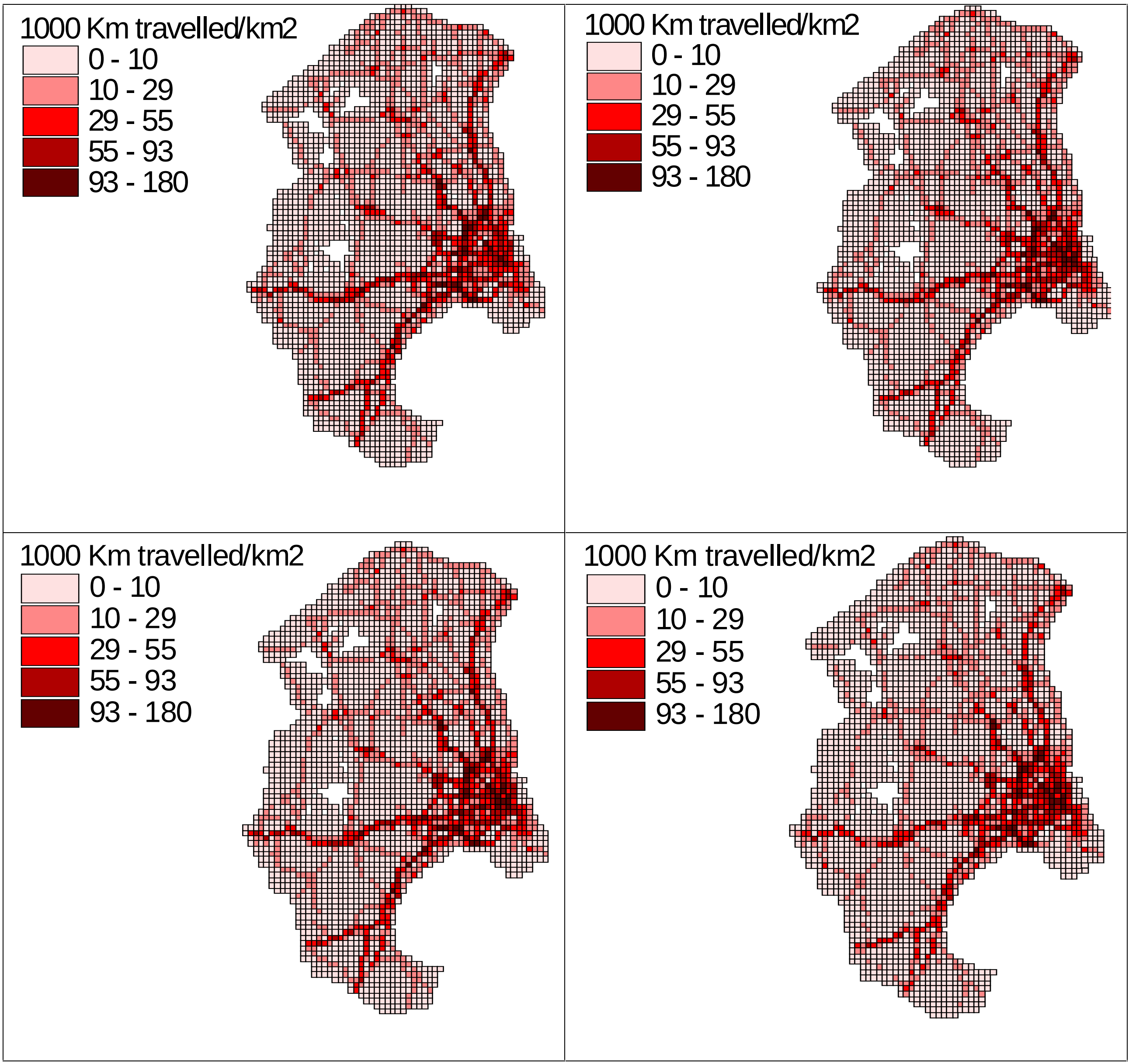


Figure 3.12 Spatial distribution of km travelled in different scenarios all with 75% emission reduction. Upper left: Copenhagen incl. Frederiksberg (TU1). Upper right: Cities with 10,000-100,000 inh. (TU4). Lower left: Cities with 2,000-10,000 inh. (TU5). Lower right: rural areas (TU7).

The emissions are almost directly proportional to km travelled. Emissions are shown in the table below.

Table 3.6 Emissions in Scenarios in Greater Copenhagen Area

Scenario		NOx	CO	Benzene	PM10	Average emission reduction
		(tonne/year)	(tonne/year)	(tonne/year)	(tonne/year)	
Sc-R100	Reference	41821	325496	1198	2379	
		(Fraction)	(Fraction)	(Fraction)	(Fraction)	(%)
Sc-R75-TU1	25% reduction in Copenhagen incl. Frederiksberg	0.973	0.973	0.973	0.972	2.7
Sc-R25-TU1	75% reduction in Copenhagen incl. Frederiksberg	0.920	0.920	0.920	0.916	8.1
Sc-R75-TU4	25% reduction in cities with 10.000-99.999 inh.	0.946	0.946	0.946	0.946	5.4
Sc-R75-TU5	25% reduction in cities with 2.000-9.999 inh.	0.993	0.993	0.993	0.992	0.7
Sc-R25-TU5	75% reduction in cities with 2.000-9.999 inh.	0.978	0.979	0.979	0.977	2.2
Sc-R75-TU7	25% reduction in rural areas	0.868	0.867	0.867	0.869	13.2

Concentration data

The spatial distribution of the concentrations reflects the different scenarios because the emission reduction has a different spatial distribution. In the below figure the NO_2 concentration distribution of the reference scenario is shown.

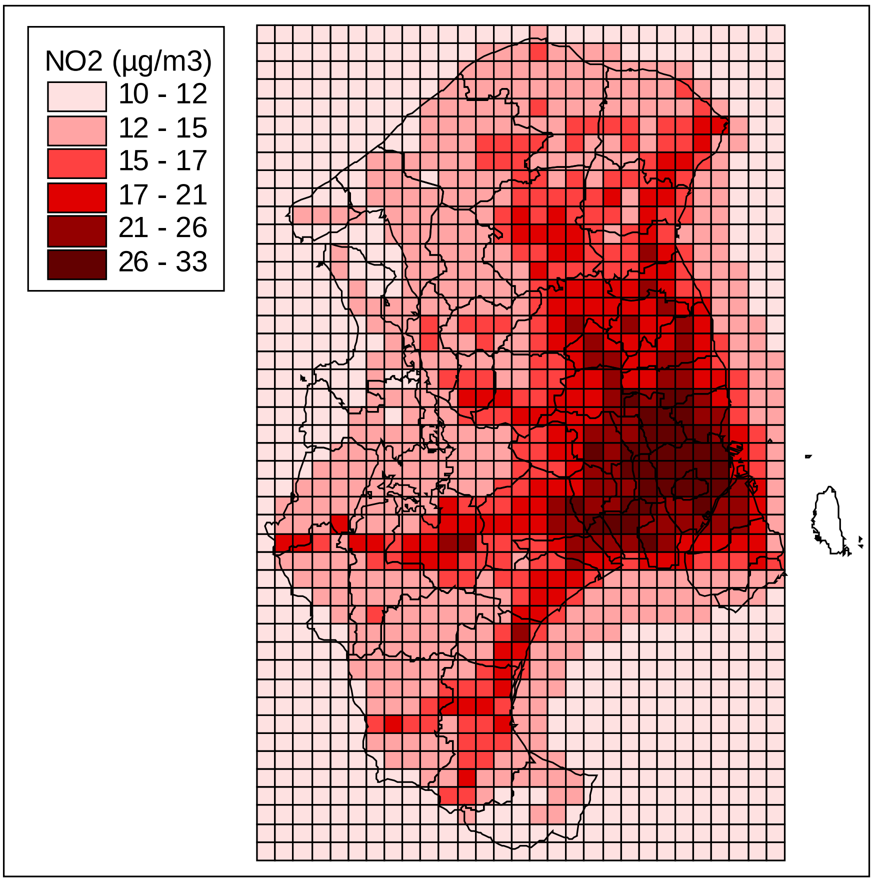


Figure 3.13 NO_2 concentration distribution of the reference scenario on a 2x2 km^2 grid.

The computing time on a powerful PC per scenario was at first 30 hours which was reduced to 7 hours by limiting the emission influence areas that contributes to a calculation point to an appropriate 20 km and by further optimisation of the computer code.

Comparison of modelled and measured data

A comparison between modelled and measured data was carried out for the monitor stations in GCA, see Table 3.7. The UBM modelled data includes the regional contribution. Modelled concentrations slightly overestimated measured data for NOx and NO_2.

Table 3.7 Comparison of annual means of modelled and measured data in 1999 (μg/m^3). Modelled UBM data. The locations of stations are shown in Figure 3.4. Copenhagen station is H.C. Ørsted Institute urban background

Station	NO_x (Measured)	NO_x (Modelled)	NO_2 (Measured)	NO_2 (Modelled)
Copenhagen	34	48	26	32
Lille Valby	15	18	12	15
Frederiksborg	12	21	10	17

Population data

The population data is based on the Central Person Registry (CPR) that gives the number of person on every address in Denmark. The CPR data has been linked to the address dataset of the National Survey & Cadastre (KMS) and summarised on a 1x1km^2 grid (Danish standard grid). The 1x1 km^2 grid was summarised to a 2x2km^2 grid equivalent to the concentration grid.

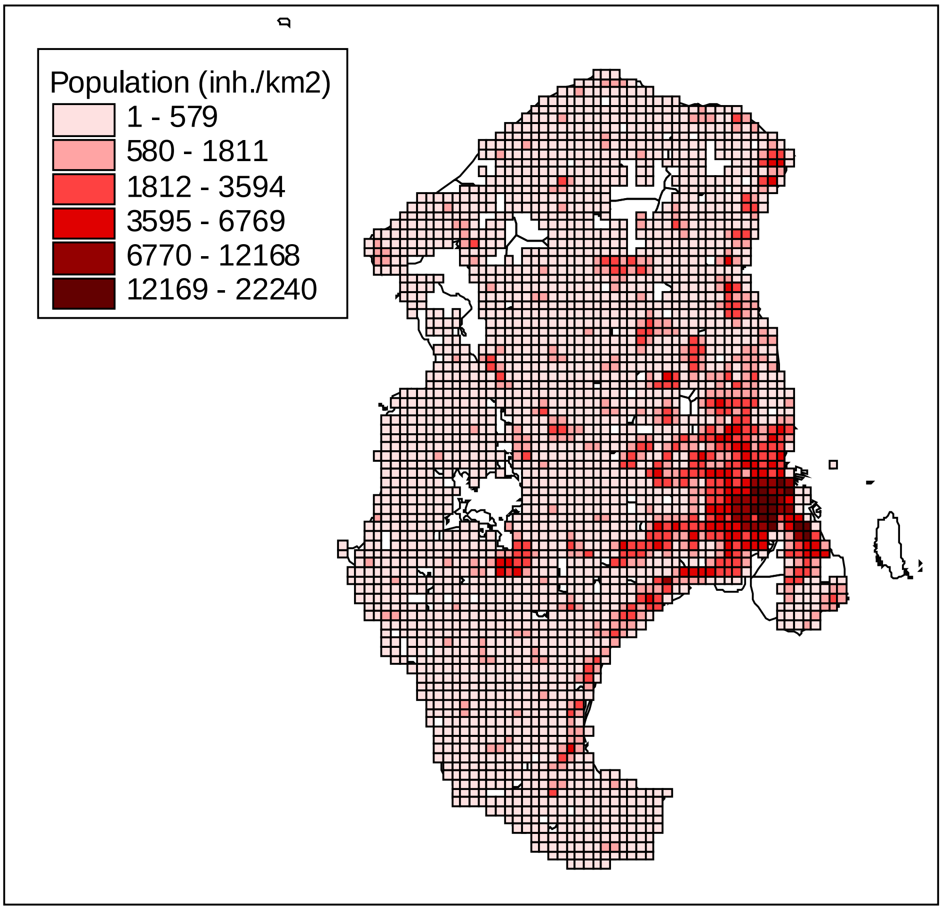


Figure 3.14 Population distribution in GCA on a 1x1 km^2 grid

Table 3.4 Approx. percentage of inhabitants in the different urban categories

Category	Description	Percentage
TU1	Copenhagen	25
TU2	Suburbs to Copenhagen	14
TU3	Cities with more than 100.000 inhabitants	0
TU4	Cities with 10.000-99.999 inhabitants	23
TU5	Cities with 2.000-9.9999 inhabitants	4
TU6	Cities with 200-2.000 inhabitants	2
TU7	Rural areas (<200 inhabitants)	32
	Total	**100**

Table 3.5 Exposure factors for the local contribution (UBM)

Scenario		NOx	NO2	O3	CO	Benzene	Benzene	PM10
		Person $\mu g/m^3$	Person $\mu g/m^3$	Person $\mu g/m^3$	Person $\mu g/m^3$	Person $\mu g/m^3$	Person $\mu g/m^3$	Person $\mu g/m^3$
		per tonne NOx	per tonne NOx	per tonne NOx	per tonne CO	per tonne benzene	per tonne NMVOC[1]	per tonne PM10
Sc-R75-TU1	25% reduction in Copenhagen incl. Frederiksberg	3143	1442	-1336	3163	3165	63	3155
Sc-R25-TU1	75% reduction in Copenhagen incl. Frederiksberg	3143	1616	-1517	3163	3165	63	3155
Sc-R75-TU4	25% reduction in cities with 10.000-99.999 inh.	792	424	-400	798	797	16	786
Sc-R75-TU5	25% reduction in cities with 2.000-9.999 inh.	332	210	-201	338	333	7	331
Sc-R25-TU5	75% reduction in cities with 2.000-9.999 inh.	332	214	-205	334	333	7	331
Sc-R25-TU7	25% reduction in rural areas	336	194	-185	339	339	7	328

Note 1: It is assumed that benzene is 2% of NMVOC

Discussion of results for local contribution

Linearity

If the relation between emission and concentration is linear then the values of the exposure factors would be the same for all scenarios.

There is a linear relation for NOx, CO, benzene and PM10 for the reduction scenarios 25% and 75% since the exposure factor is the same due to a linear relation between emissions and concentrations.

Non-linearity

It is seen that there is a non-linear relation for NO_2 and O_3. This is due to the photo-chemical reaction between NO, O_3 and NO_2, see Figure 3.15. NOx emissions are dominated by NO emissions (about 95% NO and 5% NO_2). NO and O_3 form NO_2 in the atmosphere (steady state that also depends on sunlight and temperature). Forming of NO_2 is therefore depending on the availability of ozone. For high ozone concentrations high NO_2 concentration may be generated (if NO is available). The relation between NO_2 and NOx is not proportional (however it is for low NOx concentrations where ozone is not depleted). If ozone is already depleted by NO or if the ozone levels are low, then NOx emission reductions will only have a little impact of NO_2 concentrations.

The exposure factor for O_3 is negative because the change in concentrations is positive (O_3 increases when NOx emissions decrease due to less depletion of O_3 by NO). NO_2 increases equally as ozone decreases (in ppb) since Ox is constant (=NO_2 +O_3) for a given emission condition.

The exposure factor for NOx (NO_2 units based on ppb) is about twice as high as for NO_2 since it also includes NO and NO concentrations in the urban background are same as NO_2 (in ppb).

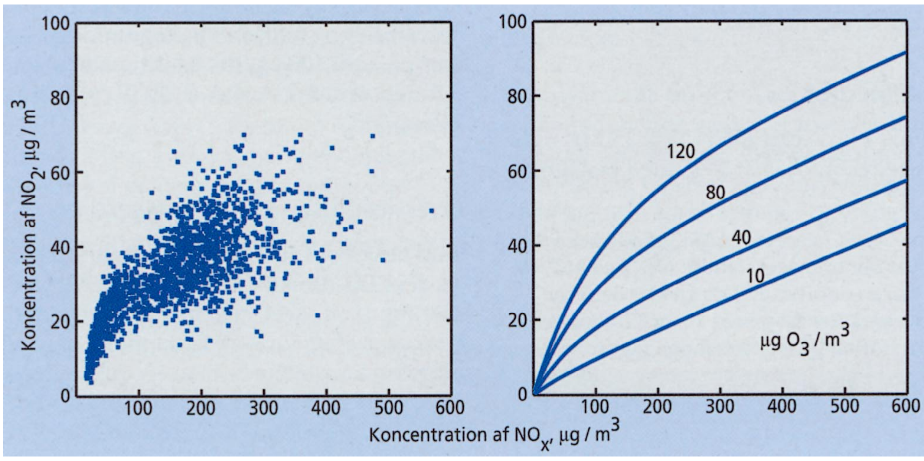


Figure 3.15 NO_2 concentrations depending on NOx (NO_2 and NO) concentrations in a street environment in Copenhagen and the availability of ozone in the urban background. The higher the ozone levels the higher the NO_2 levels (Palmgren et al. 1997)

Exposure factors for emission reductions in different urban classes

It is seen that the largest change in exposure in relation to a reduction of one tonne of emission is obtained in Copenhagen because the location of emission reduction is in a populated place with a relatively high change in concentrations (TU1). The second largest change in exposure factor is achieved for urban areas with 10,000-100,000 inhabitants for similar reasons (TU4).

Although, the emission reduction in the rural areas (TU7) involves about 30% of the population of GCA the exposure factor is similar to that of cities with 2,000-10,000 inhabitants that only account for about 4% of the population of GCA (TU5). This is because the change in concentrations in the rural areas is small and the population density low compared to the urban areas.

The results indicate that one tonne of emission reduction in Copenhagen has a 10 times higher impact on exposure compared to rural areas.

Comparison of regional and local exposure factors for urban and rural conditions

In Table 3.10 a comparison of the regional and local exposure factor for urban and rural conditions are given. For urban conditions the exposure factors represent scenario TU1: a 25% emission reduction in Copenhagen. For rural conditions the exposure factors represent scenario TU7: a 25% emission reduction in rural areas. The regional exposure factor represents 25% emission reduction.

For urban conditions with Copenhagen as case the local exposure factors are about 10 times as high as the regional exposure factor indicating that the local impacts are much higher than the regional impacts.

For rural conditions in the GCA the local exposure factors are about twice as high as the regional exposure factors.

Table 3.6 Comparison of regional and local exposure factors for urban and rural conditions (Person μg/m^3/tonne emission)

Exposure factor	**Urban**		**Rural**	
	Local	**Regional**	**Local**	**Regional**
PM10/PM10	3155	n.a.	328	n.a.
Nitrates/NOx	n.a.	13.1	n.a.	13.1
NOx/NOx	3143	137	336	137
NO_2/NOx	1442	123	194	123
Sulphates/SO_2	n.a.	36	n.a.	36
SO_2/SO_2	n.a.	52	n.a.	52
O_3/NOx	-1336	-95	-185	-95
O_3/NMVOC	n.a.	-237	n.a.	-237
Bzn/Bzn	3165	n.a.	339	n.a.
Bzn/NMVOC	63	n.a.	7	n.a.
CO/CO[1]	3163	1371	339	1371
CO/NMVOC	n.a.	1310	n.a.	1310

Note 1: The same regional exposure factor for CO is crudely assumed to be as for NOx since they are the same at the local level. At present CO emissions are a factor of NMVOC emissions in the DEOM model and it is not possible to relate modelled CO concentrations and CO emissions directly.

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Addresses:

URL: http://www.dmu.dk

National Environmental Research Institute
Frederiksborgvej 399
PO Box 358
DK-4000 Roskilde
Denmark
Tel: +45 46 30 12 00
Fax: +45 46 30 11 14

Management
Personnel and Economy Secretariat
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Department of Environmental Chemistry and Microbiology
Department of Arctic Environment

National Environmental Research Institute
Vejlsøvej 25
PO Box 314
DK-8600 Silkeborg
Denmark
Tel: +45 89 20 14 00
Fax: +45 89 20 14 14

Monitoring, Research and Advice Secretariat
Department of Marine Ecology
Department of Terrestrial Ecology
Department of Freshwater Ecology

National Environmental Research Institute
Grenåvej 12-14, Kalø
DK-8410 Rønde
Denmark
Tel: +45 89 20 17 00
Fax: +45 89 20 15 15

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