Ministry of Environment and Energy
National Environmental Research Institute

A Geographic Approach to Modelling Human Exposure to Traffic Air Pollution using GIS

PhD Thesis

Steen Solvang Jensen

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Data sheet

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Abstract: A new human exposure model has been developed that combines data on traffic air pollution and population data on a high spatial (postal address) and temporal (one hour) resolution. The model system is using a Geographic Information System in combination with available digital maps (buildings, streets, address points, property limits) and administrative databases on people, traffic and buildings. The air pollution is calculated with the Danish Operational Street Pollution Model (OSPM). Simple human exposure estimates are predicted by combining air pollution data with the number of people living or working at a given address during a given time period. The model system may be used for exposure impact assessment of traffic control measures, and exposure assessment in health studies.

Keywords: Human exposure, model, air pollution, traffic, GIS.

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Preface

The present PhD thesis concerns the development of a new approach for modelling human exposure to traffic air pollution using Geographic Information Systems (GIS). The model is further discussed for potential application as a decision-support tool for local authorities for air quality planning, and as a tool for exposure assessment in air pollution epidemiological studies.

The report summaries the author's PhD work conducted at the Department of Atmospheric Environment (ATMI), the National Environmental Research Institute (NERI) and matriculated at the Department of Environment, Technology and Social Studies at the University of Roskilde (RUC).

The PhD work has focused on the development of an integrated model using an existing air quality street model (Operational Street Pollution Model, OSPM) and existing available data to be able to predict air pollution levels with a high spatial (postal address) and high temporal (one hour) resolution, and to link this data to the presence of people to estimate human exposures. The model predicts the presence of people using standardised time profiles and constant indoor-outdoor ratios. The model requires the following input data: digital maps (cadastre, buildings, streets and address points), data from administrative databases (Building and Dwelling Register, Central Population Register, Central Business Register), meteorological parameters, and Average Daily Traffic (ADT). ADT data are the only input data that have to be delivered by local authorities. The input data are currently available for most parts of Denmark and will be available for the entire country within a few years.

Different methodologies within specific areas of the integrated model have been developed. Three methods have been developed to meet the requirements of the OSPM to be able to facilitate the automatic prediction of air pollution levels at any address location. A method to generate the temporal variation in traffic parameters based on information about ADT (Jensen 1997b) and a method for estimation of background concentrations (Jensen 1998). This work is reported in details in two separate NERI reports. A method for automatic generation of street configuration data for the OSPM using digital maps, the Building and Dwelling Register and a GIS has also been developed. Furthermore, methods have been developed to identify individual buildings (geocoding) and to assign traffic to a digital road network.

The PhD thesis was defended and approved at the University of Roskilde, Denmark on the 1st of February 1999.

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The author would like to thank my advisors senior scientist DSc Ole Hertel, the Department of Atmospheric Environment (ATMI) at NERI and Ass Prof Henning Schroll and my opponent Ass Prof Per Homann Jespersen, the Department of Environment, Technology and Social Studies at the University of Roskilde (RUC) for valuable suggestions to the study. I would also like to acknowledge the assistance of senior advisor Henning Sten Hansen, the Department of System Analysis (SYS) at NERI for development of the applied Avenue GIS applications for geocoding of buildings and generation of street configuration data, and senior scientist PhD Ruwim Berkowicz, ATMI for valuable help in application of the Operational Street Pollution Model (OSPM) including preparation of an additional module for exposure calculations.

I also appreciate the institutions that have contributed with data. Digital maps and data from central administrative databases, traffic data and time-activity data have been obtained by various sources: the Office of Central Population Registration (CPR), the Ministry of Housing through the Kommunedata (Data Processing Company for All Danish Municipalities and Counties) (BBR), the Statistics Denmark (CER), the Municipalities of Middelfart and the consulting company TetraPlan (traffic data), the National Survey and Cadastre Denmark (cadastral map and address map), the Map Base Funen (technical digital maps) and the RIVM, The Netherlands (time-activity data). Data collection and strategy for use of GIS have also been discussed with the Institute of Planning at the Technical University of Denmark.

An advisory group including my advisors and opponent has followed the project and participated in two fruitful seminars. The group included:

- Senior scientist Hans Bendtsen, the Danish Road Directorate
- Senior Scientist PhD Ruwim Berkowicz, ATMI, NERI
- Senior Scientist PhD Linda Christensen, Department of System Analysis, NERI
- Medical Doctor Lis Keiding, the Danish Institute of Clinical Epidemiology
- Senior scientist PhD Finn Palmgren, ATMI, NERI
- MSc Leif Hald Pedersen, the Transport Council, (now with the Road Safety and Transport Agency)
- MSc PhD Ole Raaschou-Nielsen, the Danish Cancer Society.

Executive Summary in English

New exposure model

A new exposure model has been developed that is based on a physical, single media (air) and single source (traffic) microenvironmental approach that estimates traffic related exposures geographically with the postal address as exposure indicator. The microenvironments: residence, workplace and street (road user exposure) may be considered. The model estimates outdoor levels for selected ambient air pollutants (benzene, CO, NO_2 and O_3). The influence of outdoor air pollution on indoor levels can be estimated using average I/O-ratios. The model has a very high spatial resolution (the address), a high temporal resolution (one hour) and may be used to predict past, present and future exposures. The model may be used for impact assessment of control measures provided that the changes to the model inputs are obtained. A simple exposure index is defined that assumes that the person is present at the address all the time, and an exposure estimate is also defined that takes into account the time the person spends at the address assuming standardised time-profiles depending on age groups. The exposure model takes advantage of a standard Geographic Information System (GIS) (ArcView and Avenue) for generation of inputs, for visualisation of input and output, and uses available digital maps, national administrative registers and a local traffic database, and the Danish Operational Street Pollution Model (OSPM). The Municipality of Middelfart has been used as a case study area to develop and demonstrate the exposure model. Input requirements are: digital maps including buildings, geocoded addresses, geocoded roads, geocoded cadastres; data from the Building and Dwelling Register (BBR); traffic data (ADT of passenger cars, van, lorries and busses) for linking to a segmented road network; population data on gender and age from the Central Population Register (CPR); the number of employees from the Central Business Register (CER); standardised time-activity profiles for the different age groups in the residence and workplace microenvironments; and meteorological parameters (hourly).

New methods

The exposure model presents a new approach to exposure determination by integration of digital maps, administrative registers, a street pollution model and GIS. New methods have been developed to generate the required input parameters for the OSPM model: to geocode buildings using cadastral maps and address points, to automatically generate street configuration data based on digital maps, the BBR and GIS; to predict the temporal variation in traffic and related parameters; and to provide hourly background levels for the OSPM model.

Potential applications

The potentials for application of the exposure model have been discussed within air pollution epidemiology and urban air quality management, and future research needs have been discussed within refinements of the exposure model, development of a personal exposure model, and development of a model for national exposure and health risk assessment.

Resume på dansk

En geografisk metode til modellering af befolkningens eksponering med luftforurening fra trafik ved brug af GIS

Phd afhandling, 1999

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En ny eksponeringsmodel

En ny eksponeringsmodel er udviklet, som er baseret på en mikromiljø metode. Modellen kan karakteriseres som en fysisk, enkelt medium (luft) og enkelt kilde (trafik) fremgangsmåde, som estimerer trafikrelateret humaneksponering geografisk med adressen som eksponeringsindikator. Modellen omfatter mikromiljøerne: bopælen, arbejdspladsen og gaden (trafikanteksponering). Modellen estimerer udendørsniveauerne af luftforureningerne: benzen, CO, NO_2 and O_3. Udendørsniveauernes påvirkning af indendørs-niveauerne bestemmes vha. gennemsnitlige litteraturværdier for indendørs-udendørs forholdet. Modellen har en høj rumlig (adressen) og tidslig (en times) opløsning, og kan forudsige tidligere, nuværende og fremtidige eksponeringer. Modellen kan anvendes til konsekvensvurdering af reguleringstiltag forudsat at ændringer i modellens input parametre kendes. Et simpelt eksponeringsindeks er blevet defineret ved at antage at en person er tilstede hele tiden på adressen, og et tidsligt eksponeringsudtryk er blevet defineret, som tager hensyn til den tid personer i bestemte aldersgrupper gennemsnitligt opholder sig i det pågældende mikromiljø vha. tidsprofiler. Modellen anvender geografiske informationssystemer (GIS) (ArcView og Avenue) til generering af input, til visualisering af input og output, og anvender tilgængelige digitale kort, nationale administrative registre og en lokal trafik database, samt den danske Operational Street Pollution Model (OSPM). Middelfart Kommune er anvendt som case studie for udvikling og demonstration af modellen. Input forudsætninger er: digitale kort med bygninger, geokodede adresser, geokodede veje, geokodede matrikler; data fra Bygnings- og Boligregisteret (BBR); trafikdata (årsdøgntrafik for personbiler, varebiler, lastbiler og busser) for sammenkobling med et segmenteret vejnet; befolkningsdata om køn og alder fra Det Centrale Person Register (CPR); antal ansatte fra Det Centrale Erhvervsregister (CER); gennemsnitlige tidsprofiler for de forskellige aldersgrupper i bopæls- og arbejdspladsmikromiljøerne; samt meteorologisk parametre.

Nye metoder

Eksponeringsmodellen er en ny metode til eksponeringsestimering, som bygger på integration af digitale kort, administrative registre, en gadeluftkvalitetsmodel (OSPM) og GIS. En række nye metoder er blevet udviklet med henblik på at genere de nødvendige input parametre til OSPM modellen: en metode til geokoding af bygninger vha. matrikelkort og addresspunkter; en bylandskabs-model til automa-

tisk generering af gadekonfigurationsdata baseret på digitale kort, BBR og GIS; en metode til at forudsige den tidslige variation i trafikken og relaterede parametre; samt en semi-empirisk baggrundsmodel til bestemmelse af timebaserede baggrunds-niveauer.

Potentielle anvendelsesmuligheder

De potentielle muligheder for anvendelse af eksponeringsmodellen er diskuteret indenfor luftforureningsepidemiologi, og luftkvalitetsplanlægning i større byer. Endvidere er fremtidige forskningsbehov diskuteret indenfor forfinelse af eksponeringsmodellen, udvikling af en personlig eksponeringsmodel, og udvikling af en national model for eksponerings- og sundhedsvurdering.

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Part I

Context and Theoretical Framework

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1 Introduction

A new integrated model has been developed for the estimation of population exposures to traffic air pollution. The model is based on an existing street pollution model and available digital maps and administrative databases, and applies a Geographic Information System (GIS).

This chapter gives the background for the development of the exposure model. It describes how road transport has become the dominant source of air pollution in urban areas and the human health impacts of the air pollution exposures. The model has been developed in support of air pollution epidemiological studies, and health risk assessment and management exemplified by air quality management by local authorities. Current problems and new opportunities within these areas are described and the overall criteria for the model are defined.

1.1 Road Transport Dominant Source

Various sources

The local air quality is affected by three types of pollution contributions: releases from local traffic, releases from other local air pollution from industry, domestic heating etc., and finally long-range transport of air pollution mainly from industrial and highly populated areas of Central and Eastern Europe.

Change in sources

Over the last few decades road transport has become the dominant source to local air pollution especially in larger urban areas due to the rapid increase in passenger and freight transport and in spite of regulation of emission and fuel quality standards. At the same time, regulation of other sources like power plants, industries, and domestic heating together with a shift towards district heating have diminished the contributions from these source to local air pollution. In busy urban streets the contribution from traffic may constitute 80 to 90 per cent. Despite introduction of catalytic converters on petrol-powered vehicles, traffic air pollution is expected to dominate air pollution in cities in the years to come.

1.2 Health Effects of Air Pollution

Guidelines and levels

Present Danish air quality standards are not exceeded. However, the less stringent planning value for the irritant NO_2 is tangented at several fixed monitor stations in the capital of Copenhagen (Kemp et al. 1997), and recent measurements of the carcinogenic substance benzene far exceed the guidelines from the World Health Organisation (WHO 1987). Present air quality guidelines are under revision in the new European Union Air Quality Framework and Daughter Directives (Jol and Kielland 1997; Europe Environment 1997).

Health effects

Numerous international studies and a few Danish studies have shown that present Danish air pollution levels have a health impact, although, present Danish air quality standards are not violated. However, health impacts of air pollution can be difficult to assess since it is difficult to differentiate factors related to air pollution from other factors. Health effects of air pollution are examined in experimental studies (animal studies and controlled human studies) and epidemiological studies. The potentials and limitations of these methods and how data are used to establish air quality standards are outlined in *Larsen et al.* (1997).

Critical pollutants

The traffic air pollutants that raise most health concerns are: fine particles, nitrogendioxide (NO_2), ozone (O_3), poly aromatic hydrocarbones (PAHs), benzene, 1,3-butadiene, ethene and propene, and aldehydes (formaldehyde, acrolein, acetaldehyde) (Larsen et al. 1997).

Health effects

Numerous studies indicate that air pollution increase the risk of development of cancer, air ways and allergy diseases or aggravate the condition of people suffering from air ways or heart diseases. A threshold value exits for some pollutants and exceeding this threshold may cause acute effects e.g. in the case of short-term exposure during episodes of irritants like NO_2 and O_3. For other pollutants, it is expected that no threshold value exists and long-term exposure to e.g. carcinogenic pollutants like PAH, benzene, 1,3-butadiene, formaldehyde and acetaldehyde may cause cancer.

Particles as carriers of carcinogenic pollutants may contribute to development of cancer. Further, epidemiological studies show that fine particles ($PM_{2.5}$) are associated with increased morbidity and premature mortality especially among people suffering from air ways and cardiovascular diseases. Fine particles may have a health effect that is not just attributed to their chemical composition but to the large number of small particles that penetrate deep into the lung that may overload the natural defence and elimination mechanism of the lungs. However, these processes are not fully understood as described in the review by *Larsen et al.* (1997) and *Jensen et al.* (1997).

Risk groups

Sensitive groups are at risk for increased morbidity or premature death e.g. children; sick or elderly people, and persons with heart disorder or respiratory diseases e.g. asthma and bronchitis. The prevalence of chronic respiratory diseases among the Danish adult population is about 6 per cent and also 6 per cent suffer from cardio-vascular diseases. About 5 per cent of Danish children suffer from asthma, see review by *Larsen et al.* (1997).

Highly exposed groups have an increased risk e.g. people who live or work along heavy trafficked streets particularly in street canyons and in the central parts of the larger cities. Commuters who spent much time in cars and buses in larger cities are at risk. Heavily exposed occupational groups are special risk groups e.g. bus drivers (Hertel et al. 1996).

Rough exposure assessment

All other things equal, the ambient air pollution concentrations will increase with increasing city size, with traffic intensity in street environments, and decrease from the city centre to the outskirts and further to the rural areas. There are about 5.2 million inhabitants in Denmark and about 1.8 million people live in the Greater Copenhagen Area and other cities with more than 100,000 inhabitants where relatively high air pollution levels can be expected. About 1.1 million people live in medium sized cities with moderate air pollution levels and 2.3 million in small towns, villages and rural areas with low air pollution levels. People living along busy streets will experience high exposures to air pollutants from traffic. About 300.000 people live along streets with high traffic levels based on residences exposed to high levels of traffic noise (above 65 dB(A)). The Municipality of Copenhagen has about 500,000 inhabitants and about 24,000 people live along streets where the recommended guideline for NO_2 (135 $\mu g/m^3$ as 98-percentile) is violated based on modelled concentrations performed with the simple Nordic Street Pollution Model (BLB).

The outdoor air pollution levels influence the indoor levels. However, the presence of indoor source may strongly influence the personal exposure. The indoor microenvironment is important since most people spend more than 90 per cent of their time indoors, see the review by *Larsen et al.* (1997).

Rough health impact assessment

Based on lifetime risk estimates, the present levels in Copenhagen of PAH, benzene and estimated levels of 1,3-butadiene result in 3-6 extra annual cancer cases. However, these estimates are likely to underestimate the actual effects due to combination effects between different carcinogenic compounds and between carcinogenic compounds and particles (Larsen et al. 1997). Since the prevalence of asthma and bronchitis is high many people may be affected during episodes of NO_2, O_3 and particles.

If the dose-response relations of recent American epidemiological studies are transferred to Danish conditions a reduction of present PM_{10} levels in Copenhagen of about 30 per cent (about 10 $\mu g/m^3$) would correspond to a four per cent reduction in the annual mortality i.e. about 500 persons per one million urban citizens. A reduction of 30 per cent has been chosen since it would place Copenhagen at the low end of the range of levels recorded in the American studies. Further reductions may decrease the mortality even more since WHO does not consider a threshold value for particles to exist, see review by *Jensen et al.* (1997). About 0.5-1 per cent excess days lost through sickness in Copenhagen have been suggested (Moseholm 1994).

Although the uncertainty is large on the above rough quantification of the health impact, the figures suggest that the health impact of air pollution exposures may be at the magnitude of traffic accidents (about 500 annual deaths).

1.3 The Needs of Exposure Assessment

Human Exposure assessment involves a description of the population exposed, to what pollutants, and the magnitude and duration of the exposures. Exposure assessment is basically applied in air pollution epidemiology that has a scientific purpose, and in health risk assessment and management that have both scientific and regulatory purposes.

1.3.1 Exposure Assessment in Air Pollution Epidemiology

Air pollution epidemiology

The study of health effects of air pollution is strongly linked to air pollution epidemiology which requires estimation of human exposures. Air pollution epidemiology studies the human health effects of air pollution by epidemiological methods, that is, the relationship between the distribution of disease in the population and determinants. In air pollution epidemiological studies, hypotheses concerning the relationships between air pollution and health endpoints are investigated and dose-response relationships are established (Williams 1991).

Different exposure assessment methods

The health endpoints in air pollution epidemiology have often been better characterised than the exposures leading to difficulties when the correlation between health endpoints and exposures is investigated. Different exposure assessment methods have been applied in air pollution epidemiology. Categorical classification (e.g. rural/urban, traffic density etc.) has been used as an exposure indicator, however, this crude method is considered inadequate in current air pollution epidemiology.

The use of fixed monitors is the most common exposure indicator. However, fixed monitor stations are generally poor indicators of personal exposure as they represent a single point in space and obviously they are not able to reflect the variety of personal exposures but they may be able to reflect the general temporal variation in personal exposure. The geographic variation in air pollution levels within a urban area is very high. Levels may be 5-10 times higher in a busy street canyon compared to the backyards, and air pollution levels at a location obviously depend on the traffic levels in the street and the distance to traffic sources. In recent years, personal monitoring using portable measurement equipment and the microenvironment approach (continuous measurements in microenvironment with the person's time-activity pattern) are increasingly applied. These methods are better indicators of personal exposure than using categorical classifications and fixed monitors but due to the measurement costs they are limited to studies of small numbers of subjects (Williams 1991). As indicated above there is a move towards more detailed exposure estimation, and the developed exposure model follows this line by taking a microenvironmental approach to exposure estimation using the residence address as an exposure indicator.

The address as exposure indicator

Two Danish studies - the Childhood Cancer study and the MACBETH Study - have evaluated the relationship between outdoor, indoor and personal exposure. These studies indicate that the outdoor air pollution levels may be taking as a fair indicator of personal exposures useful in epidemiological studies (Raaschou-Nielsen et al. 1996, 1997; Skov et al. 1998).

Dispersion models and exposure assessment

The application of air pollution models in air pollution epidemiology has increased. The Danish Childhood Cancer Project headed by the Danish Cancer Society is an example where the postal address of the children were taken as an indicator of long-term personal exposure. The design is a case-control study of the relationship between long-term exposure to traffic air pollution and development of childhood cancers where the exposures were estimated at the children's home address during their childhood by the National Environmental Research Institute using the OSPM model and inputs generated from a questionnaire. The air pollution levels during 1960-1995 at the front-door of about 20,000 addresses covering almost all municipalities in Denmark were estimated (Raaschou-Nielsen et al. 1996, 1997; Vignati et al. 1997; Jensen 1997b, 1998). The collection of street configuration data and traffic data for the OSPM by means of questionnaires distributed to a large number of municipalities was a demanding task. The final results concerning the association between development of cancer and exposures have not yet been published.

Another example is the Grenland study on short-term health effect of air pollution in an industrial area in Norway in which population data were generated on a crude 1x1 km grid and time-activity data were related to these grids as a rough indicator of short-term personal exposure. The study did not find an association between lung function (measured as Peak Expiratory Flow (PEF)) and air pollution, but showed an association between self-reported symptoms and air pollution. The study also showed that sensitive groups reported health effect symptoms clearly below international and Norwegian air quality guidelines (Clench-Aas et al. 1992).

In a Danish context the Operational Street Pollution Model (OSPM) developed by NERI has also been used to estimate the personal exposure of bus drivers and postmen at selected routes in Copenhagen. Comparison between measurements and predictions of NO_2 showed good correlation. Furthermore, Ames tests indicated increased cancer risk for the bus drivers (Hertel et al. 1996).

The challenge in exposure assessment is to provide the best exposure assessment taking into consideration the epidemiological design. However, air pollution epidemiological studies comprise of different types of designs that pose very different model requirements depending on the number of subjects or groups studied, and the geographic extent and time periods considered. Therefore, it is not possible to develop a unified exposure model that satisfies all these diverse requirements.

Among the different types of epidemiological studies the developed exposure model is of prime interest in analytic epidemiology: cross-sectional, case-control and cohort studies that consider the individual level, as well as, in small-areas studies, that uses e.g. the residence address as exposure indicator and it may be applied anywhere in Denmark provided the input data requirements can be met.

GIS and epidemiology

The integration of GIS and environmental simulation modelling is an expanding area in epidemiological research e.g. *Vine and co-workers* (1997) discuss the capabilities of GIS for use in environmental epidemiological research and give examples of applications.

GIS is a promising tool for exposure modelling because the GIS technology is developing fast becoming more user-friendly and expanding and improving its analytic functionalities. At the same time the digital maps and databases that can be linked to geographic features are developing fast in geographic coverage and data quality, and they will be available for any location in Denmark within a few years. Digital maps and the use of GIS are widespread in the developed countries but few countries have such detailed national administrative databases on population, health etc. as in Denmark. Favourite conditions exist in Denmark for application of GIS and administrative databases in exposure modelling with the address as an exposure indicator and as the link between the digital maps and the administrative databases.

The developed exposure model takes advantage of GIS to generate street configuration data for the OSPM model, to manage, analyse and visualise input and output data, and to link data from administrative databases to digital maps.

The application of the exposure model in air polluiton eqidemiology is further discussed in chapter 7. The potential for further development of the approach into a personal exposure model is also discussed by applying Global Positioning System (GPS) receivers, and microenvironment and activity sensors to collect time-activity data for individuals. Activities to develop a personal exposure model is undertaken under the Danish National Research Programme (SMP) (Poulsen et al. 1997).

1.3.2 Exposure Assessment in Health Risk Assessment and Management

Exposure assessment is an integrated element of health risk assessment and management.

Health risk assessment

Health risk assessment of airborne compounds focuses on how risky the compound is which involves hazard identification, exposure assessment and effects assessment. An exposure assessment is required to be able to quantify the health risk to the population when a hazard has been identified and an effect assessment (exposure/dose-response relations) has been established based on e.g. experimental and epidemiological data. However, the exposure assessment is the “missing link” in this process as few Danish studies have been performed to determine the exposure and dose of different population groups.

Health risk management

Health risk management focuses on what we are willing to accept and what we shall do about it. Risk management is mainly a political process whereas risk assessment is mainly a scientific process (Van Leewen and Hermens 1995).

Exposure models

Various exposure models have been developed in support of health risk assessment and management (e.g. NEM, AirPEx, SHAPE). These exposure models use the microenvironmental approach based on the time weighted-average concept where concentration levels in microenvironments are weighted according to the fraction of time people spent in these microenvironments. *Fugas* (1975) was the first to introduce this concept for exposure modelling in the mid 1970'ties. These models are not designed for air pollution epidemiological studies.

Type of exposure models

Exposure models may be devided into statistical, physical, and physical-stochastic models (Sexton and Ryan 1988). The statistical approach is based on human exposure data and factors likely to determine the exposure. These data are combined in a statistical model e.g. regression analysis or factor analysis. In the physical approach the processes believed to determine the exposure are given a quantitative description. A simple physical model may assume that personal exposure is a function of ambient air pollution. The physical-stochastic approach combines elements of both the physical and statistical approaches. A random or stochastic component is introduced into the mathematical exposure model to account for the stochastic nature of the variables.

NEM

The "American National Air Quality Standards Exposure Model" (NEM) is an example of a physical model that uses a microenvironmental approach where the personal exposure is the product of air pollution concentration in identified microenvironments and the time spent in these microenvironments. The model was designed to estimate the effect of new air quality standards on population exposure (Sexton and Ryan 1988).

AirPEx

A recently developed "Air Pollution Exposure Model" (AirPEx) by the National Institute of Public Health and the Environment in the Netherlands is another example of a physical model based on the microenvironment approach. The model is developed to give realistic exposure and dose estimates to evaluate the effects of these pollutants to public health. The model estimates personal exposure by combining hourly concentration levels in a number of microenvironments based on ambient monitor stations and 24 hour diurnal time-activity patterns recorded for about 5,000 people (Freijer et al. 1997).

SHAPE

Another example is the model "Simulation of Human Air Pollution Exposures" (SHAPE) that uses Monto Carlo simulation techniques to combine data on activity patterns of the population with statistical descriptions of concentrations of pollutants in specific microenvironments (Ott 1985). The SHAPE model also takes a microenvironmental approach to exposure modelling. In Monto Carlo analysis variables or parameters in a model are replaced with probability distributions and samples are randomly taken from this distribution. The result of the exposure estimate may be presented as a frequency distribution or a cumulative frequency distribution function (Moore 1996).

None of the current exposure models mentioned above (NEM, SHAPE, AirPEx) take advantage of administrative databases or GIS.

Danish Exposure Model

At present, there are no Danish exposure models available for population exposure assessment which is required to support health risk assessment and management. Such an exposure model should be able to estimate:

- who and how many are exposed
- where the exposure takes place
- the time duration of exposures
- exposures to critical air pollutants
- the impact of various control measures on exposures in support of management.

An exposure model system may be set up at a national, regional or local scale. Recently, activities have been undertaken by NERI to develop a national exposure model by combining the presented exposure model and a prognostic transport behaviour model to assess population exposure as a consequence of different transport behaviour scenarios (e.g. increase of fuel taxes) (Rich et al. 1997). Since the presented exposure model operates with a very high geographic resolution few representative geographic areas will be selected and findings will be generalised to the national level.

Below the background for a potential application of the presented exposure model at the local scale in the context of urban air quality management by local authorities is given.

Urban Air Quality Management

Present Danish urban air quality management mainly consider air quality monitoring at few locations, and public alert and information systems. Comprehensive emission inventories, mapping of air quality and action plans are almost entirely missing.

Traffic has become the dominant source to air pollution in larger urban areas with severe adverse health effects to the exposed urban population. At the same time, new stricter EU air quality limit values will have to be met by 2005 and 2010 for 13 pollutants, and air quality management is required that encompasses monitoring, assessment (e.g. by modelling), and information to the public. This situation calls for upgrading of urban air quality management.

At present air quality management systems that are able to map air pollution levels and carry out assessment of various control strategies are not applied in major cities in Denmark although such systems are in place in many European cities of comparable sizes. *Fedra* (1997) provides an overview and state-of-art description of the application of GIS and simulation models in integrated risk assessment and risk management. Examples of decision-support systems for local authorities are the Norwegian AirQUIS system, the Swedish EnviMan, and the Austrian AirWare.

AirQUIS

AirQUIS is developed by NILU and established in several large Norwegian cities (e.g. Oslo) and a few cities around the world (Bøhler et al. 1997). AirQUIS considers traffic, industry, household and energy sources and the geographic resolution of AirQUIS is based on grids. For example, contour plots may be presented based on dispersion models for point, area and subgrid line sources. These concentration estimates may be linked to population data to give exposure estimates. However, these population data are not an integrated part of AirQUIS. AirQUIS is the air pollution module of a more comprehensive Environmental Surveillance and Information System called ENSIS (http://www.nilu.no).

EnviMan

The company OPSIS has developed a software designed for air pollution management in cities and regions. EnviMan includes tools for the surveillance and analysis of the air quality as well as tools for forecasting and planning. The software does not include exposure assessment. The system is based on a GIS engine with a user-interface developed by OPSIS. The system is in operation in e.g. Stockholm, Helsingborg and Lund (OPSIS 1998).

AirWare

AirWare is developed by Environmental Software & Services in Austria together with a number of other partners and is another example of a GIS based information and decision-support system for air quality assessment and management. AirWare is designed for major cities and industrial areas (http://www.ess.co.at/AirWare/). AirWare has been implemented in a number of cities around the world e.g. Geneva. The system may produce simple exposure estimates combining population data and air pollution estimates. Population data is gridded (e.g. by hectare) or associated with building block boundaries. The system also includes a traffic model (EMME/2).

However, available air quality decision-support systems like AirQuis, EnviMan and AirWare generally apply simple air quality models, have low spatial resolution that does not fully correspond to the high spatial variation found in urban areas, and they only consider simple exposure assessment if any. Further, they are general purpose systems developed to be marketed in many countries and they obviously don't take advantage of specific Danish condition within GIS data and administrative database.

GIS and traffic planning

Within the last few years the use of GIS is developing in various aspects of traffic planning in Denmark. The Institute of Planning at the Technical University of Denmark is doing research with focus on issues of GIS application in decision-support systems for environmental impact assessment of transport infrastructure, traffic models and accessibility (Nielsen and Rehfeld 1995; Kronbak 1995). A decision-support system developed at the Technical University of Denmark to evaluate the transport economics and environmental impacts of transport infrastructure considers a number of environmental parameters although air quality is not included. One of the parameters is a very simple but also disputable exposure indicator defined as the annual road emission per area multiplied by the number of people in the area. The areas constitute the zones in a traffic model for the Copenhagen area ("Ørestadsmodellen"). Using GIS the decision-support system can visualise the exposure index of the zones on a map (Rehfeld 1997). Further, the consulting company TetraPlan has developed a method for mapping of traffic noise using existing digital maps, a national building and Dwelling Register (BBR), local traffic data and the Nordic Noise Model (Bloch 1997), and the consulting companies TetraPlan and COWI are integrating methods from traffic safety into GIS (Høj and Studstrup 1998). As indicated above the air quality and human exposure have been left out in the development of environmental assessment systems related to traffic in a Danish context.

The application of decision-support tools is an opportunity for improving air quality planning in the largest cities in Denmark. Decision-support systems should encompass the following main elements:

- Air quality monitoring.
- Emission inventories.
- Air quality and exposure mapping.
- Air quality and exposure impact assessment of various traffic control strategies in support of evaluation of action plans.
- Information to the public about past and present air quality levels but also forecasts for next-day levels.

1.4 Exposure Model Criteria and Project Objectives

Exposure model criteria

As described above, exposure assessment is an integrated part of health risk assessment and management at a national, regional and local scale but presently no Danish exposure models exist to support these areas. Furthermore, epidemiological studies are important to study health effects of air pollution and exposure models could benefit air pollution epidemiological studies. Both exposure assessment in health risk assessment and management and in epidemiological studies requires estimation of air pollution levels in space and time and people's contact to these levels to determine exposures. To solve this core problem is the foundation for application in epidemiological studies and in health risk assessment and management. In health risk assessment and management the capability of impact assessment of control measures are also important to consider management issues. Hence, the overall exposure model criteria can be stated in the following way. The model approach should:

- reflect the high spatial and temporal variation of ambient air pollution found especially in urban areas
- be able to estimate past, present and future exposures to health related traffic air pollutants
- characterise the exposed population

- be able to be applied for any location in Denmark
- take advantage of existing air quality models and minimise input data generation by relying on available data sources to the extent possible
- support air pollution epidemiological studies
- support health risk assessment and management e.g. national exposure assessment and local urban air quality management.

Project aims and objectives

Based on the above introduction the overall aims of the project are to contribute to:

- assessment of health effects of traffic air pollution through air pollution epidemiology
- health risk assessment and management at national, regional and local scale.

The project objectives are to:

- develop a human exposure model using GIS, the existing Danish Operational Street Pollution Model (OSPM) and available digital maps and registers (BBR, CPR, CER) together with simple estimates for time-activity patterns. A simple population dynamics model will be established to model the number of people present in a given location during a given time using simple profiles for time spent in the various areas (at home, at work, in transit). Additionally, ratios between indoor and outdoor concentrations will be taken into account. The model considers the address as an exposure indicator
- apply the exposure model to a Danish urban environment as a case study (the Municipality of Middelfart) and demonstrate the model capabilities through examples
- discuss the applicability of the model as a tool in air pollution epidemiology and as a tool for health risk assessment and management illustrated by urban air quality management by local authorities.

The project has concentrated on a number of scientific issues in the development of the exposure model. Firstly, how to model exposures by integrating an existing air quality model and available digital maps, registers and GIS. Secondly, how to generate input data for the OSPM model to be able to estimate air quality levels at any address location. This issue has been addressed by development of various methods: a method to assign traffic to a digital road network, a method to generate the temporal variation of traffic, a method to generate background concentration levels, and a method to generate street configuration data from digital maps and the BBR register also requiring development of a method to geocode buildings. Thirdly, the potentials and limitations of the application of the model has been discussed.

Compared to existing exposure models, the developed exposure model adds a geographic dimension to exposure modelling with a very high spatial resolution as the address is exposure indicator. The use of existing population data from national registers linked to addresses is also a new approach. Finally, the generation of street configuration data for a dispersion model (OSPM) from digital maps and a national register using GIS is also new and to the knowledge of the author it has not been reported in context of air pollution modelling.

1.5 Outline of Thesis

The report falls in three parts: Part I Theoretical Framework, Part II Model Development and part III Model Applications. Part I focuses on the context and theoretical framework relating the exposure model to the DPSIR concept, the risk management process and the source-effect chain. This part also introduces the terminology related to exposure modelling. Part II outlines the methodology of the developed exposure model and describes data collection and evaluation of results. This part also discusses model evaluation, and presents model results from the case study area. Part III discusses the application of the model in context of air pollution epidemiology, and in context of health risk assessment and management illustrated by application as a decision-support system for local authorities in air quality planning. Furthermore, the potentials and limitations of the model are discussed and future research needs are identified. An English-Danish glossary is included in appendices.

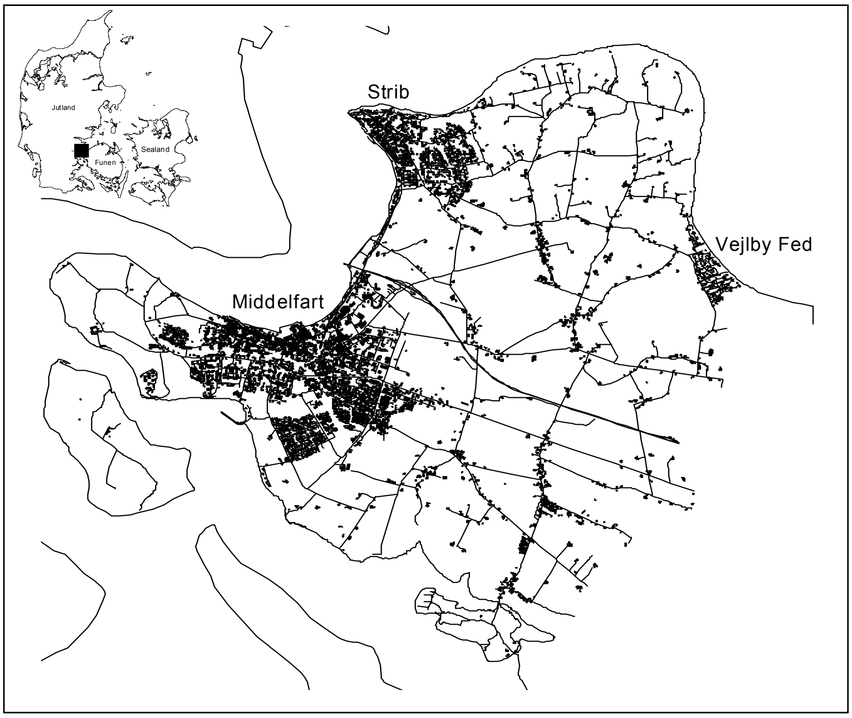

Figure 1.1 The study case area of the Municipality of Middelfart.

2 Theoretical Framework and Definitions

This chapter places the developed exposure model in a theoretical framework by relating exposure assessment to the DPSIR-concept, the health risk assessment and management process, and the source-effect chain. The exposure terminology and related terms are also defined. The framework is related to traffic air pollution, human exposure and health aspects.

2.1 The DPSIR-Concept

The DPSIR-concept was developed by the RIVM in the late 1980'ties and has been adapted by the European Environmental Agency (Jol and Kielland 1997). NERI has also adapted the concept e.g. in research programmes on integrated environmental information systems. The DPSIR is a conceptual model used to describe and analyse environmental problems. *Driving forces* like transport and industry lead to environmental *pressures* that degrade the *state* of the environment that has an *impact* on human health or the environment which makes the society carry out a *response* through various actions. In Figure 2.1 the concept has been illustrated using the case of air pollution with focus on transport.

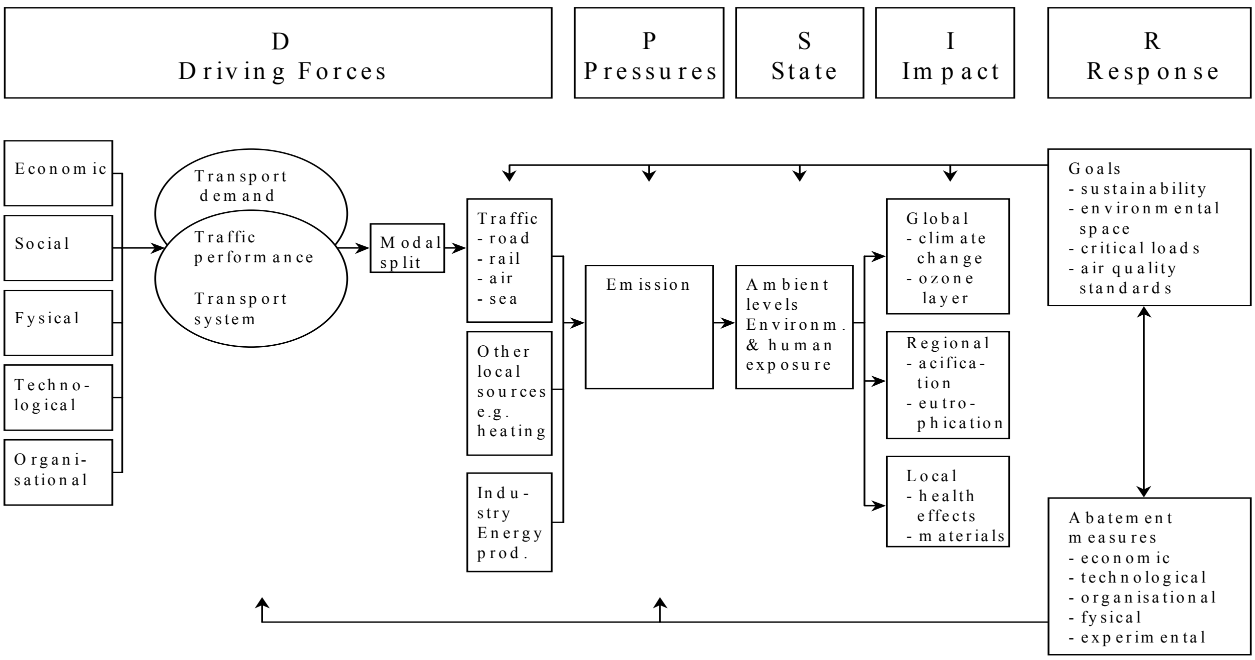

Figure 2.1 The DPSIR concept applied to air pollution with focus on transportation.
(Modification of figure prepared by Henrik Gudmundsson, NERI on transportation and the environment)

The present project focuses on modelling the *state* of human exposure taking into account the pressures from traffic. It is also related to the associated health *impacts*, and the exposure model may be used as a tool for evaluating various abatement *responses*.

2.2 The Risk Assessment and Management Process

Exposure assessment is an integrated part of risk assessment and risk management. *Van Leewen and Hermens* (1995) describe risk assessment and risk management as a eight step process as visualised in Figure 2.2. Compared to the DPSIR concept, risk assessment focuses on *state* and *impact*, and risk management on *response*.

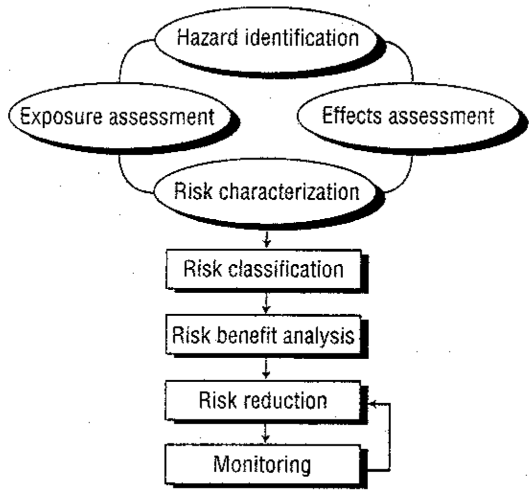

Figure 2.2 Steps in the risk assessment and risk management process from *Van Leewen and Hermens* (1995).

Risk Assessment

Risk assessment focuses on how risky a substance is and includes the first four steps given in Figure 2.2: hazard identification, effects assessment, exposure assessment and risk characterization. Risk is the probability of occurrence of a health effect resulting from a given exposure to a pollutant.

Hazard identification

Hazard identification is the identification of adverse health effects that a substance has an inherent capacity to cause.

Effect assessment

Effect assessment describes the quantitative relationship between exposure or dose to a hazardous substance and the extent of the health effect. Effects assessment involves assessment of dose-response relationships drawn from experimental studies (animal studies and controlled human studies) and epidemiological studies.

Exposure assessment

Exposure assessment is the estimation of the concentrations that the human population is exposured to. It may also include a determination of the dose e.g. as total daily intake (mg per body weight per day). The prediction of exposure concentrations may involve determination of emissions, pathways, transformation and degradation of the pollutant. Exposures may occur via different medias (e.g. air, soil, water) and have different exposure routes (e.g. lung, skin). For most air pollutants the main media of exposure is obviously through the air with the lung as the main exposure route.

Risk characterization

Risk characterization is the estimation of the incidence and severity of the health effects likely to occur in a population due to actual or predicted exposure. Risk characterization integrates the former three steps: hazard identification, effect assessment and exposure assessment. It may include risk estimation i.e. the quantification of the likelihood of health effects.

Threshold values exist

For pollutants that have a threshold value for which exceedances may cause acute effects, the available data are assessed to identify the No Observed Adverse Effect Level (NOAEL) or the Lowest Observed Adverse Effect Level (LOAEL). To estimate the no effect level in a population to protect especially sensitive persons, safety factors are applied to e.g. take into account the need to extrapolate from animal studies to humans, from studies of healthy persons to sensitive persons, and to adjust for the quality and relevance of the data (Danish EPA 1992). The setting of safety factors involves scientific uncertainties, and the level of acceptable safety is essentially a political assessment.

No threshold values

For pollutants where no threshold value is determined, lifetime risk assessment is introduced which involves estimation of the dose-response relationships and determination of tolerable risk levels. The Danish EPA considers a lifetime risk of 10^{-6} for tolerable for carcinogenic substances, that is, an exposure level which for a lifetime of 70 years theoretically causes one extra cancer case annually among one million people, and the "One-Hit Model" is used to estimate this exposure level (Danish EPA 1992).

Risk Management

Risk management is concerned with the actions to reduce risks. It is a decision-making process based on the information from risk assessment but focuses on the political, social, economic and engineering aspects of various regulatory options and responses to reduce a potential health hazard. It includes the four last steps in Figure 2.2: risk classification, risk benefit analysis, risk reduction and monitoring.

Risk classification

Risk classification is the valuation of the risk in order to decide if risk reduction is required. This is a field for policy makers since it is related to acceptability of risks. The acceptability of risk varies in time, place and culture, and for known risks and new risks.

Risk benefit analysis

If the risk classification showed that risk reduction is required the next step is risk benefit analysis that includes an analysis of the benefits of various risk reduction actions. Cost-benefit analysis or cost-effectiveness analysis may be applied. The Auto-Oil Programme initiated by the EU-Commission in co-operation with the European auto and oil industry is an example of the use of cost-effectiveness methods in the risk management process. The Auto-Oil Programme aims at identifying the most cost-effective strategy to comply with future air quality standards by evaluating different mixtures of options among emission standards, fuel quality standards and non-technical measures (Jensen et al. 1997).

Risk Reduction

Risk reduction is taking measures to protect humans against identified risks.

Monitoring

Monitoring is the last step in the risk management process and may serve four functions: (i) a control function that checks if risk reduction leads to compliance with standards, (ii) a signal and alarm function to detect sudden changes e.g. air pollution episodes (iii) a trend recognition function to be able to follow the development in the state of the environment (iv) an instrument function to help analysis underlying physical and chemical processes. The Danish Air Quality Programme and the smog alarm system are designed to serve the four functions of a monitoring system described above (Kemp et al. 1997).

Quality standards

Setting of quality standards is a widely applied measure in context of risk management of air pollution and includes criteria, guidelines, objectives and standards. *Criteria* are quality guidelines based on the evaluation of scientific data. An example of proposals for Danish air quality criteria is outlined in *Larsen et al.* (1997). *Guidelines* are limits set to protect human health e.g. the WHO Air Quality Guidelines (WHO 1987). For the control of air pollution from industrial sources the Danish EPA has established emission and concentration contribution guideline values (Danish EPA 1992). *Objectives* may be set to protect human health and the environment. In Denmark, goals have been set for reduction of national emissions for various pollutants in support of protection of human health and the environment and specific goals have also been set for the transport sector (Palmgren et al. 1997). *Standards* may be fixed upper limits of emission, fuel qualities and concentration exposures given by law and which are legally binding.

The Danish air quality standards/limit values applied for a few selected pollutants are under revision as part of the new European Union Air Quality Framework and Daughter Directives (Europe Environment 1997). Apart from health considerations other aspects like political, economical, technical and administrational considerations may play a role in the setting of air quality standards. If a less stringent standard is set it may reflect that sensitive groups in the population will be affected although the standard is not violated. As a consequence of EU directives, Denmark has vehicle emission standards which have led the car industries to equip petrol-powered vehicles with catalysts to comply with standards. Denmark also has standards for content of e.g. benzene in petrol and sulphur in diesel (Palmgren et al. 1997).

2.3 The Source - Effect Chain

Conceptual health risk assessment model

A comprehensive health risk assessment may be considered as a chain of links including: emissions, ambient levels, exposure, dose and effect as illustrated in Figure 2.3. The main factors that influence the five links are also illustrated.

Compared to the DPSIR-concept the source-effect chain focuses on *pressure*, *state* and *impact*, and related to the risk assessment and risk management process it focuses on *exposure assessment* and *effect assessment* in risk assessment.

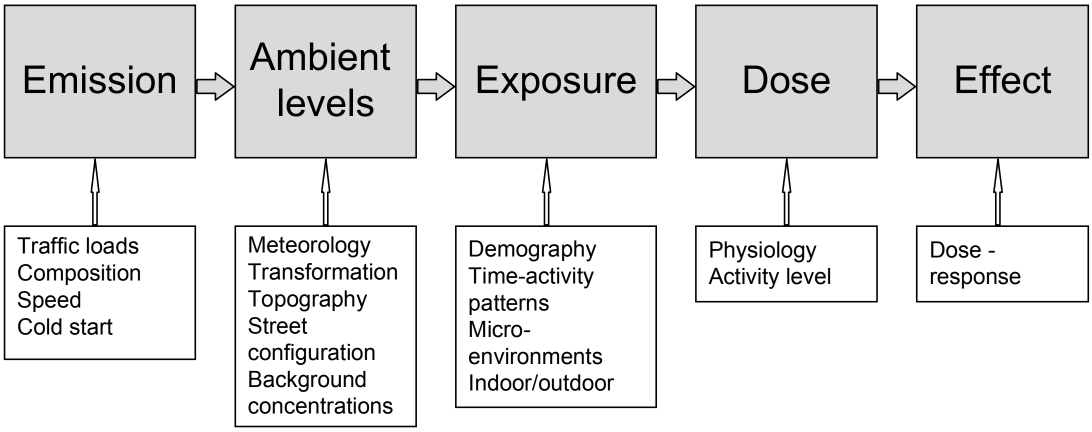

Figure 2.3 The source-effect chain applied to traffic air pollution. Elaboration on conceptual model from *Ott* (1985) and *Hall* (1996).

In a Danish context the processes that determine the first two links: emission and ambient levels have been studied intensively over the years whereas exposure and health effect studies have been limited in numbers. Exposure assessment may be seen as the "missing link" in the source - effect chain (Larsen et al. 1997). A description of the source-effect chain and the factors that influence each link will here be limited to a description of definitions of exposure and related terms since the focus of the present thesis is exposure modelling.

2.4 Definition of Exposure and Related Concepts

In the following the total human exposure concept that emphasises exposures from all exposure routes will be introduced together with definitions of exposure and dose. The related concepts microenvironments, indoor-outdoor ratio, and time-activity patterns used in exposure assessment are also defined. Finally, the different exposure methods will be described.

Exposure Definitions

Total human exposure

Environmental regulation is directed towards control of pollutants in various geophysical carrier medias (e.g. air, water, soil) where monitoring has been carried out. Instead of considering the medias, the total human exposure concept focuses on personal exposures in daily life. "The Total Human Exposure approach considers a three-dimensional bubble around each person and measures the concentrations of all pollutants contacting that bubble through different exposure routes air (lung, skin), water (skin, gut), soil (skin, gut) and food (gut)". These exposure routes: may also be termed inhalation, ingestion, and dermal exposures. The concept has been applied in the American Total Exposure Assessment Methodology (TEAM) field studies (Ott 1990). The present study only considers the air media with the lung as exposure route.

Different terms for exposure and dose

Many diverse and often confusing definitions have been used for exposure and dose. In the following the definitions proposed by *Zartarian et al.* (1997) are applied because they are consistent phased in mathematical terms.

Agent and target

"An exposure agent is defined as a chemical, physical, mineralogical, or biological entity that may cause deleterious effects in a target after contacting the target", and "a target of exposure is a physical, biological, or ecological object". In this case the agents are air pollutants and the targets are human beings.

Exposure

Exposure is in general defined as "contact between an agent and a target" and in human exposure to air pollution it is a person's contact with an air pollutant.

Point exposure

Zartarian and co-workers define the instantaneous point exposure E(x,y,z,t) as the "contact between an agent and a target at a single point in space and at a single instant in time". The contact is the joint event of a target meeting an agent at the same location at the same time:

{Point i of the target is located at (x_i, y_i ,z_i) at time t}

$\cap$

{Agent of concentration C_i is present at location (x_i, y_i, z_i) at time t}

The unit of the instantaneous point exposure is that of concentration C(x_i, y_i, z_i, t) i.e. the amount of agent per volume of medium in the contact zone e.g. with the unit $\mu g/m^3$.

Contact boundary

A contact boundary is defined as "a surface in space containing at least one exposure point on the target of interest". In Figure 2.4 a contact boundary for human exposure to air pollutants is illustrated.

Contact zone

Since concentration measurements are related to a volume in which the agent is contained, a contact zone has been defined as "a volume adjoining a contact boundary in which an agent has a high probability of contacting the contact boundary in the time interval of interest". The contact boundary in Figure 2.4 is a surface over the oral/nasal region and consists in principle of many exposure points where the average could be taken as the person's exposure. Measurements of concentrations in the contact zone close to the contact boundary would provide these exposure points. For practical reasons the air inlet of a personal monitor may be placed in the vicinity of a person's nose assuming that the air pollution concentrations are well-mixed and represent the exposure at the person's oral/nasal region.

Spatially-related exposure definitions

The point exposure may vary from point to point over the contract boundary. The average of all the point exposures in the contact zone is termed the spatially-averaged exposure E_{sa}.

Temporally related exposure definitions

The instantaneous exposure gives the exposure at an instant in time (as short time interval). However, the integrated and average exposure are also of interest.

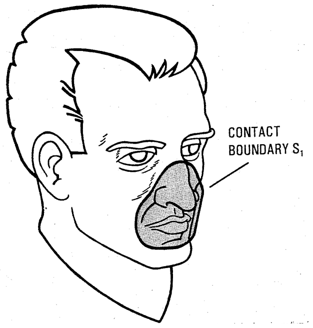

Figure 2.4 An example of the contact boundary for human exposure to an air pollutant from *Zartarian et al.* (1997).

Integrated exposure

The temporally-integrated exposure E_{ti} is the integral of the instantaneous point exposure values over the time period (Eq. 2.1). The unit of the integrated exposure is concentration multiplied by time e.g. $\mu g/m^3 \cdot$hours.

$$E_{ti}(x,y,z) = \int_{t1}^{t2} C(x,y,z,t)dt \qquad (Eq.\ 2.1)$$

Average exposure

The temporally-averaged exposure E_{ta} is E_{ti} divided by the duration of the exposure time period, see Equation (Eq. 2.2). The unit of the average exposure is that of concentration e.g. $\mu g/m^3$.

$$E_{ta}(x,y,z) = \frac{\int_{t1}^{t2} C(x,y,z,t)dt}{t_2 - t_1} \qquad (Eq.\ 2.2)$$

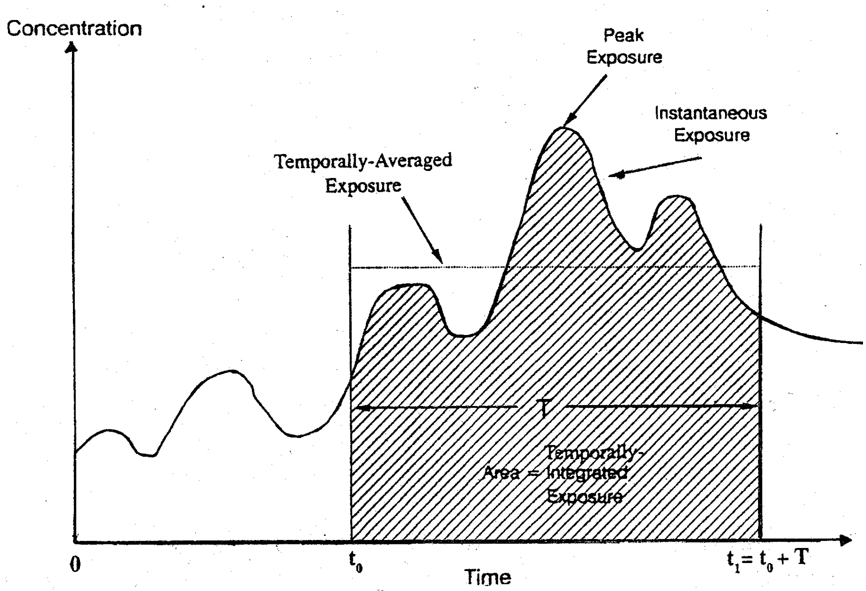

Figure 2.5 A hypothetical exposure time profile that illustrates the instantaneous point exposure, the integrated exposure, the average exposure and the peak exposure (maximum exposure) from *Zartarian et al.* (1997).

Exposure Related Concepts

Dose

Exposure estimation is a requirement for estimation of dose. The dose is defined as "the amount of an agent that enters a target after crossing a contact boundary" (Zartarian et al. (1997)). The unit of dose is e.g. μg.

For airborne pollutants the dose can be estimated by multiplying the exposure (e.g. in μg/litre) by the inhalation rate (e.g. in litre/minute). The inhalation rate is depending on the physiology of the person (depends on age) and the activity level of the person (Larsen et al. 1997).

Microenvironment

During daily activities a human being will pass through various locations with different air pollution concentrations. *Duan* (1981, 1982) termed these locations microenvironments. In a microenvironment the concentrations are assumed to be spatially homogeneous and a person occupies it for a limited period of time. A microenvironment is also characterised by specific types of air pollutants and human. Examples of microenvironments are indoor at home, outdoor at home, at work, in transit in a car etc.

Time-activity patterns

Microenvironments are used to describe the location of a person in space and the time-activity pattern is used to describe a person's movement between these microenvironments in time and the associated activity level. The time a person spends in each microenvironment may be recorded to estimate exposure. If the physical activity level is recorded, the inhalation rates can be estimated for dose determination (Ackermann-Liebrich et al. 1995). *Freijer et al.* (1997) identified three types of time-activity data applied in exposure modelling:

- standard profiles
- human activity pattern surveys
- simulated activity patterns

The simplest method is to apply standard time profiles assigned to a group of people. This approach is used in the present exposure model. A more accurate but also more resource demanding method is to carry out surveys to generate time-activity data for individuals, collected e.g. by questionnaires and diaries. The time-activity profiles may also be simulated e.g. the SHAPE model.

Indoor-outdoor ratio

If human exposure determination is based on the ambient air pollution then the indoor-outdoor ratio (I/O-ratio) becomes important in estimating personal exposure as most people spend the majority of their time indoors. *Yocom* (1982) has identified the factors that influence the I/O relationship:

- Outdoor air quality
- Indoor generation of pollution e.g. indoor sources like gas stoves, building materials, consumer products, tobacco smoking
- Pollution depletion mechanisms in the indoor environment e.g. conversion, deposition and absorption of pollutants
- Meteorological factors e.g. differences in indoor-outdoor temperatures influence the air exchange rate

- Permeability of structures influences the penetration of pollutants from outside into the building (and vice versa), and the dilution of pollutants generated indoors
- Ventilation e.g. the ventilation technology (natural, mechanical) and ventilation behaviour influence air exchange and thus the I/O ratio. The same counts for air-cleaning devices which may be part of ventilation and air-conditioning systems.

Indoor levels are generally lower than outdoor levels except if indoor sources play a significant role. The I/O ratios for different traffic related air pollutants are given in *Larsen et al.* (1997).

2.5 Exposure Assessment Methods

Human exposure may be estimated by different methods. Exposure methods may be classified in direct and indirect approaches (Sexton and Ryan 1988; Williams 1991; Ryan 1991).

Direct methods

Personal monitoring and *biological monitoring* are direct measures. Personal portable samplers are used in personal monitoring to measure the concentrations the person are exposed to. Biological monitoring is also a personal monitoring method where the concentration of a pollutant or the metabolite of a pollutant is determined in bodily material e.g. urine or blood.

Indirect methods

Indirect methods seek to estimate personal exposure by combining concentrations at fixed locations with information about the time people spend in specific environments.

A crude indirect method is the *categorical classification* of the population based on indirect indicators of exposure like the type of residence (e.g. rural, urban and industrial) job classification (occupational exposure), presence of indoor sources e.g. gas stoves, passive smoking etc. This method is considered inadequate for application in air pollution epidemiology (Williams 1991). The use of *fixed location measurements* is a widely applied method to obtain an indicator for population exposure e.g. from the routine ambient air quality monitoring stations.

The Air Quality Monitoring Programmes may be used to estimate population exposure assuming that fixed stations are a good indicator for personal exposure. However, this is a very rough assumption as argued below. In Denmark, there are three types of stations in the Danish Air Quality Monitoring Programmes: street, urban background and rural background stations. Monitoring stations in heavy trafficked street canyons are established to measure worst case conditions for comparison with air quality guidelines. However, from an exposure point of view people spend little time in these microenvironments. These stations are only located in a few cities in Denmark (Copenhagen, Odense and Aalborg) and only in one or few places in each city. Urban background stations are located in the centres of large cities at roof top level (height approx. 20 m, nearby street stations) to determine urban background levels which primarily serve research requirements. The difference between pollution concentrations in streets and in the urban background may be a factor of 2 for NO_2 and a factor of 10 for CO. The concentrations at these stations may be taking as an exposure indicator for persons located in some distance from major roads. Rural background stations are located in remote areas primarily to determine long-range transport of air pollutants to Denmark and deposition to forest, agricultural land, in-land waters and inner seas. Few people live in these areas. Fixed stations represent outdoor levels and most people spend more than 90 per cent of their time indoors. Furthermore, individuals may have very different time-activity patterns e.g. differences in time spent indoor and outdoor, and differences in time spent in different microenvironments e.g. streets, urban centres, suburbs, work environments etc. All in all, the coverage and the representation of the stations in the monitoring programmes are too limited for detailed personal exposure assessment. Therefore, fixed monitor stations are generally poor indicators of personal exposure.

Microenvironmental approach

Another indirect method is the microenvironmental approach where air pollution data in different microenvironments are combined with the time people spend in these microenvironments.

Using the microenvironmental approach the integrated exposure of an individual can be calculated as:

$$E_i = \sum_{j}^{J} c_{ij} * t_{ij} \qquad (Eq.\ 2.3)$$

where E_i is the integrated exposure of an individual i who visits J different microenvironments with the average concentration C_j in microenvironment j during the time period t_{ij}. (Williams 1991) (Duan 1982). The unit of integrated exposure is e.g. $\mu g/m^3 \cdot$hours.

Similar to Equation 2.2 the average exposure of an individual i can be calculated by dividing E_i with the total time spent in the J microenvironments. The average exposure is the same as the time-weighted concentration.

Exposure models like NEM, AirPEX and SHAPE are based on an indirect exposure method using a microenvironmental approach. The models combine air quality data in selected microenvironments with the time-activity patterns of individuals that describe how long time individuals spend in these microenvironments. The presented exposure model is also based on a microenvironmental approach.

The author has further discussed the potentials and limitations of the different exposure methods in *Larsen et al.* (1997). A visual interpretation of the different methods are illustrated in Figure 2.6.

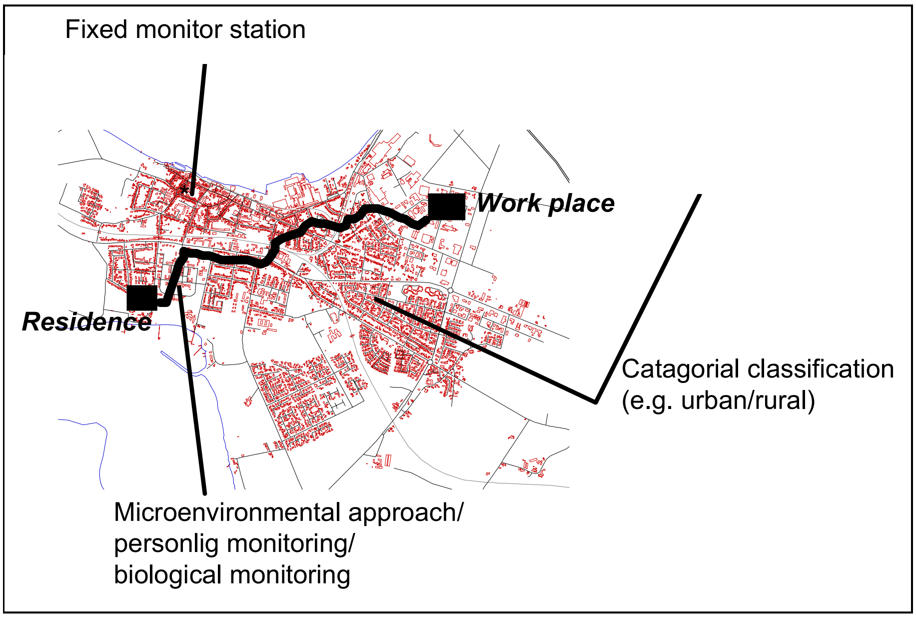

Figure 2.6 Illustration of the different exposure methods.

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Part II

Exposure Model Development

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3 Methodology of the Population Exposure Model

This chapter gives an introduction to environmental modelling and describes the applied exposure modelling methodology.

3.1 Environmental Modelling

Model elements

A model can be defined as "formal expressions in mathematical terms of the essential elements of a problem". An environmental model has five elements in its mathematical formulation: Forcing functions or external variables (input variables), state variables (output variables), mathematical equations to describe processes, parameters, and universal constants (Jørgensen 1991).

The OSPM model

As an example, the forcing functions in the Operational Street Pollution Model (OSPM) are variables like meteorology, traffic emission, street configuration and background concentrations. The state variables are the concentration levels at the receptor point. The chemical and physical processes that determine the state variables are described by equations, parameters and universal constants which link the forcing functions and state variables.

3.2 The Modelling Procedure

Modelling procedure

The modelling procedure is illustrated in Figure 3.1. The modelling procedure is an iterative process where the complexity of the model, the bounding of the problem, and the quality and available data are assessed in relation to the problem to be solved and assessed against repeated model evaluation.

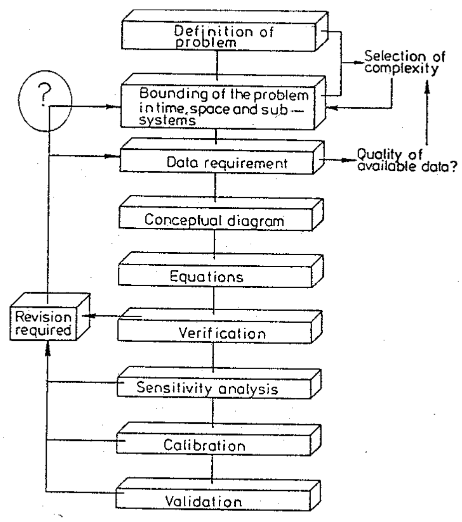


Figure 3.1 Illustration of the modelling procedure from *Jørgensen* (1991).

Definition of problem

The exposure model is developed with the aim to be a tool for health risk assessment and management of health effects of traffic air pollution, and a tool for air pollution epidemiological studies.

Bounding of the problem

The model needs to be able to predict past, present and future exposures. Spatially, the model should be able to predict exposures anywhere in Denmark with a focus on urban environments where the health problems are most severe. The model includes two main subsystems: air pollution modelling and population modelling. These subsystems are further divided into more subsystems.

Selection of complexity and data availability

The selection of the complexity of a model must be determined by the problem to be solved. However, it is constrainted by the quality and availability of data and the knowledge about the involved processes.

Spatial resolution

A static location - the address - has been chosen as the exposure indicator, that is, the air pollution concentrations at the front-door represent human exposures. Although the address may be seen as a very high spatial resolution for an exposure model, it is necessary since the spatial variation in air pollution levels within a city may be a factor of 10 between e.g. street levels and backyard levels.

GIS

GIS was chosen as a tool for exposure modelling since digital maps and administrative databases are available for large parts of Denmark and will be complete for the entire country within a few years. Since GIS originally is developed to handle static geographic data the exposure model is basically a geographic model. ArcView was chosen as the GIS software because it is user-friendly and it is a standard GIS software applied and supported at NERI. The more complex and comprehensive ArcInfo could have been applied but it does not offer crucial benefits compared to ArcView. Further, ArcInfo would in most cases be a too complex system for use in risk management for e.g. local authorities.

Case study

The Municipality of Middelfart on the Danish island Funen has been chosen as the case study area due to easy availability of traffic and digital map data, and since a small municipality of about 19,000 inhabitants is sufficient for development and testing of the methodology although air pollution levels are relatively low.

Air quality predictions

The OSPM model has been applied for prediction of the air quality at the address level. The model has been chosen because it has been developed by NERI, because generation of inputs are manageable, and because it computes one hour time-series suitable for exposure assessment. Apart from meteorological inputs, the model requires detailed inputs concerning: traffic, street configuration and background concentrations. For each of these subsystems methods have been developed to satisfy input requirements. The OSPM model predicts ambient air pollution levels and it does not take into account the emission from indoor sources like e.g. gas stoves. To take into account indoor sources would require an indoor model and detailed data that are not readily available. Instead empirical values for the indoor- outdoor relationship are applied assuming no indoor sources. Nor does the exposure model take into account specific point sources e.g. industrial air pollution. However, such sources could be modelled with the OML model (Olsen et al. 1992) developed by NERI but it would require emission data gathered from the specific sources which are not readily available.

Population data

At present, time-activity data for individuals have not been compiled for Danish conditions. Therefore, it has not been possible to estimate personal exposure e.g. following a person's movement in a city and the concentration levels experienced although this approach is a possibility using GIS. Two types of population data are related to the address: residences (CPR) and working places (CER). These data make it possible to derive exposures related to individual persons at the residence microenvironment. For the workplace microenvironment exposures can only be related to the total number of people working at the workplace. Based on vehicle occupancy data for the different vehicle categories, the total number of persons present in street environments and the associated exposure can be estimated.

Model evaluation

Model evaluation includes verification, sensitivity analysis, calibration and validation. *Verification* is a test of the internal logic of a model to verify that the model behaves as expected. A *sensitivity analysis* is used to investigate how sensitive the results are to changes in the forcing functions and parameters e.g. changes in street configuration data like the width of a street. *Calibration* aims at the best agreement between computed and observed data by adjusting parameters in the model. The OSPM model has been calibrated at the time of development. Calibration of the exposure model is not possible for the time being since observed exposure data are not available for the case study area. *Validation* is a systematic evaluation of the agreement between computed and observed data e.g. by statistical analysis. Model validation is preferably carried out using different observation datasets than those used for the model development. It has not been possible to validate the exposure model as such because exposure measurements have not been available. Evaluation of the model is discussed in further details in chapter 5.

3.3 Exposure Model Methodology

A conceptual diagram of the methodology of the exposure model is presented in Figure 3.2.

Basic approach

For a given geographic location the basic approach is to combine one hour time-series of concentration levels and one hour time-series of persons being present at the same location to predict exposure. The address point is used as an exposure indicator, and air pollution levels are calculated for each house number and all people living or working at the address are assigned the estimated air pollution.

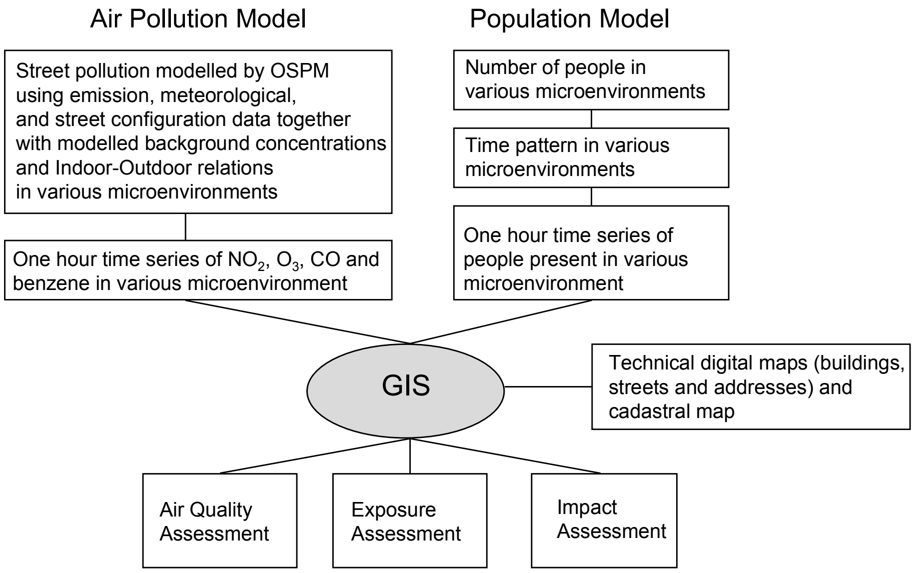


Figure 3.2 A conceptual diagram of the methodology of the exposure model.

Model Applications

The model has three main features: assessment of air quality, exposure and impacts. Air quality assessment is concerned with comparison of predicted levels with air quality guidelines. Exposure assessment deals with where, how long and to what people are exposed. Impact assessment focuses on evaluation of the consequences of "what if" questions. The model may be used for diverse purposes. The application of the model in e.g. air pollution epidemiology and e.g. as a tool for decision-support for local authorities in air quality planning. These application are further discussed in chapter 7 and 8.

Air Pollution Modelling

Receptor point

Calculated concentrations represent ground level since the OSPM model was developed for reproducing levels at the monitor stations (at the facade in the height of 2-3 m). Air pollution levels will decrease from the ground floor to the top floor of a building. At present, no attempt is made to calculate the air pollution levels at the actual floor where people live. Some observations suggest that levels are higher at about 1 m compared to 3 m indicating that children receive a higher exposure than adults (Micallef et al. 1998). Danish observations are not available for assessment of the vertical gradient in a street canyon.

OSPM

The OSPM model calculates hourly concentration levels of: CO, NO_2, NO_x (NO + NO_2), O_3 and benzene. However, concentration levels for any non-reacting pollutants may be calculated if data concerning traffic emission factors and urban background concentrations are obtained.

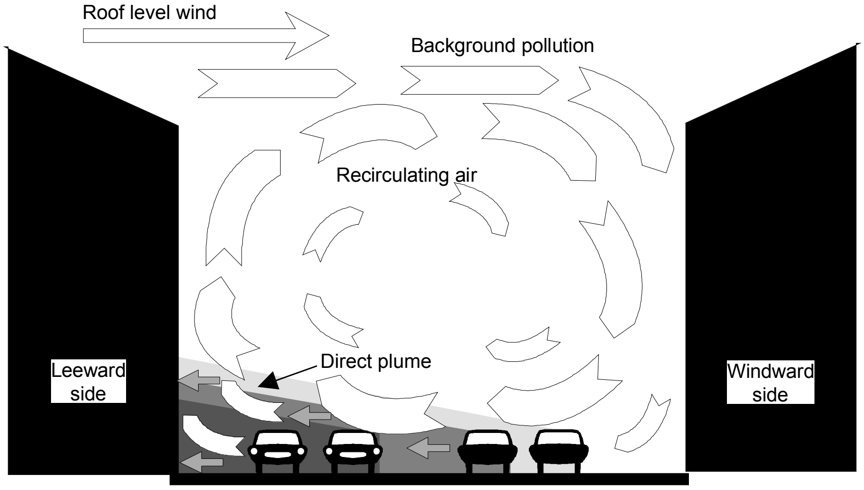


Figure 3.3 Illustration of the recirculation of air in a street canyon with the wind perpendicular to the street orientation. Concentrations are higher at the leeward side than at the windward side.

The model describes the physical and chemical processes governing the concentrations in the street. The model computes levels as the sum of the direct contribution from traffic and the contribution from the recirculating air pollution. The direct contribution is described by a plume dispersion model and the recirculation by a box model that takes into account the exchange with the urban background air. The model also takes into account simple photochemistry between NO, NO_2 and O_3. The model takes into account the street configuration. A description of the OSPM model is given in *Hertel and Berkowicz* (1989a,b,c) and *Berkowicz et al.* (1997a,b) where also validation studies are described. The structure of the OSPM model is illustrated in Figure 3.4 together with new methods developed.

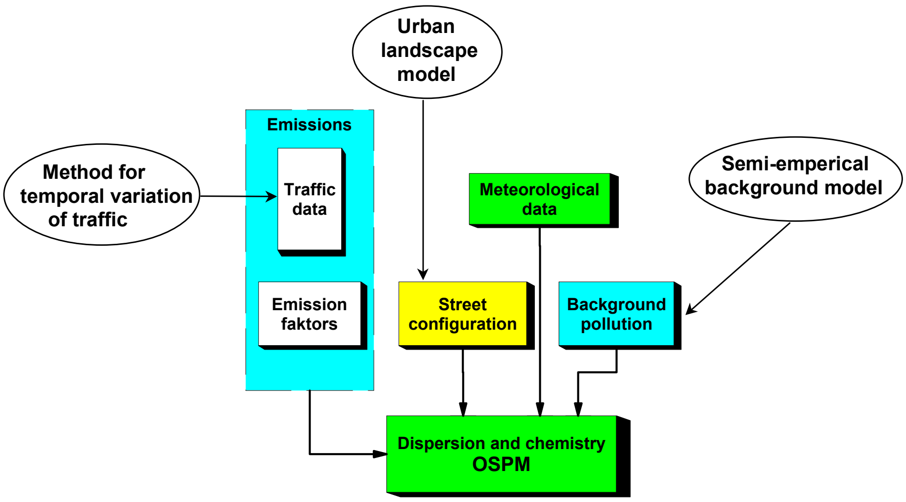


Figure 3.4 Structure of the OSPM model together with the methods developed in the PhD study for generation of inputs illustrated with circles.

Traffic emission

Traffic emissions are estimated from emission factors and traffic data. The OSPM model includes default values for emission factors for each vehicle category. These factors are defined as emission per km travelled depending on the travel speed. Emission factors are drawn from an emission model developed by the Technical University of Denmark (Sorenson and Schramm 1992; Krawack 1991; Jensen 1992, 1995). The emission factors may be substituted by other datasets to represent historic or future conditions. The emission factors applied in the case study correspond to 1996. Petrol-powered passenger cars equipped with catalytic converters are assumed to have emission factors that are one tenth of a non-catalyst car under warm engine conditions. Therefore, the fraction of catalyst cars has to be known. The fraction of catalyst cars is assumed to be 50 per cent in 1996 (Winther, private communication). Since emissions are much higher during cold compared to warm engine conditions, the diurnal variation in cold starts are taken into account as outlined in *Jensen* (1997b).

Traffic data

Traffic data includes Average Daily Traffic (ADT), and the travel speed for the different vehicle categories for each street in the municipality. However, the OSPM requires traffic data on hourly basis, therefore, an empirical method has been developed based on traffic data for selected locations to generate the temporal variation of traffic as standardised monthly, weekly and diurnal variation in traffic loads in order to obtain hourly traffic inputs. Default values for cold starts have also been established empirically. This method is documented in details in a separate NERI report (Jensen 1997b). Additionally, a method was developed to assign the traffic data obtained from the municipality to the digital road network, see chapter 4 for further details.

Background concentrations

The OSPM model also requires hour by hour background concentrations. A semi-empirical background model based on standardised urban and rural background concentrations of NO_2, NO_x, O_3 and CO derived from monitor stations has been developed. Rural background concentrations in any region in Denmark and urban background concentrations for different city sizes are estimated. The procedure is documented in details in a separate NERI report (Jensen 1998). The city of Middelfart has been considered as an urban area and the rest of the municipality as a rural area.

Street configuration

Street configuration data are static data that describe the physical street environment around the receptor point e.g. street orientation, street width, building heights etc. An urban landscape model has been developed using the ArcView 3.0, the associated object-oriented program Avenue, digital maps and BBR data to automatically generate street configuration input parameters required by the OSPM model. The urban landscape model requires geocoding of buildings in order to make use of information in the Building and Dwelling Register (BBR) e.g. for estimation of building heights. The data requirements and method are described in *Hansen et al.* (1997) and in greater details in chapter 4.

Meteorological data

For the case study area of Middelfart, the meteorological parameters are obtained from a meteorological mast at a nearby larger city (Odense).

Outdoor-indoor relationship

To determine the resulting pollution levels indoor empirical indoor/outdoor ratios for the different pollutants have been applied.

Population Modelling

Standard time profiles

The methodology for modelling the presence of persons at different geographic locations is illustrated in Figure 3.5.

Figure 3.5 Illustration of the simple method used to model the time-activity pattern of persons present at either the residence, working place or street microenvironment using standard time profiles for different population groups.

The method is based on simple standard time profiles for the residence, workplace or street microenvironments. At present, Danish data to generate these standard time profiles are not available. However, the principle of using standard time profiles is illustrated through a few examples using Dutch time-activity data. It is possible to account for the contribution from indoor and outdoor exposures when the standard time profile contains information about the person being indoors or outdoors for a specific hour of the day as is the case for the Dutch data.

Residence microenvironment

The number of people who live in the residence microenvironment at a given address has been estimated applying the Central Population Register (CPR). CPR has information on each person in Denmark and the database is used to identify the gender, age and number of people living at their residence address. The presence of persons at the residence address has been estimated applying the standard time profiles for this microenvironment.

Workplace microenvironment

The Central Business Register (CER) is used to estimate the number of people in the workplace microenvironment. CER contains information on all public and private companies. For the workplace microenvironment it is only possible to estimate population exposure for the total number of people working at different workplaces. The presence of persons at the workplace address is estimated by applying the standard time profiles for this microenvironment.

Street microenvironment

The total number of persons present in the street environment can be estimated from hourly traffic levels and vehicle occupancies of the different vehicle categories to predict exposures. These data are available.

Exposure indicators

It is not possible to predict personal exposure by linking the exposures at the workplace microenvironment and the residence microenvironment The model is a geographic exposure model in the since that exposure assessments are related separately to the different microenvironments. The potentials and limitations of the model for estimation of human exposure are discussed in further details in chapter 5 and 6.

Overall Calculation Procedures

In Figure 3.6 an outline of the submodels and data flow in the air quality and exposure calculations are presented.

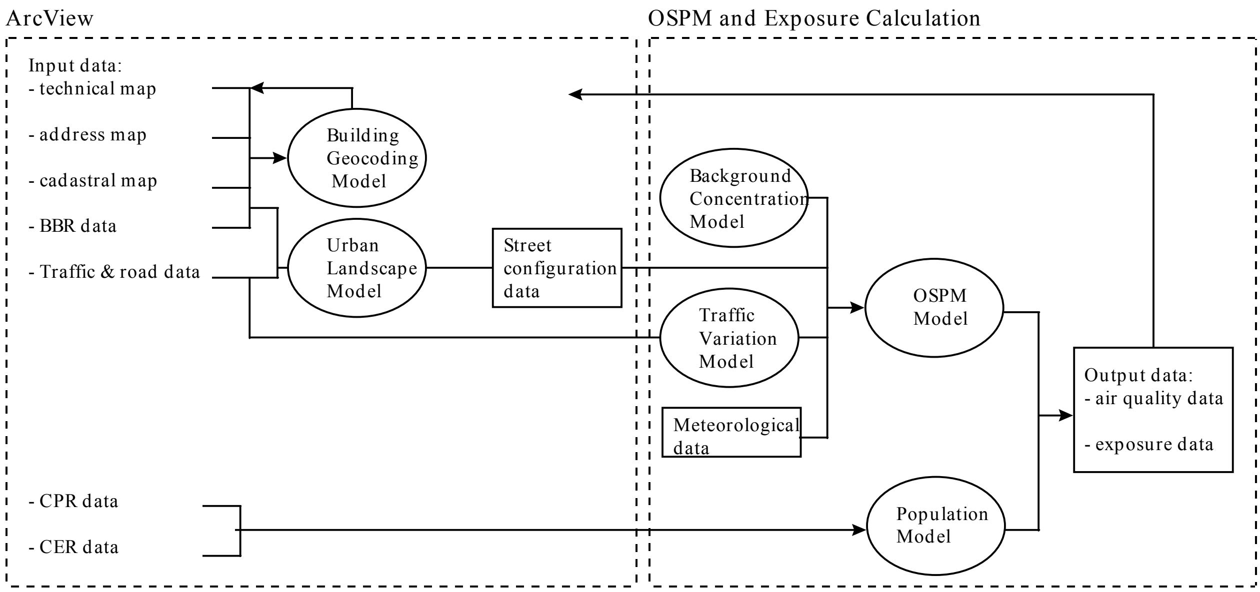


Figure 3.6 llustration of sub-models and data flow for air quality and exposure calculations.

ArcView runs in a PC environment and is used for handling digital maps and georelated data. Two sub-models written in Avenue also runs under ArcView. The Building Geocoding Approach geocodes the buildings and the Urban Landscape Model generates street configuration data. The Urban Landscape Model generates an ascii file with street configuration data for each address. These submodels are described in details in chapter 4. The GUI - the Graphic User Interface - of ArcView has been modified in a way that the submodels run as menu driving in ArcView.

The OSPM model written in FORTRAN runs outside the GIS environment using the street configuration data generated in ArcView, and data generated from the sub-models: the standardised traffic variation model and the background concentration model, together with meteorological data. The latter models are also written in FORTRAN and are pre-processer sub-models. A specific submodel written in FORTRAN and integrated into the OSPM calculations estimates the exposure hour by hour related to each address by combining air quality data with population data. In order to improve the user-friendliness of the exposure model a DLL (Dynamic Link Library) structure will be developed enabling the OSPM calculations to run from inside ArcView.

3.4 Simple Exposure Indices

In the following an outline is given of the calculation procedures. A *simple exposure index* is presented that does not include time profiles and indoor-outdoor ratios, and an *exposure estimate* that includes these variables. Since the exposure does not represent personal exposure but exposures related to geographic locations, the exposure estimates are given for each microenvironment separately.

Simple exposure index

The simple exposure index is defined as the ambient air pollution at a geographic location times the total number of people at the location. The simple exposure index does not take into account indoor-outdoor relationships:

$$E_{index} = C_{address} * P_{address} \qquad (Eq.\ 3.1)$$

where:
E_{index} is the simple exposure index at a geographic location with units of e.g. µg/m³* persons
$C_{address}$ is the ambient air pollution at the "front-door" of the address as a single value e.g. usually as a mean but it may also be stated as a percentile or a max value
$P_{address}$ is the total number of people at the location.

Residence and workplace microenvironment

For the residence microenvironment, *P* is the total number of people who live at the address and for the workplace microenvironment *P* is the total number of people employed at the workplace address. The index assumes that the person spends all his time at the location outdoors.

For the residence and workplace microenvironments the simple exposure index is a population weighted concentration that gives information about the relative differences in exposures at different locations. The index makes it possible to compare exposures within a microenvironment. It is also possible to compare microenvironments of the same nature, in this case, the residence and the workplace microenvironment but not the street microenvironment. Accumulated distribution functions can be calculated for the residence and workplace microenvironment to indicate e.g. the percentage of people exposed to concentration levels beyond a certain threshold value in the residence microenvironment. The index gives additional information compared to just concentration levels at the address. For example, for two addresses that have the same concentration level the address with the highest number of people obviously have the highest exposure index.

However, the index may be misinterpreted as a low concentration and a high number of people can have the same index as a high concentration and a low number of people. If health effects are associated with short-term exposure to high concentrations, the index will be misleading because the relationship between exposure and effect is non-linear as acute effects are experienced beyond certain thresholds. However, for health effects that are associated with long-term exposure e.g. cancer the index may be justified as the risk in the two cases could be the same since the relationship between exposure and effect is assumed to be linear.

The integrated exposure index for a microenvironment is the sum of the exposure indices of all addresses:

$$E_j = \sum_{a}^{A} E_{ja} \qquad (Eq.\ 3.2)$$

where:
E_j: the integrated exposure index of a microenvironment
E_{ja}: the exposure index of address *a* in the *j* microenvironment.

The integrated exposure of the residence and the workplace microenvironments can be compared but caution should be taking in the interpretation of the comparison since the index does not take into account the time spent in the microenvironment. The strength of the simple exposure index is in comparisons between addresses within a microenvironment and not between microenvironments.

Street microenvironment

For the street microenvironment, *P* has another interpretation since *P* are the road-users, that is, the total number of people who passed through the street during an average day and night:

$$E_{street} = C_{street} * P_{street} \qquad (Eq.\ 3.3)$$

where:
C_{street} is the concentration level in a street calculated as the average concentration of levels estimated at the curb side of the street for each address in the street as opposed to the concentration levels at the facade of buildings. C_{street} may be stated as mean, percentile or max values.

$$P_{street} = \sum_{v}^{V} ADT_v * O_v \qquad (Eq.\ 3.4)$$

where:
ADT is the Average Daily Traffic of a vehicle type *v* (vehicle per day)
O_v is the average vehicle occupancy of vehicle type *v* (average number of persons per vehicle during one day and night)
v includes the vehicle types: passenger cars, van, trucks and busses.

E_{index} for the street microenvironment has the units of e.g. µg/m^3* persons/day.

The exposure index adds new information compared to the concentration levels in a street since the number of people that are exposed in the street may be compared with other streets. Consider a situation in which two streets have the same traffic levels and the same concentration levels. The street that carries most bus traffic will have a higher exposure index reflecting that more people pass through this street. Note that the simple exposure index for the street environment reflects an exposure intensity that is independent of the length of the street and the time spent in the street.

3.5 Exposure Estimates Using Standard time Profiles

Residence and workplace microenvironment

Another exposure estimate has been defined that takes into account simple standard time profiles to describe the presence of people at a given geographic location and the concentration outdoors and indoors. The exposure estimate for the residence or the workplace microenvironment is defined as:

$$E_{address} = \sum_{t1}^{t2} C_{address} * \Delta t * (F_{pop,t} * P_{address}) \qquad (Eq.\ 3.5)$$

where:
$E_{address}$ is the integrated time profile exposure estimate with the units of e.g. $\mu g/m^3$*person*hours. The average exposure is $E_{address}$ divided by the residence time $t_2 - t_1$
$C_{address}$ is the concentration either outdoors or indoors during Δ t
$P_{address}$ is defined in equation 3.1
Δt is the time interval considered. In the case of OSPM calculations it is one hour time intervals. t runs from the start t_1 to the end t_2
$F_{pop,t}$ is the fraction of people present in the microenvironment in question during Δ t. People may also be defined as a subgroup e.g. depending on gender or age
F_{pop} times $P_{address}$ is the total number of people present at an address during the time interval Δ t.

The calculation procedure for the time profile exposure estimate is visualised in Figure 3.7.

The time profile exposure estimate is a better indicator of personal exposure than the exposure index since it takes into account the residence time in the microenvironment and the concentrations during that time. However, it is not personal exposure in the sense that the person is followed through the different microenvironments visited during a day. The strength of the time profile exposure estimate is that it takes into account the correlation between the variation in concentrations and the variation in presence. The time profile exposure estimate makes it possible to carry out a reasonable comparison between exposures in the residence and the workplace microenvironments since the time spent in these microenvironments are considered.

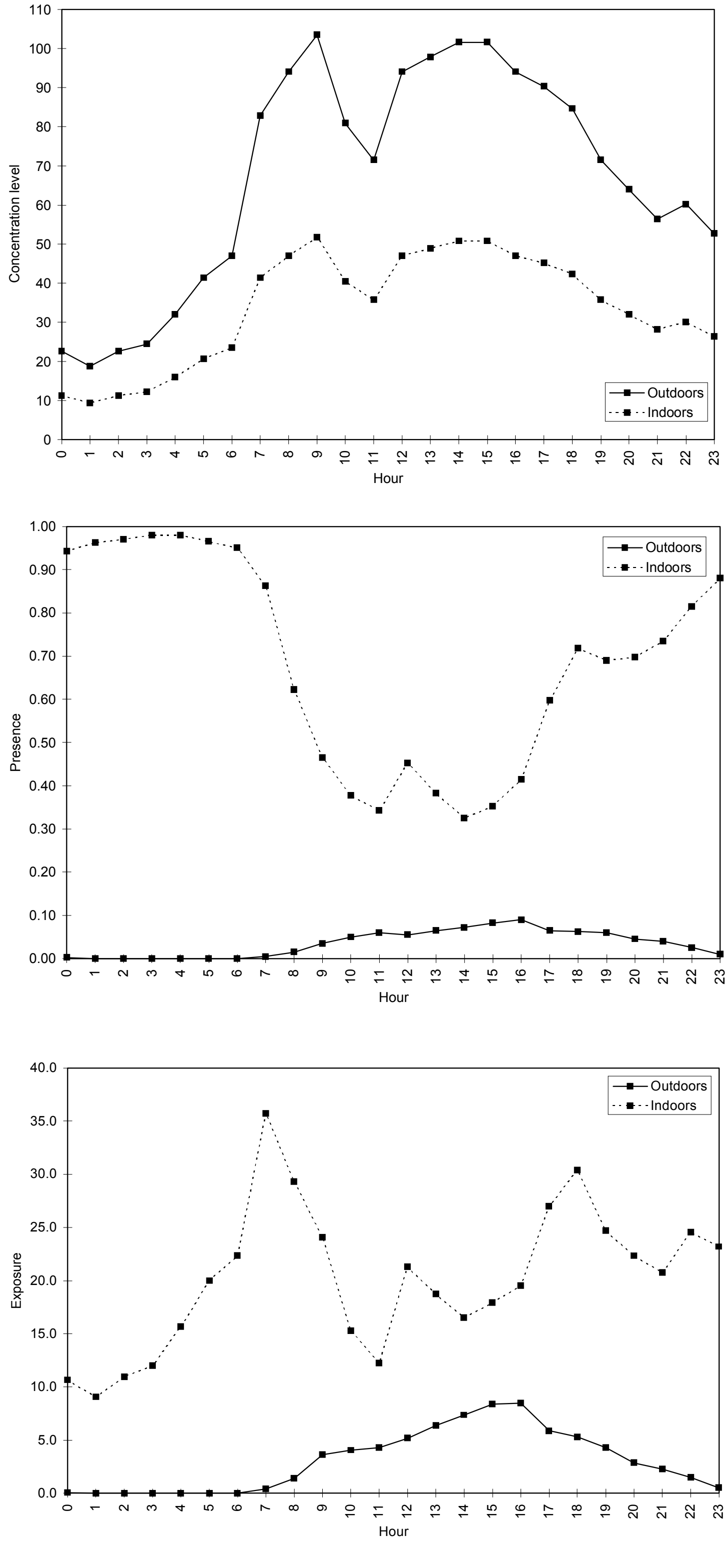


Figure 3.7 Example to illustrate the calculation procedure for exposure estimates using standard time profiles at a given address. *Upper:* The figure gives the hourly diurnal variation in concentrations outdoors and indoors. *Middle:* The number of people present indoors and outdoors at the address estimated as the total number of people living at the address times the fraction of people present either indoors or outdoors. Since the potential number of people at a location is a constant the figure shows the variation in the fraction of people present at the address. *Lower:* The exposure estimate indoors and outdoors on hourly basis calculated as concentration levels times presence of people with the units e.g. $\mu g/m^3$*person. The integrated exposure is the area under the curves with the units of e.g. $\mu g/m^3$*person*hours.

Street microenvironment

For the street microenvironment the time profile exposure estimate is determined by the concentration level in the street and the road users present in the street:

$$E_{street} = \sum_{t1}^{t2}(C_{street} * \Delta t * \sum_{v}^{V}(N_v * O_v * \frac{L}{V_v} * \frac{1}{L})) \qquad (Eq.\ 3.6)$$

Where:
E_{street} is the time profile exposure estimate in a street e.g. µg/m^3* person*hours/km. E_{street} is the average road user exposure in the street.
C_{street} is one hour concentration levels defined as in Eq. 3.3
V_v is the travel speed of vehicle category v
L/V_v is time spent in the street
L is the length of the street
N_v is the traffic level of vehicle category v during the time interval Δ t (vehicles per hour)
O_v is the vehicle occupancy of vehicle category v during the time interval Δ t (persons per vehicle)
1/L: division by L to generate an exposure intensity independent of the street length for comparison of streets with different length.

The time profile exposure allows comparison of different streets taking into account the correlation in time between concentrations and presence of road users in the streets. It is not possible to compare the time profile exposure in the street environment with the residence and work place environments since exposure in a street is not associated to the same individuals but to all the people who pass through the street and only spends a short time in the street.

If information are available on pedestrians and cyclists these road users can be included in both the simple exposure index and the time profile exposure estimate. Limited data are available on the indoor-outdoor relationships for vehicles compared to I/O-ratios for buildings. However, if I/O-ratios are available they can be included in the time profile exposure estimate.

3.6 GIS, Digital Maps and Administrative Registers

The exposure model builds on the integration of available digital maps and administrative registers using GIS. The following will focus on the administrative registers applied in the exposure model.

Definition of GIS and digital maps

A geographic information system (GIS) may be defined as "a computer-based information system that enables capture, modelling, manipulation, retrieval, analysis and presentation of geographically referenced data" (Worboys 1995). A digital map for vector GIS is a map that may include points, polylines and polygons or more complex spatial objects to represent geographic objects. An introduction to GIS and digital maps, and the applied GIS software

ArcView and the associated program Avenue is given in the appendix "GIS and Digital Maps".

Administrative databases and common keys

The authorities manage a number of comprehensive and detailed national databases for administrative purposes. The administrative databases are founded on two important features. All objects are uniquely identified. Therefore, it is possible to combine the data from different databases based on common keys. An example of a common key in the address. The geographic objects and administrative databases used in the exposure model are illustrated in Figure 3.8.

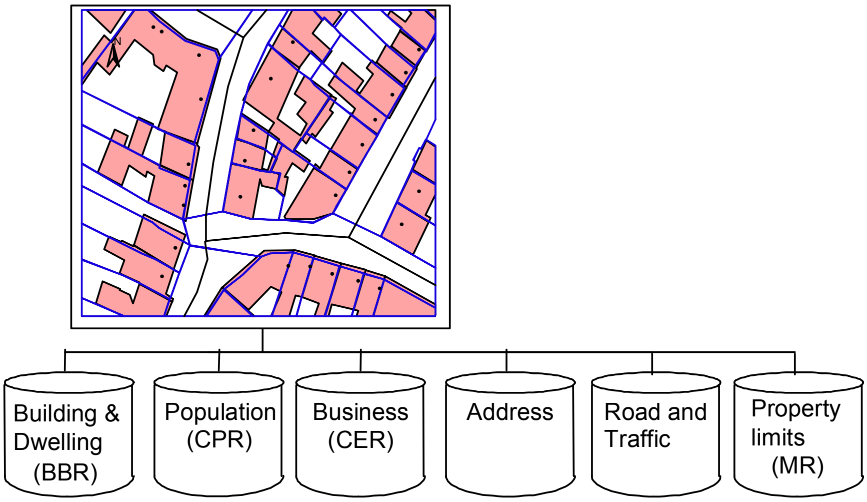


Figure 3.8 Geocoded addresses (points), buildings (polygons), streets (polylines) and property limits (polygons) in the digital map and various administrative databases that can be linked to these geographic objects.

BBR

The Building and Dwelling Register (BBR) managed by the Ministry of Housing contains detailed information on all buildings and residences. Buildings are identified by a property number and a building number. The database is used to estimate the height of buildings required as one of the street configuration parameters of the OSPM model. Data were obtained through the Kommunedata (Data Processing Company for All Danish Municipalities and Counties).

CPR

The Central Population Register (CPR) managed by the Ministry of Home Affairs contains information about each person in Denmark. Each person has a unique CPR identification number. CPR data have been obtained from the Office of CPR and the database is used to identify the gender, age and number of people living at given addresses.

CER

The Ministry of Economic Affairs manages the Central Business Register (CER) which contains information on all public and private companies. The database does not identify the individual employees but gives data in crude categories on the total number of people working at each working place which can be identified by the address. Data from CER was obtained through the Statistics Denmark.

MR

The Ministry of Housing is also in charge of the digital cadastral map and Parcel Register but it is managed by the National Survey and Cadastre Denmark (KMS). Property limits are identified by the cadastral district number and the cadastral number. The cadastral map with property limits is used to geocode buildings, described in further details in chapter 4. Data were obtained from KMS.

KKR

Data in the national administrative databases can be linked based on common keys. These keys are stored in the Cross Reference Register (KRR) and are used for administrative purposes. Common KRR keys exist between BBR, CPR and MR. However, these keys have not been obtained.

Addresses

The Ministry of Housing has started to built up a new register containing the co-ordinates of addresses. The database is managed by the National Survey and Cadastre Denmark (KMS) and preliminary address data were obtained from KMS covering the Municipality of Middelfart. A pilot project for semi-automatic generation of addresses has been carried out for Funen (http://www.kms.dk).

Traffic

Most municipalities maintain a road and traffic database for road maintenance. All roads in the municipality has unique names and have a unique four digit identification code. Traffic and road data have been obtained from the Municipality of Middelfart. Initially, the data were not linked to the digital street network and a method was developed to provide this link, see chapter 4.

Availability

The BBR, CPR and CER do not include digital maps but just the possibility for linking the data to digital maps. The MR database include both property limit maps and attribute information. All databases are national. The address database is expected to provide national coverage within a few years. The database on traffic in Middelfart is a local database and for the time being no national traffic database is available covering all types of roads. A national traffic and road database with a digital road network is available for state and country roads but it only includes major municipal roads (VejNetDk).

Identification

The keys that identify the objects in the various databases and maps are listed in Table 3.1. Keys that are common to two databases can naturally be used to join information. A project specific identification number has been generated for each building polygon as part of the geocoding process.

The Danish data protection agency

Registration of personally related information in databases and merging of these databases are regulated by law. An application to the Danish Data Protection Agency (Registertilsynet) revealed that research projects are not directly regulated by the law other than they have to report to the agency in the case of use of sensitive data. The agency may then impose restrictions on use of data to protect the integrity of individuals etc. The agency did not find age and gender from the CPR to be sensitive personally related information and the project did not have to be registered. However, the Office of Central Population Registration (CPR kontoret) has imposed certain constraints and requirements concerning use, storage, safety etc. of CPR data. These requirements have been met by the current project.

Table 3.1 Keys used to identify objects and to link information between databases.

Identification keys	Definition of the key	BBR	CPR	CER	Map of Property Limits (MR)	Map of Address Points	Map of Buildings	Map of Road Network
Address	RoadCode + HouseNo incl. Letter + Floor + Side	X	X	X				
HouseNo	RoadCode + HouseNo incl. Letter	X	X	X		X		
RoadCode	Four digit road code	X	X	X				X
RoadSegmentId	RoadCode + SegmentId							X
BBRBuildingId	PropertyNo + BBRBuildingNo	X						
CadastralId	Cadastral district No + cadastral No				X			
PropertyId	Property No				X			
ProjectBuildingId	Project generated identification number						X	

4 Collection, Generation and Evaluation of Data

Data have been collected from various sources and processed to generate input data for the exposure model. This chapter describes the collection, generation and evaluation of data for the case study area of the Municipality of Middelfart.

4.1 Cadastres

Purpose

The purpose of the cadastral maps and the Parcel Database (MR) is to identify properties, to protect property rights and to serve as a tax base. As a legal map it differs from the technical digital maps.

Identification

The country is divided into cadastral districts that are subdivided into cadastres that are even further divided into lots. The Municipality of Middelfart includes 20 cadastral districts. Each cadastral district is identified by a unique identification number and each cadastre has a unique identification number termed the cadastral number. The concatenated key: the number of the cadastral district (e.g. 401752) and the cadastral number (e.g. 7ag) gives a unique link to the Parcel Register (MR). A property may consist of several cadastres, and the same property number is associated to each of the cadastres. The first three digits of the property number is the municipal code e.g. 4450033073 where 445 is the municipal code for Middelfart.

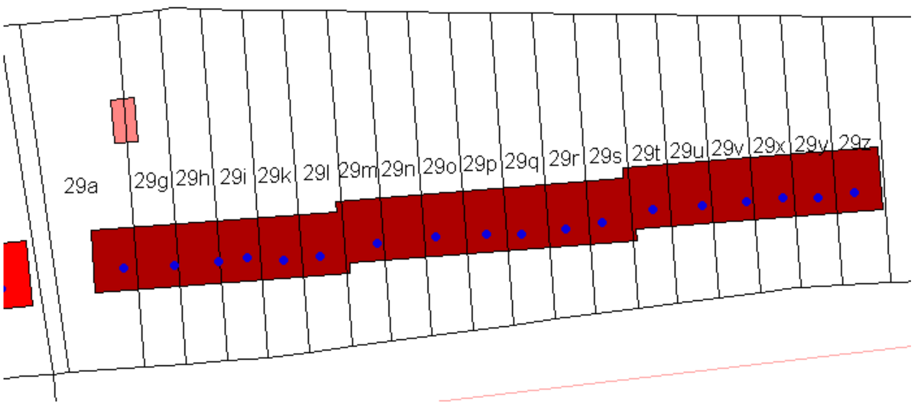


Figure 4.1 Illustration of cadastre polygons with cadastral numbers.

Accuracy

The highest accuracy is about 0.1-0.2 meters in most urban areas. The lowest accuracy is about 5-10 meters in some rural areas (Enemark and Kristensen 1994).

Data collection and evaluation

Data were obtained from the National Survey and Cadastre Denmark (KMS) as 20 ascii-files in DSFL-format with the cadastres defined as polygons. NERI has developed an Avenue program for conversion of DSFL-format to the shape format of ArcView. The programme is only developed for simple DSFL codes like points, polylines and polygons. However, the program was not able to handle cadastre polygons that included other cadastre polygons the so called island polygons which are defined by a certain DSFL code. An island polygon is illustrated in Figure 4.2. The island problem was solved by modifying the DSFL converting program. However, in the mean time the KMS delivered the data in ArcView format ready for use. The data were tested for missing polygons and attribute data and no irregularities were identified.

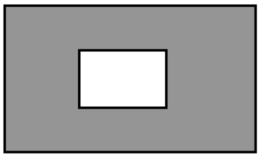


Figure 4.2 An island polygon consists of two polygons: the outer "doughnut" and the "hole".

4.2 Address Data

Identification

Addresses is one of the most important keys to link administrative databases. The address is uniquely defined and includes: municipal code, street code, house number and letter, floor and side e.g. 259-4980-9A-3-right, see Figure 4.3.

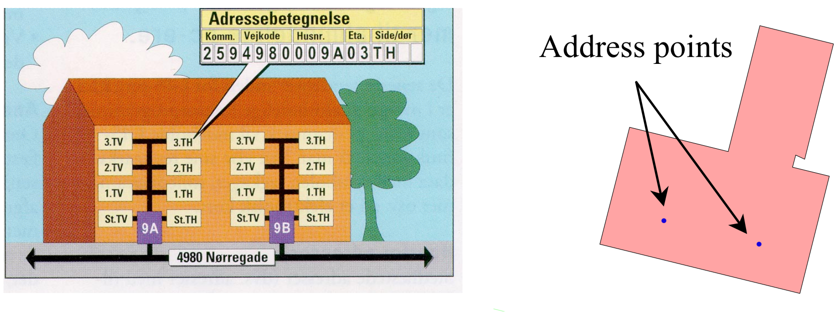


Figure 4.3 The address is uniquely defined in administrative databases and corresponds to the address point in the digital map.

The various national administrative databases have information about the administrative address e.g. CPR, BBR, CER etc. Most technical maps include address points that correspond to the house number and letter in Figure 4.3. The address point is located about 1-2 meters from the front-door inside the building.

Pilot Address Project Funen

However, a national address database that includes co-ordinates is not available at present. A large-scale pilot project was initiated in the Spring of 1996 by the Map Base Funen in co-operation with the Ministry of Housing and the National Survey and Cadastre Denmark with the purpose to bring into agreement the addresses in the administrative databases and the addresses in the technical maps at Funen. Funen has about 200,000 addresses, and the Municipality of

Middelfart is part of Funen. Addresses that are not available in the technical maps are generated automatically based on neighbour addresses, land registers etc. and all addresses will be manually checked and corrected. Most of the municipalities at Funen had completed the registration by the end of 1998 (Kort- og Matrikelstyrelsen 1997). The experience from the project is expected to be used in establishment of a national database.

Data collection

Four address datasets were obtained over a longer period to receive the most updated version. The final version from the National Survey and Cadastre Denmark was obtained in July 1997 but based on data from September 1996. Data were delivered as a comma separated ascii-file. The address dataset is still a preliminary version since some addresses have no co-ordinates and as much as seven per cent have preliminary co-ordinates, see Table 4.1 and Figure 4.3. The Municipality of Middelfart is expected to have all addresses correctly located during 1998 (Knudsen, private communication 1997).

Table 4.1 Type and No. of addresses in the Municipality of Middelfart.

Type of address	No. of addresses	Percentage
No co-ordinates	19	0.02
Preliminary located	661	7.1
Correctly located	8,586	92.7
Total	9,266	100

Figure 4.3 Example of preliminary located address points (marked yellow) where some are located outside the building polygon. Many preliminary located address points are a result of subdivision of the address into a house number with letters (A, B, C, D) as is the case in the presented example.

Address match testing

A match between the address database and the BBR, CPR, and CER databases was carried out to identify the number of addresses that did not have a co-ordinate location in the various databases, see Table 4.2.

Table 4.2 Match Between the Address Database and the BBR, CPR and CER Databases.

Database	No. of addresses in database	No. of addresses with no match	Percentage with no match
BBR	17,120	164	0.96
CPR	19,099	69	0.36
CER	1,463	98	6.7

BBR and CPR

Less than one per cent of the addresses in the BBR and CPR databases were not found in the address database. When the address database is fully developed a nearly 100 per cent match is expected. There should be a 100 per cent match of addresses between the BBR and CPR databases. A reason for unmatched addresses may be that the data have not been delivered for exactly the same date and that the address database has been updated.

CER

Almost seven per cent of the addresses in the CER database were not found in the address database indicating that the addresses in the CER database are of fairly low quality. The CER database is not part of the cross reference database like the CPR and BBR database.

Addresses with no link

The address database included 852 addresses or 9.2 per cent that could not be found in either BBR, CPR or CER. These addresses are removed as they are associated to buildings or areas where no people live or work e.g. plots of unbuilt ground, parks, noise barriers, pump houses etc.

Address points outside building polygons

As shown in Figure 4.4 some address points are located outside the building polygons. However, the geocoding of the buildings and estimation of street configuration parameters require that all address points are located inside the building polygons, therefore, all 360 address points outside the buildings were removed, see Table 4.3.

Table 4.3 Evaluation of Address Points.

Type of address	Number	Percentage
All address points	9,266	100.0
Address points with no match to BBR, CPR or CER	852	9.2
Address points outside building polygons	360	3.9
Address points used for geocoding/ street configuration	8,054	86.9

Address Points and Database Attribute Data

Among the address points used for geocoding, the number of address points with attribute data from the different databases is shown in Table 4.4.

Table 4.4 Number of Address Points with Database Attribute Data.

Type of address	Number	Percentage*
Addresses with BBR attribute data	7,797	97.7
Addresses with CPR attribute data	6,942	86.2
Addresses with CER attribute data	1,055	13.1

* Compared to the 8,054 address points used for geocoding/street configuration.

893 address points out of 8,054 or 11.1 per cent had neither CPR nor CER attribute data. Most of these addresses were summer houses located at the North and East coast of the municipality.

4.3 Buildings

Data collection

The Municipality of Middelfart operates a simple GIS called LIGS that has been developed by GIS-Danmark, a company owned by all the municipalities. LIGS was originally developed for one of the natural gas companies for registration of natural gas pipelines. The system can not handle polygons. A building theme as lines was delivered from the Municipality of Middelfart in the exchange format DWG that ArcView can import. The data can be characterised as spaghetti data since the end and start co-ordinates of two adjacent lines in a building may not have identical co-ordinates. However, it is a requirement for geocoding of the buildings that the buildings are polygons.

Converting lines to polygons

An attempt was made to convert the buildings from lines to polygons. ArcInfo was used for the automatic conversion because it has more in-built features than ArcView. The lines were forced to snap to one another to connect the end and start co-ordinates of two adjacent lines in a building to create a polygon. However, it is not possible to make a 100 per cent correct conversion because of the character of the spaghetti data that causes wrongly shaped buildings to be generated as shown in Figure 4.4.

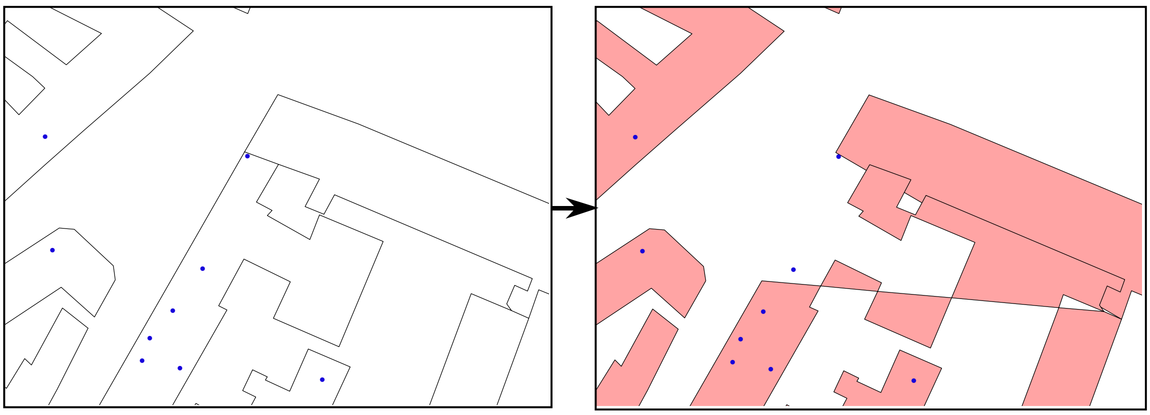


Figure 4.4 An example of converting buildings as lines (left) to polygons by forced snapping that generates wrongly shaped building polygons (right). Address points are also shown.

An attempt was made to manually edit the wrongly shaped polygons using ArcView. Digital ortho photos were also used as background pictures behind the buildings to identify if a strange looking shape of a building was wrong or right. It was soon realised that it would take weeks to edit all wrongly shaped polygons and the approach was therefore abandoned. The original DSFL format for the buildings as lines was obtained from the Map Base Funen. An attempt was made to translate this theme with the DSFL conversion program developed by NERI but wrongly shaped buildings were still encountered as illustrated in Figure 4.4.

Upgraded building polygon theme

The attempts to convert lines to polygons were carried out over a longer period of time. During this time the Map Base Funen had upgraded the building theme from lines to polygons and a building theme defined as polygons was obtained in DSFL format. However, the data included island polygons as illustrated in Figure 4.2, therefore, the DSFL converting program had to be modified to be able to convert the DSFL format to ArcView's shape format.

4.4 Geocoding of Buildings

Geocoding method

A method has been developed to geocode the buildings that makes it possible to link BBR attribute data to individual buildings thereby estimating the building height needed. The building height is required as one of the street configuration inputs to the OSPM model. The geocoding process involves five steps (see the Figures 4.5 to 4.9):

1. Generation of a property theme
2. Forming separate building polygons by intersection of the building theme with the property theme
3. Decompose composite building polygons
4. Slivers removal
5. Geocoding the resulting buildings using the address points.

Generation of a property theme

A new property theme is created from the cadastral theme by merging cadastre polygons with the same property number. In this way 9,755 cadastre polygons were converted into 7,587 property polygons. 451 polygons did not have a property number because they are roads or plots of unbuilt grounds. There are several reasons why it is more efficient to intersect a building theme with a property theme compared to a cadastral theme. A building with only one address point may be located on two cadastres. If the cadastre polygons were used to intersect the building, two building polygons would be generated but the address point could only be associated with one of the building polygons and the other building could not be identified. Using the property theme the building will not be intersected and the address point can be associated with the building polygon. Furthermore, a building that extends over several cadastres but belongs to the same property is likely to have the same height. Therefore it is not necessary to cut the building polygon into smaller building polygons to estimate the height of the building, see Figure 4.5.

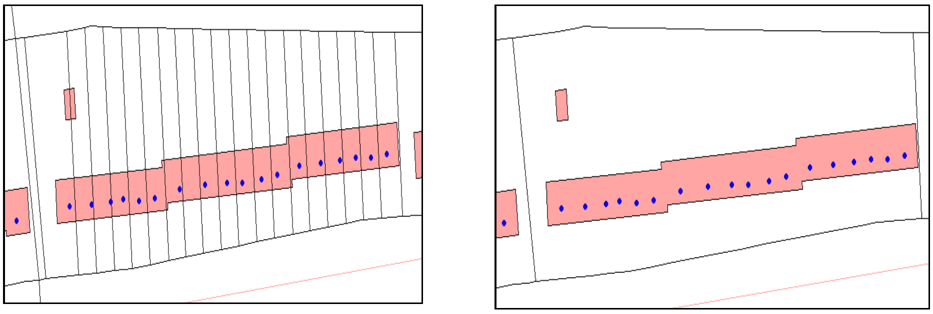


Figure 4.5 The cadastral theme with cadastres (left) is used to generate a property theme (right) defined as one polygon consisting of all the cadastre polygons that have the same property.

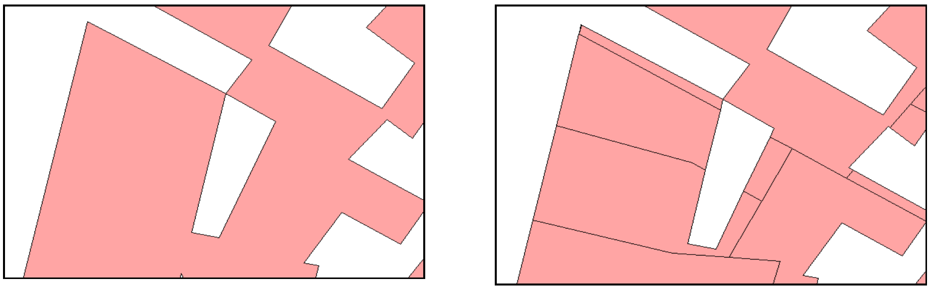


Figure 4.6 The property theme is used to intersect the building theme (left) thereby forming separate building polygons corre-sponding to each property (right).

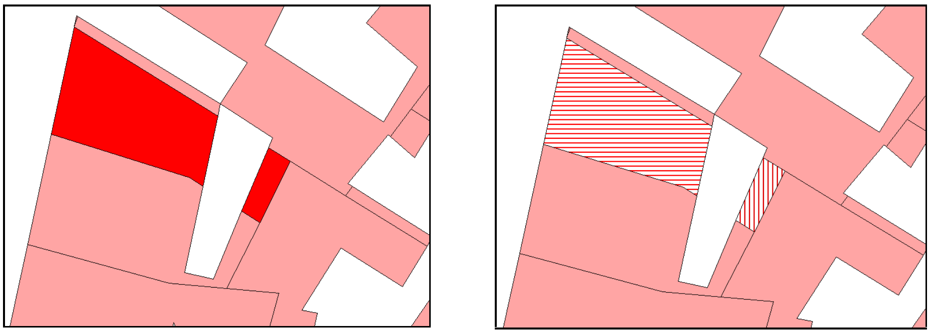


Figure 4.7 The intersect procedure may form a composite polygon (multi-polygon) that is composed of two polygons (left). These composite polygons are identified and simplified into two separate polygons (right).

Figure 4.8 Slivers (marked dark) are formed in the process of intersecting the property theme and the buildings (left). Most slivers are removed by an automatic approach supplemented by manual removal (right).

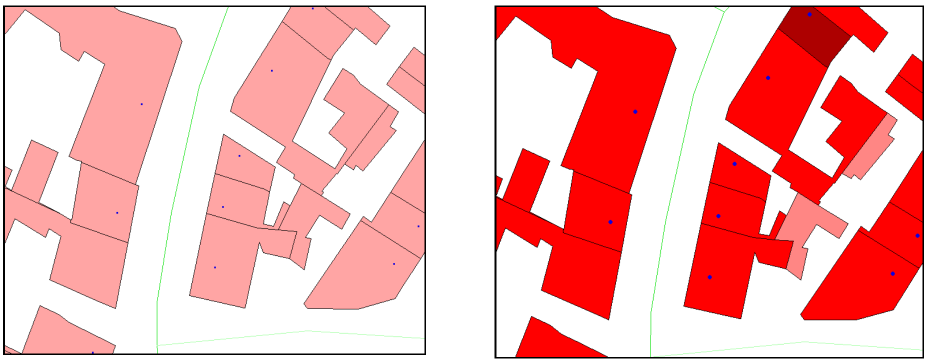


Figure 4.9 The building polygons (left) are geocoded using spatial join with the address points and assuming that all buildings with building number one in the BBR database are the buildings that includes the address points. Building heights can now be visualised (right).

Forming building polygons by intersection

An Avenue program was developed to intersect the building theme using the property theme to cut the buildings into individual building polygons, see Figure 4.6. Based on the original 11,716 buildings polygons this process generated a total of 15,583 polygons.

Decomposing composite building polygons

The process of intersection may create a composite polygon visualised as two polygons (multi-polygon). An Avenue program was developed that decomposes these composite polygons into two separate polygons, see Figure 4.7. This process increased the number of polygons from 15,583 to 15,936 polygons.

Slivers removal

Intersecting one theme with another causes slivers to be generated due to differences in the map production specifications and techniques. The form of a polygon sliver is usually long and narrow, see Figure 4.8. Slivers may be formed because most buildings are digitised based on ortho photos, that is, the building is actually the edge of the roof whereas the cadastre polygon may follow the wall of the building. Slivers are also generated due to inaccuracy in the intersecting themes. Slivers are primary removed, or unioned to adjacent polygons, to enhance the visual presentation of the map. Slivers pose a difficulty because it is not possible to set up an automatic and safe procedure that identifies the slivers and join them to the right building polygon because a sliver may touch several building polygons. Some slivers may be removed without any impact to the OSPM calculations whereas others may have an impact. A method that combines an automatic and a manual approach to removal of slivers was used.

Slivers may be identified in various ways taking into account their special characteristics. The ratio between the circumference and the area, or the square root of the area, may be used, or the ratio defined as the circumference divided by the maximum length of the diagonal. The area may also be used to identify slivers since they are usually small. The first two ratios and the area were used as selection criteria since they are simple to calculate. The best ratio to use for the selection are based on trial and error. 2,349 slivers were automatically removed based on the criteria that the ratio between the circumference and the area was more than 2.5. Another 57 slivers were removed based on the criteria that the area was less than 5 m^2 and that it only touched one other building polygon. Another 94 slivers were removed based on the criteria that the area was less than 25 m^2 and that the ratio between the circumference and the square root of the area was more than 6.5. Further, a selection of slivers were removed manually among slivers identified on the criteria that the area was less than 50 m^2 and that the ratio between the circumference and the square root of the area was more than 6.5. An additional 22 slivers were removed by visual identification. After removal of the identified slivers the building theme included 13,414 polygons.

Geocoding using the address points

So far the buildings only include the property number as an identification key. However, to identify the buildings both the property and building numbers are required. It is possible to link the building *number one* to the building polygon using a combination of spatial and tabular joins between the building and address themes and assuming that all buildings with building *number one* in the BBR database are the buildings that includes the address points. The buildings that include address points are now geocoded and it is possible to identify each building by its property and building number (see Figure 4.10 for definition of building numbers).

Building height estimation

BBR data can be tabular joined to the geocoded buildings. The BBR database does not include the building height. However, the height was estimated based on building characteristics: number of floors (3 m per floor) and type of roof (pitched (2.5 m)/flat (0.5 m)). Miscellaneous small buildings like carports and sheds are assigned a height of 2 meters. The buildings without address points are assigned a height of 4 meters. If a building includes more than one address point the spatial join will just pick one address at random. However, if a building includes several address points it is also likely that the building has the same height.

Evaluation of the geocoding process

In most cases the geocoding process is expected to give reasonable results. In the case that the building *number one* does not include the address point the building may be assigned a wrong building height when linked to e.g. building *number two* in the BBR database. There is also some uncertainty on the estimation of the building height especially for newer tall industrial buildings with only one floor. These buildings are assigned the height of 4 meters. A wrongly estimated building height will influence the predicted air pollution levels. The removal of slivers may in many cases improve the building theme because the roof overhang is removed recalling that the building theme is digitised based on photogrammetry and the cadastral theme is digitised based on mainly field measurements. Slivers removal is only expected to have a minor influence on the predicted air pollution levels because most slivers have a width less than 1 meter.

Alternative approach to geocoding of buildings

The buildings may be geocoded using a more accurate but also a more demanding approach. The GIS is used to calculate the area of the different buildings within a property and these areas are matched to the areas given in the BBR database to identify building number one, two, three etc., see Figure 4.10. It is not possible to make a 100 per cent match because of inaccuracy in the estimation of the areas and problems of identification when areas are the same. Therefore, the approach has to be supplemented by time consuming manual identification of buildings. However, the advantage of the approach is that buildings hopefully are correctly identified and buildings other than building *number one* can be assigned a height based on BBR data.

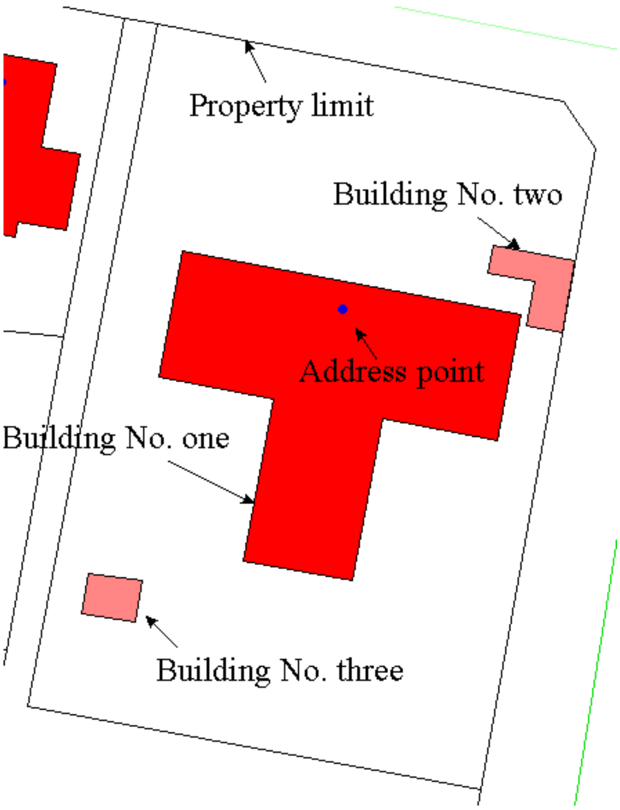


Figure 4.10 An alternative approach to geocode buildings uses GIS to calculate the area of the different buildings within a property and these areas are matched to the areas given in the BBR database to identify building No. one, two, three etc.

4.5 Road and Traffic Data

A coherent geocoded road network with assigned road and traffic data has to be established.

The Road Network

Data collection

A technical map was obtained from the Municipality of Middelfart in DWG format from their LIGS system. The technical map included the road theme among many other themes. However, the roads were not geocoded and it was not possible to identify the individual road by the road code. To acquire geocoded roads the technical map was obtained in DSFL format from the municipality, however, delivered by TetraPlan, a consulting firm that has worked on traffic noise mapping using GIS, and data from the municipality.

Spline problem

Problems were encountered when converting the data to ArcView format using the DSFL converting program because the data included several splines and the program can only convert simple DSFL codes like points and polylines. The shape of a spline is illustrated in Figure 4.11. Instead of developing a program that could handle splines, the splines were simply read as polylines. A visual test between the DWG road network and the DSFL network showed that reading splines as polylines had no detectable impact on the visual appearance of the road network.

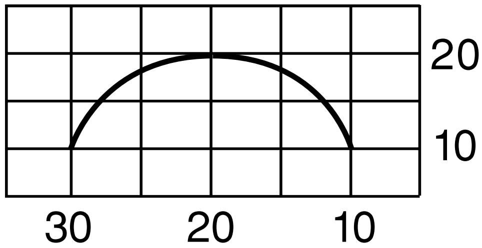


Figure 4.11 Example of the shape of a spline. A spline is mathematically defined by at least three points. From *DSFL* (1995).

However, the road network has less roads compared to the DWG road network. Therefore, an updated DSFL version of the road network was obtained from the Map Base Funen. The version had been upgraded compared to the former version due to a project carried out by Kampsax Geoplan to develop a national route guidance system.

Missing road sections

This version was converted to ArcView format. The road network included a few missing links that were digitised based on ortho photos. ArcInfo was used to clean the network snapping road lines to make a coherent road network.

Segmentation of the road network

Further, the road network was divided into road segments using ArcInfo. Each road is defined by a polyline that can be identified with a four digit road code and each road segment is a road section between two road intersections or between an intersection and the dead end of a road. Segmentation of the road network is required because traffic loads usually differ between intersections.

A simple Avenue script was drawn up to assign road segment numbers for each road code: 1, 2, 3 etc. A road segment is then uniquely defined by its road code and the road segment number, see Figure 4.12. The road network has 373 road codes and 1,907 road segments corresponding to an average of about 5 road segments per road code.

Street names

In order to display street names, a database with road codes and street names was established based on the address database and supplemented with a database from the municipality to name roads with no addresses. A close up of the geocoded road network with street names is shown in Figure 4.13.

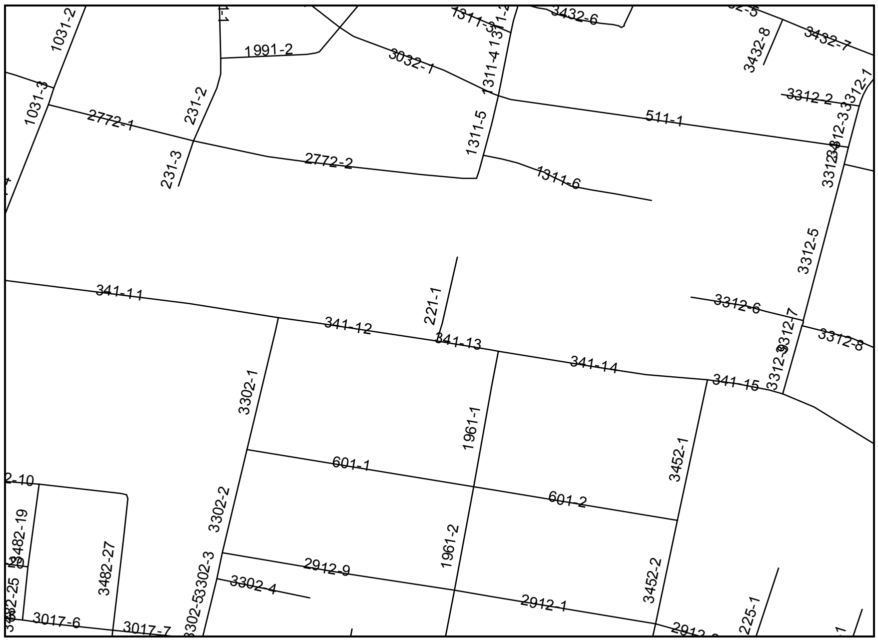


Figure 4.12 Illustration of road codes and road segments in the road network.

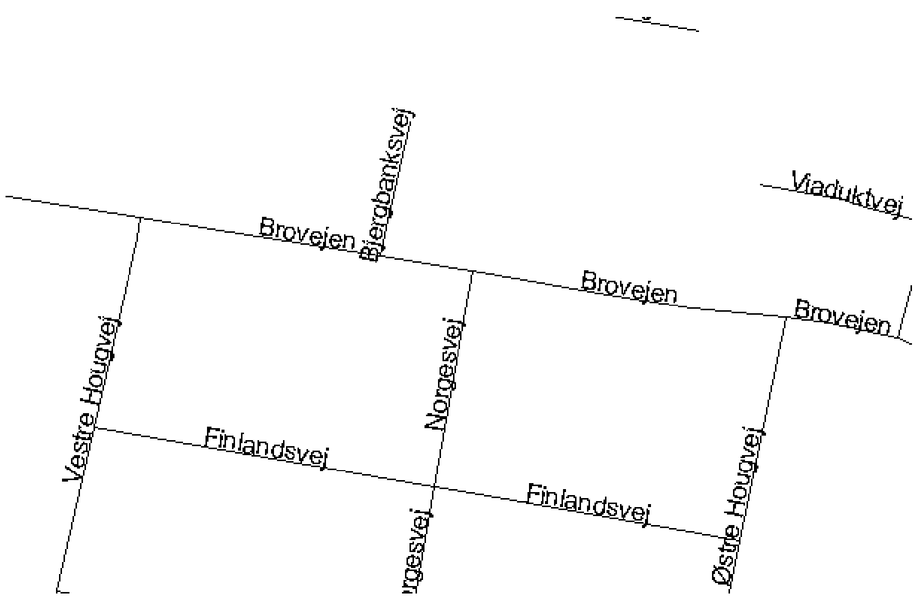


Figure 4.13 The geocoded road network with street names. A street may extend over several street intersections.

Traffic Data

The aim is to assign traffic data to the geocoded road network. However, at present the municipality does not have traffic data linked to the digital road network. Various traffic data sources and approaches were therefore considered.

Vejman

The Municipality of Middelfart operates an administrative road maintenance management system "Vejman". However, traffic is only registered as Average Daily Traffic (ADT) and 10 tonnes axle load equivalent values, and their is no link to the digital road network.

Spreadsheet

The Municipality of Middelfart has carried out a local environment and traffic action plan that included mapping of traffic loads at all traffic roads and major local roads. However, the traffic data were not linked to the digital road network but stored in a spreadsheet organised with traffic loads between two major road intersections. The spreadsheet was obtained from the municipality through the consulting firm TetraPlan that has carried out traffic noise mapping in Middelfart using GIS.

Traffic according to nodes

Traffic data were also obtained from TetraPlan that were organised according to to-from nodes where nodes represent points, see Figure 4.14. TetraPlan has developed a semi-automatic procedure for assigning traffic data from an administrative database (in this case the above mentioned spreadsheet) to a digital road network by simply digitising the road network with to and from nodes according to the way the traffic data is organised in the spreadsheet (Miljøstyrelsen 1996). However, the data did not make it possible to do it the other way around and it was not possible to assign traffic data to the road network as their was no apparent link between the nodes and the lines of the road network.

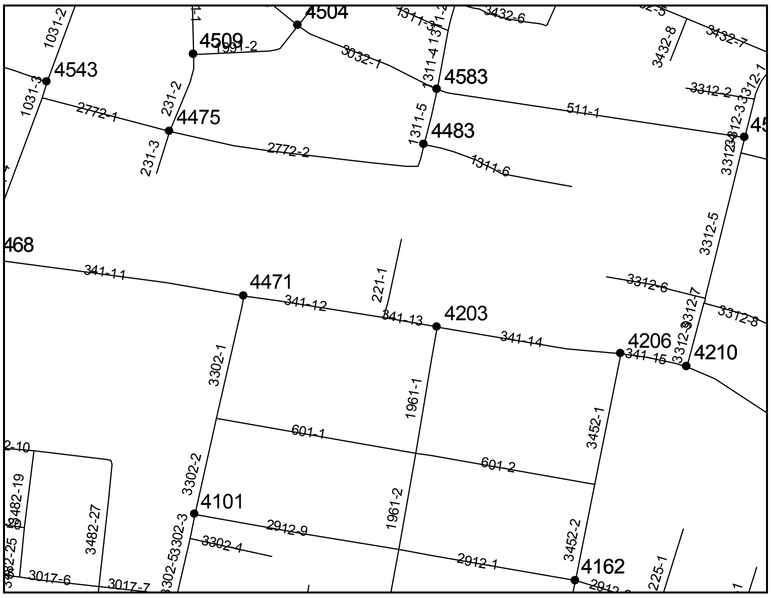


Figure 4.14 To and from nodes are shown as dark points with their identification numbers. Traffic data are given for each par of adjacent nodes. The road network is also shown but their is no apparent link between the to and from nodes and the road network.

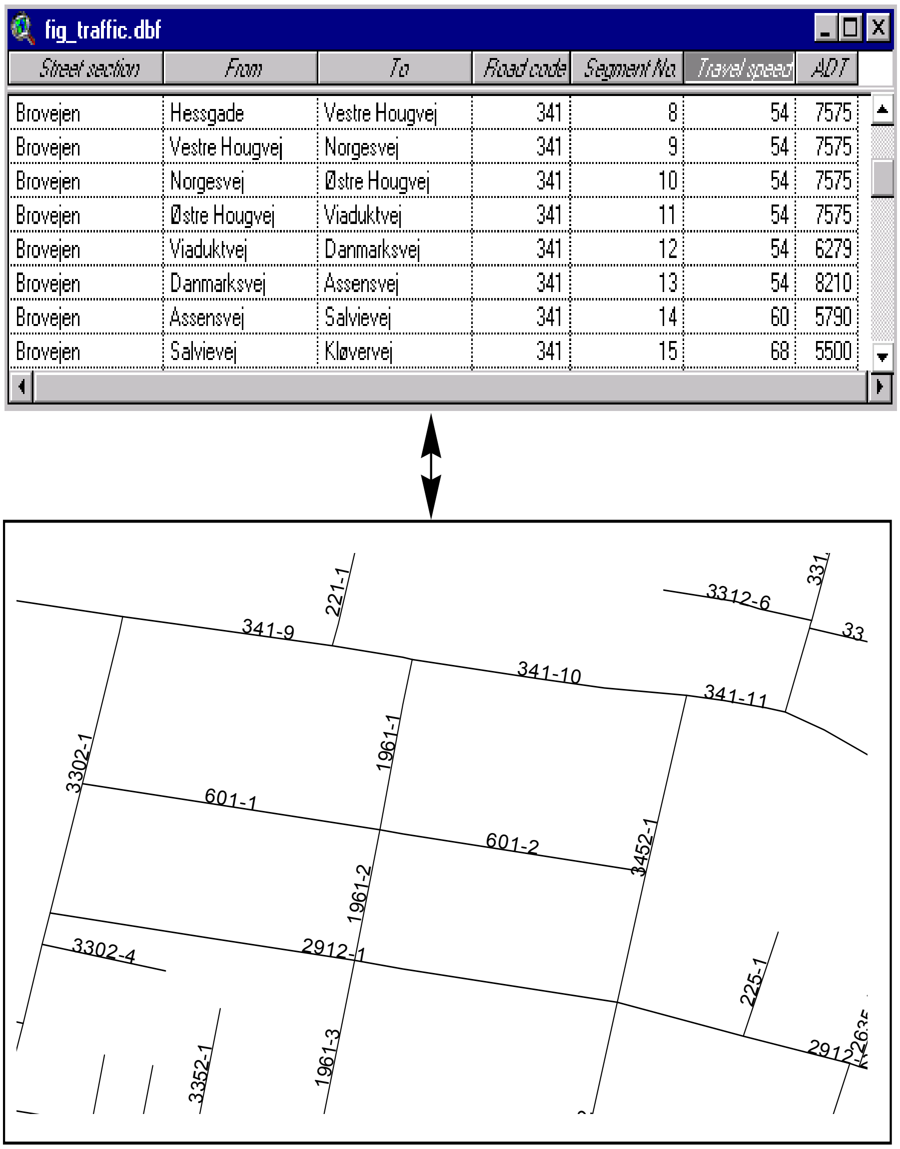
The traffic data could have been assigned to the road network manually but this would have been a very time consuming task, and it would also have been demanding to re-digitise the road network according to the way the spreadsheet was organised.

An alternative approach

An Avenue program could have been developed that generates unique nodes at the dead end of roads and at all road intersections, and that associates the road section between two adjacent nodes to these to and from nodes. Using spatial join techniques, these nodes could have been joined to the nodes generated by TetraPlan, and a link between the digital road network and the traffic data organised by nodes would have been established. However, it is also puzzling to develop such a program.

A simple approach to assign traffic data to the road network

None of the above approaches were applied. Instead, a simple but also a tedious approach was used to assign traffic data to the road network. A road section in the spreadsheet is defined as the road section between two major intersections named as to and from specific roads. These road sections were given unique segment numbers and included a total of only 200 segments compared to 1,907 segments in the digital road network. The digital road network was then manually edited to match exactly the way the spreadsheet was organised, see Figure 4.15. The road network was reduced from 1,907 to 1,613 segments in this process. The traffic data in the spreadsheet could then be joined to the digital road network.


fig_traffic.dbf

Street section	From	To	Road code	Segment No	Travel speed	ADT
Brovejen	Hessgade	Vestre Hougvej	341	8	54	7575
Brovejen	Vestre Hougvej	Norgesvej	341	9	54	7575
Brovejen	Norgesvej	Østre Hougvej	341	10	54	7575
Brovejen	Østre Hougvej	Viaduktvej	341	11	54	7575
Brovejen	Viaduktvej	Danmarksvej	341	12	54	6279
Brovejen	Danmarksvej	Assensvej	341	13	54	8210
Brovejen	Assensvej	Salvievej	341	14	60	5790
Brovejen	Salvievej	Kløvervej	341	15	68	5500

Figure 4.15 The digital road network was edited to match the way the municipal administrative traffic database was organised in order to join traffic data to the road network.

Traffic and road data

The spreadsheet with road and traffic data included the street width, travel speed and Average Daily Traffic (ADT) of the various vehicle categories: passenger cars, vans, lorries and buses. Traffic data were assigned based on best judgement for the major roads that were not assigned traffic data from the spreadsheet. The remaining roads were automatically assigned a low traffic load (50 ADT). ADT of the motorway that passes through the municipality is about 30,000 and ADT of the main roads that pass through the city of Middelfart is in the range of 5,000 - 8,000. In the downtown area of Middelfart ADT is in the range of 1,000 - 4,000. The average distribution of traffic performance (km travelled) according to vehicle categories on the road network was in per cent: 83.2, 3.9, 11.5 and 1.4 for passenger cars, vans, lorries and buses, respectively. Road segments with missing street width were assigned the width 5.5 meters. The length of the road segments were calculated using a GIS feature, and the total length is about 299 km.

4.6 Street Configuration Data

The OSPM model makes use of detailed information about the street configuration. However, to generate these data from analogue maps and field visits for all addresses in a city is a tremendous task.

Urban landscape model

A 2½ dimensional urban landscape model has been developed in Avenue to solve this problem (Hansen et al. 1997). The purpose of the urban landscape interpreter is to automatically generate the street configuration input parameters required by the OSPM model. The street configuration data are static data that only have to be generated once for each address. The output data are stored in an ascii file and sub-sequentlyprocessed by the OSPM model.

Output of the urban landscape model

The urban landscape model outputs the street configuration input parameters required by the OSPM model for each address:

1. the distance from the building facade (receptor point) to the road centre line
2. the height of the building associated to the receptor point
3. the height of the buildings in 12 wind sectors
4. the distance from the road centre line to the buildings in the 12 wind sectors
5. the average height of nearby buildings
6. the width of the carriageway
7. the orientation of the street segment.

Building height and road width

The height of the address building and the road width can easily be obtained as they are attributes to buildings and roads, respectively, whereas the other parameters require geometric calculations. The required street configuration data are illustrated in Figure 4.16.

Figure 4.16 Street configuration parameters generated by the urban landscape model for use in the OSPM model to calculate air pollution levels. The digital map includes building polygons, address points, and polylines to represent the road centre lines.

Receptor point

The receptor point is located 10 cm in front of the facade on a straight line perpendicular to the road centre line and passing through the address point. The line is generated towards the road centre line of the road defined by the address. This line is also called the orthogonal.

Distance from the building facade to the road centre line

The distance from the street kerb side (plus 2 meters) to the building facade (the receptor point) determines the dilution of pollutants and this distance can be calculated from the distance from the receptor to the road centre line given the width of the carriageway. If the building is located nearer than 2 meters to the kerb side the distance from the facade to the road centre line is applied.

Height of and distance to buildings in wind sectors

As previously discussed, the buildings influence the pollution levels in a street. This phenomenon is handled using 12 wind sectors, where each wind sector covers an angle of 30 degrees with a centre point on the road centre line generated as the intersection of the orthogonal and the road centre line. The centre line of the wind sector is used to identify the building and the associated building height of that wind sector. The distance from the centre point on the road centre line to the building in each wind sector is also calculated. If the distance is more than 25 meters it is assumed that the wind sector has no buildings that influence the recirculation of air. In such cases the address is assigned background concentrations.

Average height of nearby buildings

In the OSPM model the wind speed in the street is estimated from the top roof wind speed that is one of the meteorological input parameters. One of the parameters that determines the wind speed in the street is the average height of nearby buildings. A circle defined by the road centre point and a radius of 50 meters are used to select buildings and the average building height is calculated.

Width of the carriageway

The width of the carriageway is not generated from the digital map but is given as an attribute to each road segment. However, the width of the carriageway could be generated from a digital map provided that a kerb theme is available.

Street orientation

The street orientation (0^{o}-180^{o}) is calculated clockwise according to North. The road orientation is determined by the direction of the road centre line nearest to the receptor point. The street orientation represents the tangent line to the line perpendicular to the road centre line. A simple way to derive the orientation of a street segment would be to estimate the orientation based on the starting and ending point of the segment but this is misleading in the case of a curved street segment. Therefore, the polyline of the road segment was split in lines (edges) and the nearest edge was used to determine the street orientation.

Receptor location flag

The location of the receptor point in relation to the road orientation is also determined. This information is important because air pollution levels differ greatly from the leeward to the windward side of the road.

Input requirements of the urban landscape model

The landscape model requires geocoded address points located inside the buildings, geocoded buildings with building height attributes and a geocoded segmented road network.

Methodology for generation of street configuration data

Polylines to lines

For calculation purposes an Avenue program was developed that split up the road segments into lines. A road segment is defined by road code and segment numbers. In ArcView a road segment is represented as a polyline that consists of lines (edges) connecting the points (vertices) that originally were used in digitising the road from an othophoto. The projection of the address point on a road segment requires that the road consists of lines because a polyline may be curved and there is no standard method in Avenue to make a projection of a point on a polyline. Splitting up the road network that consisted of 1,613 road segments created 7,537 lines.

Generation of street configuration data

Another Avenue program was developed that generates the required street configuration data for each address. A conceptual diagram of the calculation procedure is outlined in Figure 4.17.

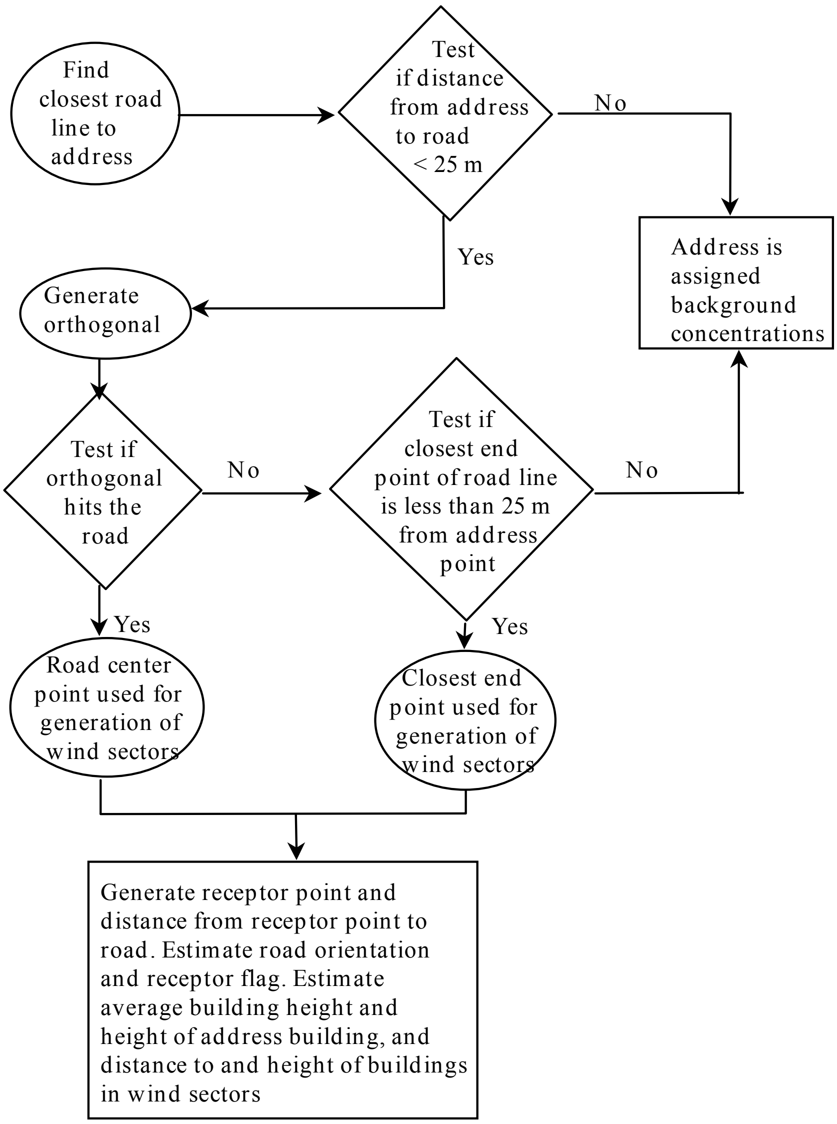


Figure 4.17 Flow diagram of the Avenue program developed to generate street configuration parameters based on geocoded addresses, buildings and line segmented roads.

Evaluation of the urban landscape model

Verification

The urban landscape model was verified by testing if the model produced correct street configuration data for selected addresses.

Testing

The urban landscape model was first tested for addresses from the downtown area of Middelfart and secondly for the entire municipality.

Evaluation

A number of problems were encountered in the evaluation of the urban landscape model either because of data errors or because the model may generate street configuration data that do not fully reflect the complexity of the street configuration from an air pollution point of view.

Road through building

In one case a road passed through a gate in a building, see Figure 4.18. The urban landscape model cannot generate street configuration data for such unusual conditions. The building was split in two building polygons to account for this problem, and using overlay techniques the building and road themes were checked for similar conditions. Another case was identified where a road extended just 2 cm into a building. In this case the road was just shorted a few cm.

Address with no associated road

The address is defined by the road code, and the urban landscape model identifies the nearest road line with the same road code within 25 meters. In five cases the road codes of the address and the road did not match either because the address or the road have been defined incorrectly, see Figure 4.19. In these few cases the addresses were considered as background addresses where street configuration data are not generated.

Orthogonal does not hit road

A basic principle of the urban landscape model is to generate the orthogonal from the address point to the road centre line to identify the centre point on the road used for generation of wind sectors. However, in some cases the orthogonal does not hit the road. These cases particularly occur when the building and the road are far from parallel to one another. In these cases the end point of the road line nearest to the address point is used as the centre point for generation of wind sectors, see Figure 4.20.

Complex street configurations

In many cases the street configuration is complex. However, the urban landscape model generates data by a simple pre-described procedure that may not reflect the street configuration from one air pollution point of view. An example of a complex street configuration is given in Figure 4.21 where the address receives air pollution from two roads but the urban landscape model only considers the nearest road that may not be the most important one. Among others, these problems will arise for the many addresses that are located close to road intersections, and it may have a major impact on the predicted air pollution levels especially in the cases where traffic levels differ significantly between the roads. The urban landscape model may in the future be further improved to consider these complex street configurations and the OSPM model may additionally be modified to consider the emission contributions from two roads to a receptor point. The example also illustrates that under complex street configurations a representative receptor point of the exposed building may be difficult to generate automatically.

Representative receptor point

The example also illustrates that under complex street configurations a representative receptor point of the exposed building may be difficult to generate automatically.

Figure 4.18 A road segment (marked yellow) passes through a gate in a building. A digital ortho photo is shown as a background picture. Street configuration data can not be generated under such tunnel conditions.

Figure 4.19 Example of missing match between the road codes of the address and the adjacent road. The addresses along a road have the road code 461 but the road is defined by the road code 3292.

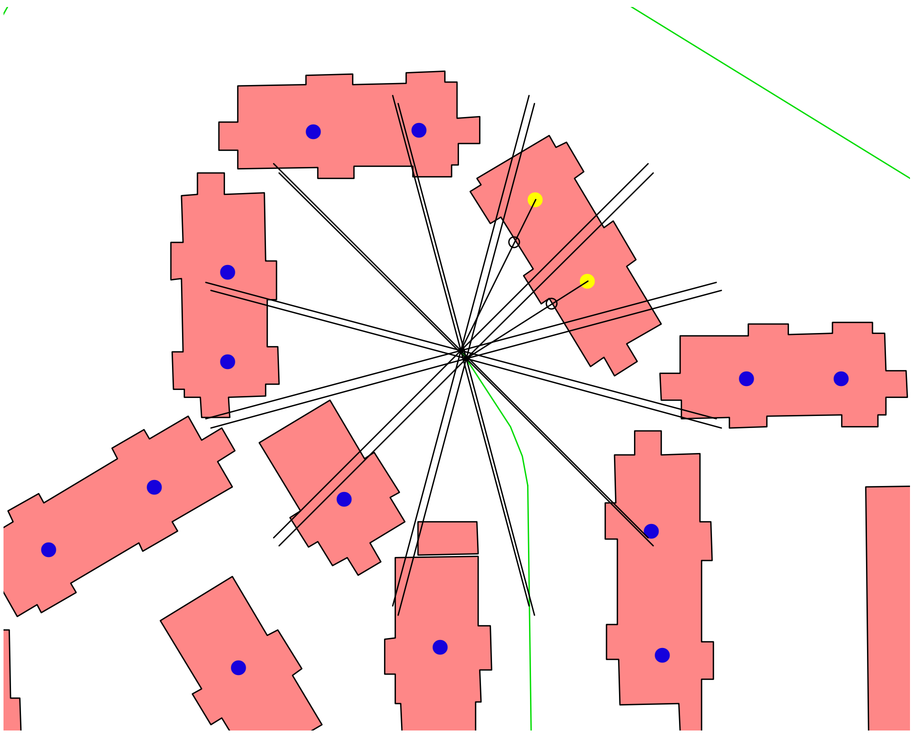


Figure 4.20 Centre lines of wind sectors are visualised for two different address points (marked yellow). The *lower* address is projected perpendicular on the road centre line and the intersection of the orthogonal is the road centre point used as the centre for the wind sectors. For the *upper* address it is not possible to generate an orthogonal and the nearest end point of the road line is used as the centre for the wind sectors. The receptor points are also illustrated as circles located in front of the building facades.

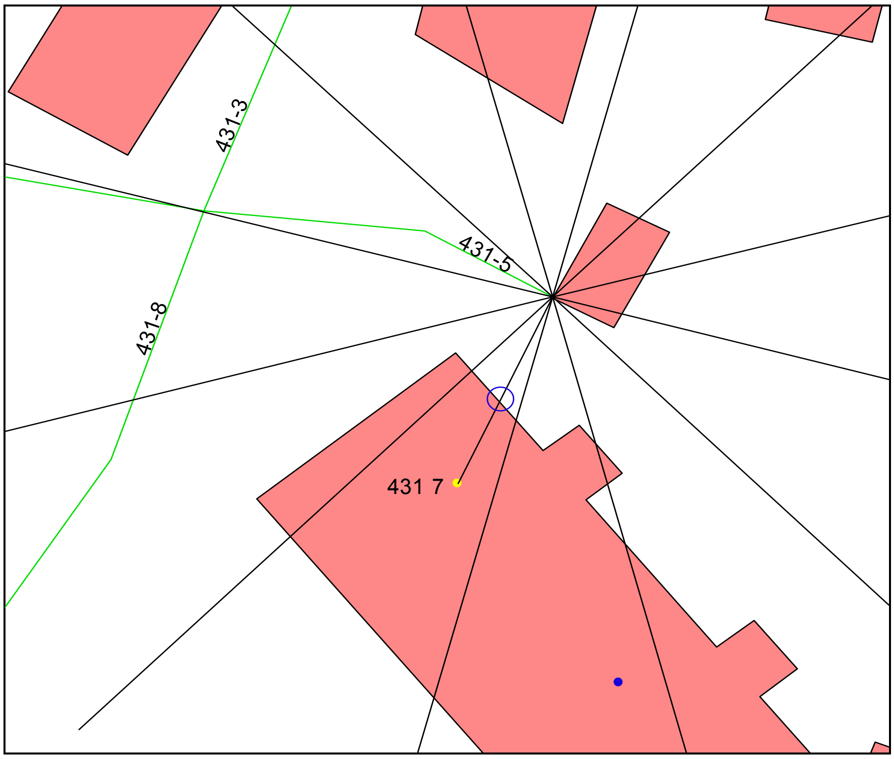


Figure 4.21 An example of a complex street configuration. The urban landscape model chooses the nearest road segment (431-5) for generation of street configuration data (centre lines of wind sectors are visualised), although the address also receives air pollution from another road (431-8).

Background address

In the case that the address is located more than 25 meters from the associated road segment, it is only assigned background concentrations and the direct contribution from street emissions is disregarded. 1,535 addresses or about 19 per cent are estimated to be background addresses, see Figure 4.22.

Figure 4.22 Example of background addresses (marked yellow).

Potential performance

Processing time may be reduced by choosing representative addresses and assign the calculated air pollution levels to nearby addresses e.g. within the same building or street. Addresses that belong to roads with very low traffic could also be assigned background concentrations, thereby, eliminating the need to generate street configuration data. Reprogramming the urban landscape model is a requirement for handling very large datasets like all addresses in the Greater Copenhagen Area (roughly 600,000 addresses). However, the software house of ESRI that has developed ArcView and Avenue has launched a new program language called MapObject that is claimed to be able to speed up calculations by a factor of 100 compared to Avenue. ESRI has also developed a new Spatial Database Engine (SDE) based on client/server technology that is faster in handling large databases. MapObject and SDE are compatible with ArcView (http://www.esri.com). Furthermore, the technological development of PCs have more than doubled their performance every second year, and PCs based on 1,000 MHz processors are within reach in a few years. If processing time with MapObject and SDE could be cut a factor of 100 it would take about 28 hours to process all the addresses of the Greater Copenhagen Area not taking into account further cuts in processing time due to faster PCs or handling fewer representative addresses.

4.7 Meteorological Data

Data collection

Meteorological data from 1996 were downloaded from the monitor database of NERI from the Odense (9159) mast located on a roof top in the downtown area of Odense. Odense has about 145,000 inhabitants and is located in the middle of Funen about 40 km from Middelfart. The meteorological parameters include: wind speed, wind direction, temperature and global radiation. The two latter parameters are used to describe the photochemical reactions between NO, NO_2 and O_3.

Evaluation

It is reasonable to assume that the meteorological parameters are almost the same in Odense and Middelfart considering the relatively short distance between the two cities. Wind speeds may be marginally higher in Middelfart due to a slightly lower urban roughness in a small city with low buildings compared to a larger city with taller buildings, and due to the location along the sea waters of the Little Belt (Lillebælt). All other things equal, marginally higher wind speeds will cause marginally lower concentration levels.

4.8 Indoor-Outdoor Ratios

Data collection

Only few data about the indoor-outdoor ratios (I/O) are available for Danish conditions. Therefore, I/O-ratios are based on empirical values taken from the literature under conditions without indoor sources (Larsen et al. 1997). The I/O-ratio for benzene has been assumed to be similar to CO since they have similar chemical properties.

Table 4.4 Indoor-outdoor Ratios for Selected Pollutants.

Pollutant	I/O-Ratio (no indoor sources)
CO	1.0
Benzene	1.0
NO_2	0.5
O_3	0.2

Data Evaluation

A number of factors determines the indoor concentrations as outlined in chapter 3. It is a crude assumption to apply constant I/O-ratios since these vary in time, for different types of buildings, for ventilation conditions etc. Under conditions without indoor sources, the indoor concentrations are characterised by a time lack and less fluctuation compared to outdoor concentrations.

Indoor sources can have a great impact on the I/O-ratio as discussed in *Larsen et al.* (1997). The BBR database has been considered as a source for determination of the presence of gas stoves but the information is considered to be too unreliable as data originate from the time of construction and they are not updated on a regular basis. Major alterations of a building requires municipal approval but installation of gas stoves or replacement by electric cookers does not.

4.9 Address Based Population Data

For the Municipality of Middelfart, address based population data have been derived from the CPR database for the residence microenvironment and from the CER database for the workplace microenvironment.

The Central Population Register (CPR)

CPR

The CPR database is a national administrative database managed by the Ministry of Home Affairs. The main purpose of the database is to identify persons and it serves numerous administrative purposes e.g. population statistics, taxation, social welfare benefits etc. CPR data were obtained from the Office of CPR as a fixed formatted ascii-file drawn from the database on the 27th of September 1996.

Identification and attributes

Each person has a unique identification number that consists of the birthday and a unique four digit number. The database has a record for each person, and attribute data: name, address, gender, occupation, type of residence, movings to and from municipalities etc. The database is only used to identify the number of people living at their residence address, and their gender and age.

Data evaluation

The database included 19,115 persons which is in good agreement with information provided by Statistics Denmark as per 1st of January 1996 stating 19,042 persons (Statistics Denmark 1996).

16 persons (0.0008 per cent) were excluded from the database since they had no permanent address because they are destitute people or temporary lodgers, leaving 19,099 people.

In order to geocode the buildings only the address points located inside buildings were selected, leaving 8,054 addresses for the entire municipality.

The number of people was reduced from 19,099 to 18,570 or 2.8 per cent in this process but the age and gender distribution changed only marginally, see Table 4.5.

The database is expected to be the most updated and reliable of those databases applied in the present project because the database serves as a key database in public administration. Furthermore, the attribute data applied originates from the unique CPR number. Therefore, the uncertainty on CPR data is expected to be extremely low.

Table 4.5 Number of People in Different Age Groups at Residences. Before and After Exclusion of Address Points Outside Buildings.

	Before exclusion				After exclusion			
Age group	Male (%)	Female (%)	All	All (%)	Male (%)	Femal e (%)	All	All (%)
0-6	4.6	4.2	1,689	8.8	4.6	4.2	1,643	8.9
7-12	3.5	3.3	1,305	6.8	3.5	3.4	1,280	7.0
13-17	2.8	2.9	1,082	5.7	2.9	2.9	1,070	5.8
18-34	11.0	10.5	4,091	21.4	10.8	10.3	3,922	21.1
35-54	15.3	15.3	5,853	30.7	15.3	15.4	5,708	30.6
55-	12.0	14.6	5,079	26.6	12.1	14.6	4,947	26.6
Total	49.2	50.8	19,099	100.0	49.2	50.8	18,570	100.0

Central Business Register (CER)

CER

The Ministry of Economic Affairs manages the national Central Business Database (CER) which contains information on all public and private companies. The database primarily serves statistic and marketing purposes. Data from the CER database was obtained through the Statistics Denmark dating the 19th of September 1996 and delivered as a comma separated ascii-file.

Identification and attributes

Information in the CER database can be identified by the address. Attributes are company or institutional name, type of ownership, detailed information about branch of trade, legal identification number (SE-number), and number of employees in categories etc. The database does not identify the individual employees but gives data on the total number of people working at each workplace which can be identified by the address.

Estimation of number of employees

The number of employees at each workplace address is given in categories based on full-time employees estimated from paid ATP (a supplementary pension for employees). The number of people at a workplace address has been assumed to be the average number of employees in a category including one owner, see Table 4.6.

Data evaluation

According to the CER database, the total number of people working has been estimated to 9,057 or 47.6 per cent of all the people in the Municipality of Middelfart. The same figure is 9,739 or 50.9 per cent according to *Statistiske Efterretninger* (1996) indicating that the total number of employed people is a fair estimate. When excluding the address points located outside buildings the total number of working people that could be identified by the address decreased by 1,148 from 9,057 to 7,909 or about 12.7 per cent, and the distribution between categories changed moderately.

Table 4.6 Estimated Number of People Employed at Work Places.

Category in the CER	Range of employees in the CER	Average estimate incl. owner	No. of employed people	No. of employed people (per cent)	No. of employed people (Excl. addresses outside buildings)	No. of employed people (Excl. addresses outside buildings) (per cent)
B	0	1	847	9.4	571	7.2
C	1	2	410	4.5	328	4.2
D	2 - 4	4	616	6.8	395	5.0
E	5 - 9	8	704	7.8	537	6.8
F	10 - 19	15	1,185	13.1	976	12.3
G	20 - 49	35	1,645	18.1	1,600	20.2
H	50 - 99	75	1,050	11.6	1,170	14.8
I	100 -199	150	450	5.0	457	5.8
J	200 - 499	350	1,400	15.4	1,050	13.3
K	500 - 999	750	750	8.3	825	10.4
L	1000 -	1,250	0	0.0	0	0
Total			9,057	100.0	7,909	100.0

4.10 Time-Activity Data

Limited Danish data

Very limited Danish data are available on time-activity patterns (Larsen et al. 1997). A recent study collected time-activity patterns of children using diaries as part of the Childhood Cancer Project (Raaschou-Nielsen et al. 1997a). Some statistical population data are available concerning the total time spent from a living condition point of view (Andersen 1988) and total time spent on transportation (Trafikministeriet 1992). However, it is not possible to derive the diurnal variation of time spent in various microenvironments for different population groups, nor is it within the scope of the present project to generate such data.

Dutch time-activity data

Instead, Dutch time-activity data were obtained from the RIVM and used for generation of standard time profiles for different age groups for the residence and workplace microenvironment. The Dutch data were collected for the development of the AirPEx exposure model by diaries covering 24 hour diurnal patterns with a time resolution of 15 min. (Freijer et al. 1997). The data are used as an example as differences in time-activity patterns of The Netherlands and Denmark are expected due to differences in climate, lifestyle, occupational pattern etc.

Microenvironments

A copy of a selection made for a Dutch purpose was received that was organised according to seven microenvironments:

1. Indoors at home, in the kitchen
2. Indoors at home, elsewhere
3. Outdoors at home
4. Indoors not at home
5. Outdoors not at home, in the city
6. Outdoors not at home, urban area
7. Outdoors not at home, rural area.

Selection of diurnal time-activity patterns

The data included the average diurnal pattern under different time and subgroup selections. The diurnal pattern was given as the fraction of presence in a microenvironment during the time interval in question. In Table 4.7 the different selections are shown. It is not possible to make combinations from the data e.g. diurnal patterns for males of age 13-17 during Summer weekends.

Table 4.7 Number of People in Different Selections of Dutch Diurnal Time-Activity Patterns.

Type of selection	Number of persons
All	4,216
Females	2,056
Males	2,160
Summer	2,043
Winter	2,173
Working days	2,975
Weekends	1,241
0-6 years	496
7-12 years	434
13-17 years	331
18-34 years	1,076
35-54 years	1,347
55 plus	532

Residence Microenvironment

Diurnal patterns for different age groups

For the residence microenvironment diurnal patterns were generated with one hour time resolution for the various age groups: 0-6, 7-12, 13-17, 18-34, 35-54 and 55 plus. The patterns represent an average day of the week and the age groups represent both females and males. The patterns were divided into indoors at home (microenvironment one and two) and outdoors at home, see Figure 4.23.

Indoors at home

For time spent indoors, the diurnal patterns of the different age groups are moderately different. Generally, almost all people are at home during the night, most people are at home during the evening and less people are at home during normal working hours although lunch time show up for some of the age groups.

Outdoors at home

Generally, the fraction of people being outdoors is relatively small but more evenly distributed over the day and evening compared to the pattern for being indoors. Children and elderly people seem to spend most time outdoors at the residence microenvironment and these groups are generally more sensitive to air pollution exposure than the other age groups. Table 4.8 shows the time spent indoors and outdoors in the residence microenvironment. On average about one hour is spent outdoors of the total time being at home.

Table 4.8 Time spent for an average person in different age groups in the residence microenvironment (hours of one day and night).

	0-6	7-12	13-17	18-34	35-54	55 plus	All working days	All weekends
Indoors	18.7	16.3	15.8	15.4	16.1	18.2	16.1	17.6
Outdoors	0.97	0.88	0.52	0.61	0.84	1.5	0.72	1.2
Total	19.7	17.2	16.3	16.0	17.0	19.8	16.8	18.8

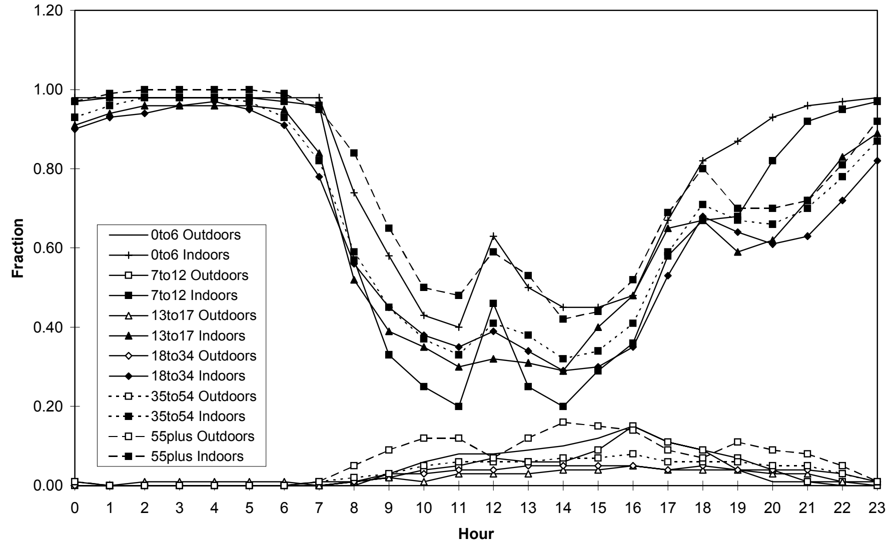


Figure 4.23 Average diurnal patterns for different age groups indoors and outdoors at the home microenvironment.

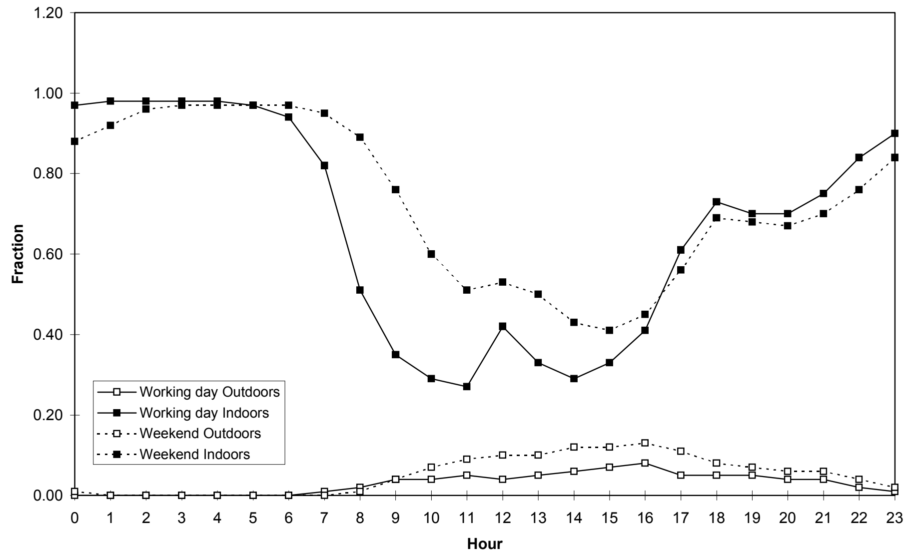


Figure 4.24 Average diurnal patterns for all groups during working days and weekends indoors and outdoors at the residence microenvironment.

Diurnal patterns for working days and weekends

Furthermore, indoor and outdoor diurnal patterns were generated for working days and weekends representing all people, see Figure 4.24.

The fraction of people being indoors and outdoors during the weekend is higher than during the working days and the fraction of people being indoors during the early morning hours is also higher during weekends compared to working days.

Workplace Microenvironment

For each of the selections given in Table 4.7, the Dutch data also include the fraction of time spent in 20 different types of activities e.g. sleeping, housework, shopping, working (paid), in transit etc.

An example

As an example the diurnal pattern of the age group 34 to 54 with the activity "working (paid)" was generated. However, only a maximum of 40 per cent were working, which seems low compared to Danish conditions where about 88 per cent of this age group work (Statistic Denmark 1997). To estimate a more realistic example for Danish conditions the same diurnal variation as in the Dutch data was assumed. However, since some people are not at work for various reasons a maximum of 80 per cent was chosen, see Figure 4.25. The assumptions correspond to a working day of 7.2 hours. All persons are assumed to work indoors. The majority of people are working during normal working hours, some during the evening and a few during the night. Lunch time is also shown in the pattern.

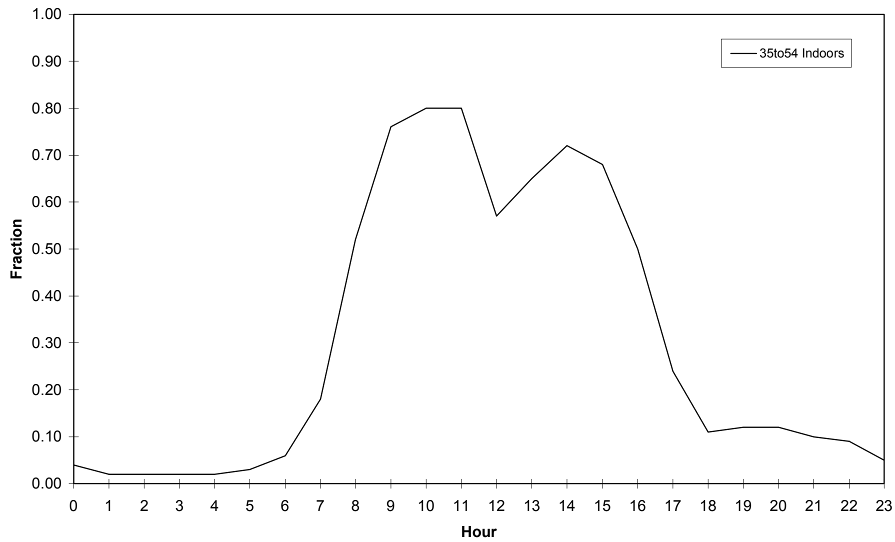


Figure 4.25 An estimate of the diurnal pattern for the Danish age group 34 to 54 being indoors at their workplace.

Street Microenvironment

It is necessary to know the diurnal variation of the vehicle occupancy for the different vehicle categories to estimate the presence of road users on a given road segment.

Data collection

Vehicle occupancies for the vehicle categories: passenger cars, vans, trucks and buses have been derived from Danish data sources and subdivided into two seasons: September to May, and June to August (Summer) and into diurnal patterns for: working days, Saturdays and

Sundays. The subdivision of data is similar to the data sources. The diurnal vehicle occupancies for passenger cars and vans are derived from a report prepared by the Danish Road Directorate (Vejdirektoratet 1997). The occupancies of trucks are assumed to similar to vans in the absence of data. Average vehicle occupancies for buses were obtained from the Municipality of Middelfart and assumed to be constant in time (Phuong, private communication). For working days, Saturdays and Sundays the occupancy of buses is assumed to be: 16.1, 5.8 and 4.8, respectively.

Data evaluation

The vehicle occupancies are shown in Figures 4.26 to 4.28 for passenger cars and vans. Buses have the highest vehicle occupancy of all vehicles although an occupancy of 5.8 and 4.8 on Saturdays and Sundays, respectively, is relatively low compared to larger cities. Passenger cars have generally a higher occupancy than vans and trucks, and the occupancies are generally higher during Summer for passenger cars and to a lesser degree also for vans.

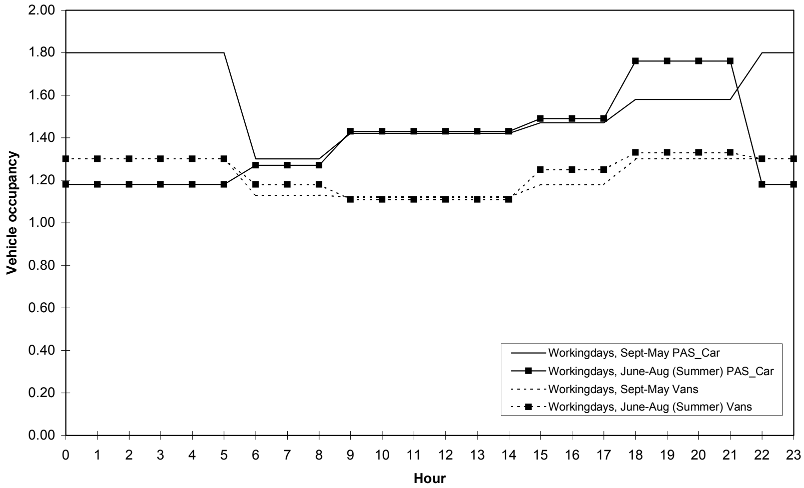


Figure 4.26 Diurnal pattern of vehicle occupancy for passenger cars and vans during working days.

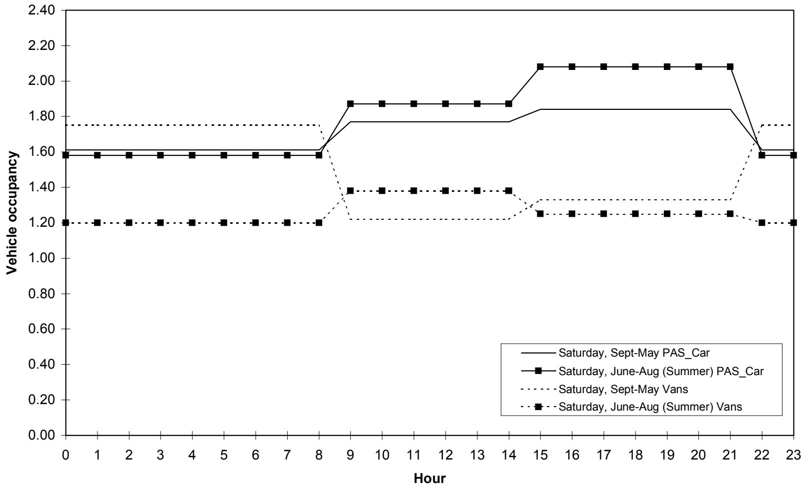


Figure 4.27 Diurnal pattern of vehicle occupancy for passenger cars and vans during Saturdays.

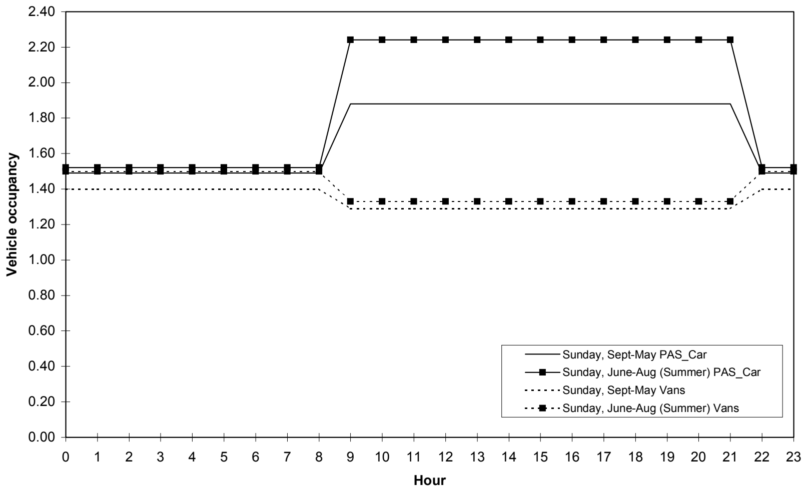


Figure 4.28 Diurnal pattern of vehicle occupancy for passenger cars and vans during Sundays.

5 Exposure Model Evaluation

As described in the previous chapter, the different input data and the methods used to generate input data have been verified to the extent possible. However, it has not been possible to carry out a comprehensive sensitivity analysis of the exposure model due to time constraints nor has it been possible to validate the predicted exposure estimates against exposure measurements because such data are not available for the Municipality of Middelfart. In this chapter the population exposure model will be evaluated by discussing the validity of the input data and the impact on exposure estimates of possible uncertainties in the input data. It is discussed how well the outdoor and indoor air pollution is determined, and how well the people's contact to the air pollution is estimated to assess the uncertainties on exposure estimations.

5.1 Outline of Input, Processes and Output of the Exposure Model

The model predicts exposures by combining results of the OSPM model and the simple population model. In Figure 5.1 the input data required for the exposure model are outlined.

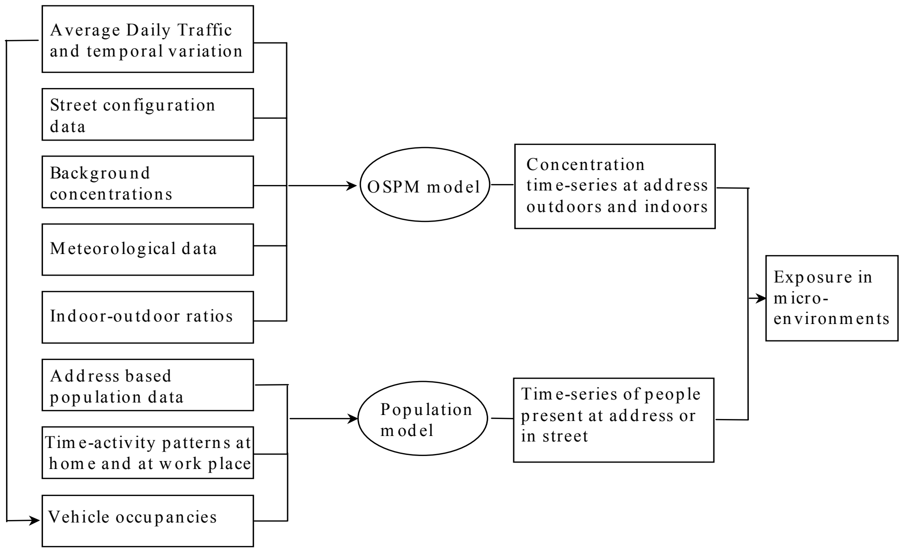


Figure 5.1 Outline of the inputs and outputs of the population exposure model.

5.2 Validation of the OSPM Model

Validation studies of the OSPM model have been carried out for St. Olavs Gate in Oslo and Vesterbrogade, H.C. Andersens Boulevard, Jagtvej and Bredgade in Copenhagen and Vesterbro in Aalborg (Hertel and Berkowicz 1989b,c; Berkowicz et al. 1997b). These studies showed good agreement between measurements and predictions.

An example of a comparison between modelled and measured one hour means of NO_x levels for Jagtvej is given in *Berkowicz et al.* (1997b). The input parameters for the model are measured hourly mean traffic loads, and measured hourly background concentrations and meteorological parameters together with measured street configuration data. Generally, there is a good agreement ($r^2 = 0.88$) between hourly mean measured and modelled levels as shown in Figure 5.2. However, for single one hour predictions the uncertainty may be large.

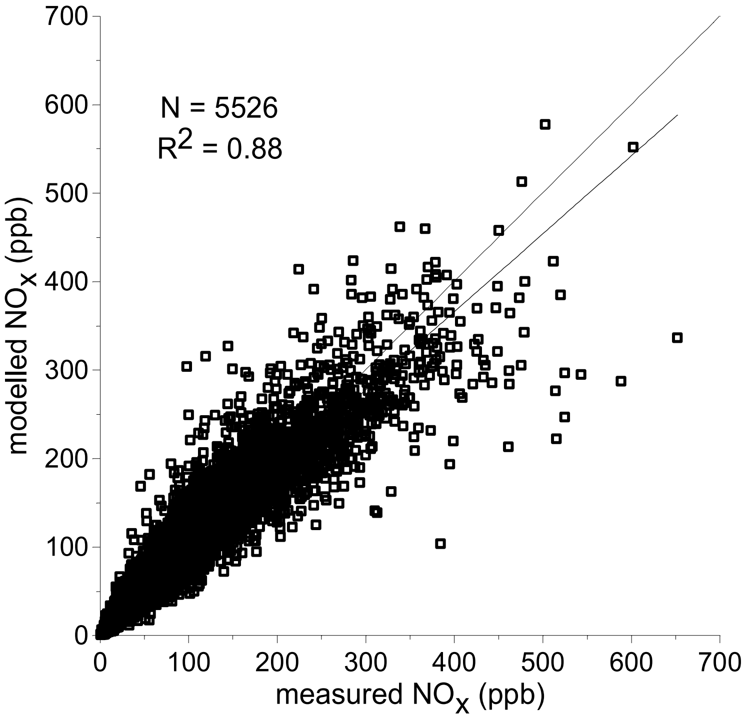


Figure 5.2 Validation of the OSPM model for one hour means of NO_x on data from Jagtvej during 1994 (Berkowicz et al. 1997b).

In Figure 5.3 it is shown that the model predicts the monthly means within 10 per cent. The difference between the two sides of a street can be substantial for short averaging times due to the recirculation of air, and even for monthly means as is the case for June. However, the difference between the annual mean of the opposite sides of a street is moderate.

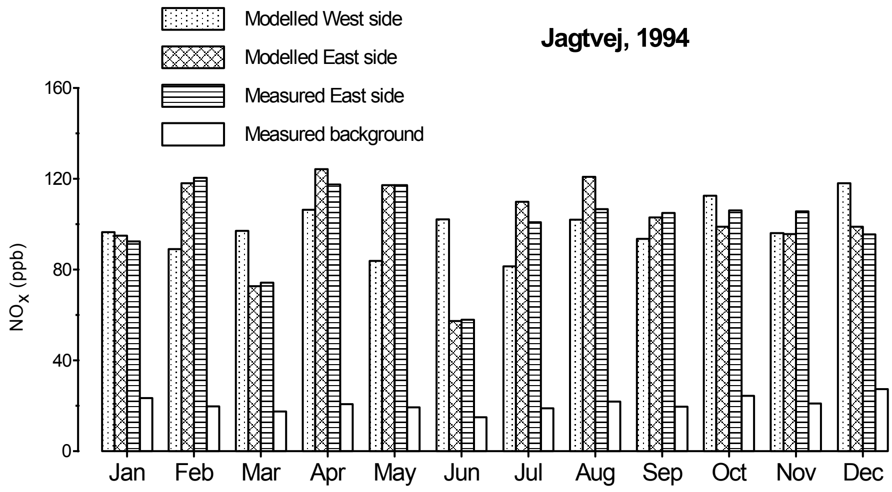


Figure 5.3 Validation of the OSPM model for monthly means of NO_x on data from Jagtvej during 1994 (Berkowicz et al. 1997b).

The validation studies show that the emission factors and the dispersion parameterisation applied in the OSPM model are well characterised. The model has been developed and extensively tested for mainly regular street canyons, and is expected to perform with higher uncertainty under more complex street configurations. As other street pollution models, the uncertainty on OSPM predictions under very low wind speeds is higher.

5.3 Traffic Loads and Temporal Variation

ADT

The Average Daily Traffic (ADT) on the road network originates from the Municipality of Middelfart and is based on a combination of automatic traffic counts and visual traffic counts. For some of the low trafficked roads, traffic loads have been estimated by best judgement. The uncertainties on ADT for passenger cars, vans, lorries and buses are expected to be relatively low. The uncertainty may be high for low trafficked roads but the impact on air pollution is low because air pollution in these streets is dominated by the contribution from the urban background.

Temporal variation

Standardised temporal variation profiles of the different vehicle categories have been established empirically based on data from traffic counting stations and guidelines from the Danish Road Directorate as documented in *Jensen* (1997b). As part of the Childhood Cancer Project the standardised temporal variation profiles were tested for three urban streets with fixed monitor stations: H.C. Andersens Boulevard and Jagtvej (Copenhagen), and Vesterbro (Aalborg) (Jensen 1997b). For the diurnal variation the validation test was limited to passenger cars on working days, Saturdays and Sundays and for vans and lorries on working days during the year (excl. July). There is generally a good agreement between predicted and observed diurnal variation for passenger cars on all days. For vans and lorries the agreement between predicted and observed diurnal variation is poor to fair depending on the street in question. It is assumed that the diurnal variation of bus traffic is similar to that of lorries. However, it is a crude assumption because the observed diurnal variation for buses is quite different from that of lorries. Bus traffic is obviously determined by the bus routes that serve the street and the fraction of bus traffic is relatively lower during normal working hours and relatively higher in the evening when compared to lorry traffic. The impact on emission estimates based on a poor to fair diurnal determination of variation of vans and lorries is minor for CO and benzene because passenger cars dominate emissions. The impact is higher on NO_x emissions because vans and lorries may constitute about 15 per cent of traffic loads in the case of Middelfart but may contribute with up to about 25 per cent of NO_x emissions (Jensen 1992). In Middelfart bus traffic is insignificant and has very little impact on emissions.

Cold starts

The temporal variation of cold starts is one of the parameteres that determines emissions. A sensitivity analysis of the impact on CO emission of changes in the fraction of cold starts showed a linear although not proportional relation between relative changes in cold starts and CO emissions. Benzene is assumed to have the same cold starts characteristics as CO. Cold starts have little influence on NO_x emissions (Jensen 1997b).

Impact on air pollution

In *Vignati et al.* (1997) a test of the same three streets showed that the differences between measured and modelled monthly and annual means of NO_2 were within 10 and 2 per cent, respectively, when the standardised temporal variation in traffic and cold starts were applied. All in all, traffic levels and the temporal variation in traffic are well characterised, and the uncertainty on predicted traffic levels has a minor influence on annual and monthly means but may have a higher influence on short term means.

5.4 Street Configuration Data

Urban landscape model

A 2½ urban landscape model was developed to automatically generate the street configuration data. The street widths were obtained from the Municipality of Middelfart.

Uncertainty

Considering a specific receptor point, the uncertainty on the estimated street configuration data is expected to be low and probably even lower than data generated manually from analogous maps and field visits.

Impact on air pollution

The uncertainty on the generated street configuration data including the street width and the building height is expected to have minor influence on predicted air pollution levels. However, under complex conditions the generated receptor point may not fully represent the real conditions and the predicted air pollution levels may not be representative for the address location.

5.5 Background Concentration

Semi-empirical model

As part of the Childhood Cancer Project a background model has been developed for use with the OSPM model in context of long-term exposure modelling. The background model is based on a semi-empirical method founded on a few monitor stations to estimate urban and rural background concentrations of NO_2, NO_x, O_3 and CO for different geographic regions in Denmark (Jensen 1998).

Test of background model

The OSPM calculates the concentration levels in the street as a contribution from traffic emissions in the street and a contribution from the background concentrations. In *Vignati et al.* (1997) a test of modelled NO_x and NO_2 background concentrations was carried out for a busy street in Copenhagen (Jagtvej) using measured traffic levels and street configuration data from 1994. The relationship between measured and calculated street concentrations was good (r^2=0.84). However, the model underestimates the highest concentrations because the background model is based on average profiles of monthly diurnal variations that will not account for extreme situations. For monthly means the differences between modelled and measured NO_x and NO_2 levels were less than 10 and 15 per cent, respectively. For annual means the differences for NO_x and NO_2 were less than 1 and 3 per cent, respectively.

Down-scaling and validation

To predict the urban background concentration of CO and NO_x in the centre of a given city the annual mean at the city centre of Copenhagen is used as a reference and this concentration is scaled down to represent the urban background concentration of smaller cities. This extrapolation method has been validated for Odense (145,000 inhabitants) and Aalborg (115,000 inhabitants). The formula predicts the same levels for the two cities. Observed annual NO_x means were overestimated by 13 per cent and 3 per cent for Odense and Aalborg, respectively (Jensen 1998). It has not been possible to validate the extrapolation procedure for small towns due to lack of monitor data.

Application for Middelfart

The down-scaling procedure has been used to calculate background concentrations in the city of Middelfart. The rural parts of the Municipality of Middelfart has been assigned rural background concentrations.

Distance to City Centre

NO_2 measurements in Copenhagen showed that concentrations are depending on the distance to the city centre. In the Childhood Cancer Project, an empirical expression was used to take into account the distance from the location of an address to the city centre. Since the town of Middelfart is small (about 13.000 inhabitants) this approach was not applied, although, the same phenomenon may be seen to some extent in small cities. If this phenomenon was to be taken into account it would be easy to calculate the distance from the address point to the city centre using GIS.

Impact of background concentrations on street concentrations

It is obvious, that the more traffic in a street the less important is the contribution from the background. In a busy street the contribution from the background may be 10-20 per cent for CO and 50-60 per cent for NO_2 (Jensen 1998). In the case of Middelfart most streets carry low traffic loads and the background contribution will dominate in many cases. Since the uncertainty on the street contribution is less than the contribution from the background, at least for short averaging times, the uncertainty on the street concentrations will be higher for streets with little traffic compared to busy streets. Since most rural areas will be characterised by low traffic levels the uncertainty on predicted street concentrations will generally be higher in rural areas compared to urban areas due to the uncertainty on the background model.

5.6 Meteorological Data

It is reasonable to assume that the applied measured meteorological parameters from Odense represent the conditions in Middelfart due to the relatively short distance between the two cities.

5.7 Indoor-Outdoor Ratios

Constant I/O-ratios

For the residence and workplace microenvironments, it has been assumed that the I/O-ratio is a constant based on literature values although it should be regarded as a variable depending on the factors described in chapter 2. For vehicles the I/O-ratios have not been considered at all and the exposure estimates in the street microenvironment should be considered to represent outdoor exposures although all motorised road users are inside vehicles.

Indoor sources

Furthermore, indoor sources may have a major impact on the I/O-ratio although this is not taken into account. Therefore, the exposure model estimates the contribution from traffic to exposure excluding the possible influence of different indoor sources.

Uncertainty

Although, the uncertainty on the average I/O-ratio is likely to be moderate, the uncertainty of the predicted indoor concentrations is high because of the factors that are not accounted for by this very simple approach e.g. possible indoor sources, and because the I/O-ratio is a variable e.g. showing a time lack between outdoor and indoor levels. If indoor-outdoor data were available the temporal variation of the I/O-ratios could be described and applied in the exposure model.

5.8 Address Based Population Data

Home microenvironment

The estimation of the number, age and gender of the people living at a residence address has been based on the CPR database. The uncertainty on CPR data is expected to be very low.

Application in Middelfart

Due to a preliminary dataset of address points some addresses were located outside buildings and omitted in the geocoding of buildings. In this process 2.8 per cent of the people were lost but the age and gender distribution was only changed insignificantly.

Workplace microenvironment

The number of people working at a work place address was estimated using the CER database that only gives the total number of employees with categories at a workplace. The estimated total number of people employed in the Municipality of Middelfart was in good agreement with what could be expected when compared to similar figures for the county level.

Uncertainty

However, the uncertainty on the estimated number of employees at a given address will be 30-50 per cent at maximum due to the categorisation of the employees. The estimation of the number of employees represents full-time employees based on ATP payments and for a workplace with many half-time employees the potential number of people present at the work place will be underestimated. In this case the maximum uncertainty of the number of employees may be even higher. When excluding the address points located outside buildings the total number of employees decreased by 12.7 per cent, and the distribution between categories changed moderately. All in all, the uncertainty on the estimated number of employees for a specific workplace address may be moderate to substantial although the total number of employees are well predicted.

5.9 Time-Activity Patterns

Limited Danish data

Insufficient Danish time-activity data materials are available for generation of standard time profiles for the residence and workplace microenvironment.

Dutch data as example

To illustrate the proposed approach for exposure calculations time-activity data were obtained from RIVM. The data have been used as an example as some differences between time-activity patterns in the Netherlands and Denmark are expected due to differences in climate, lifestyle, occupational patterns etc.

Residence and workplace microenvironment

The uncertainty on the generated standard time profiles for the residence and workplace microenvironment are expected to be substantial especially for the workplace microenvironment.

The uncertainty on the temporal variation of the presence of people is determined by the combination of the uncertainty on the potential number of people present at a residence or a workplace address and the uncertainty on the generated standard time profiles for the specific microenvironment. For the residence microenvironment the uncertainty on the number of people present at an address is primarily determined by the uncertainty on the time profiles since the uncertainty of the potential number of people living at a residence address is low. For the workplace microenvironment the uncertainty on the number of people present at an address is determined by the substantial uncertainties of both the potential number of people present and the time profiles. All in all, the uncertainty on the presence of people is expected to be higher for the workplace microenvironment compared to the residence microenvironment.

Street microenvironment

The presence of road users on a road segment is determined by the diurnal variation in traffic loads for the different vehicle categories and the diurnal variation of the vehicle occupancies. Generally, the uncertainty on the diurnal variation of passenger cars is expected to be relatively low and somewhat higher for vans, trucks and buses. The uncertainty on the diurnal variation of vehicle occupancies for passenger cars and vans is expected to be relatively low as the data originates from visual counts. The vehicle occupancy of trucks is assumed to be similar to that of vans. The occupancy of busses is assumed constant based on municipal data, and is subdivided into working days, Saturdays and Sundays. Since traffic loads are dominated by passenger cars in Middelfart the uncertainty on the presence of all road users on a road segment is expected to be low.

5.10 Uncertainties on Exposure Estimates

Outdoor air pollution and indoor air pollution

A qualitative estimation of the uncertainties on inputs and outputs of the exposure model is presented in Table 5.1. The uncertainty on outdoor air pollution is low for long averaging times (year, month, week) and moderate for short averaging times (day, hour). The background concentration model developed for long-term exposure contributes to the uncertainty on the short averaging times. The uncertainty of street concentrations will be lowest in urban areas with heavy traffic since the background levels play a minor role. Although the uncertainty is low to moderate on outdoor air pollution the uncertainty on indoor air pollution levels will be moderate to substantial because the constant I/O-ratios are uncertain.

Presence of people in microenvironments

The uncertainty on the presence of people in microenvironments is primarily determined by the uncertainty in the standard time profiles for the residence and workplace microenvironment that originate from Dutch data. However, for the workplace microenvironment the uncertainty on the potential number of people working at an address also contributes to the uncertainty in the quantification of the presence of people in the workplace microenvironment.

Simple exposure index

The simple exposure index only considers the air pollution and the potential number of people present at a location determined by population data for the residence and workplace microenvironment. The exposure index will obviously inherit the uncertainty on the air pollution and the potential number of people present. The uncertainty will be low for long averaging times of air pollution and moderate for short averaging times. The uncertainty on the potential number of people present in the workplace microenvironment will add further uncertainty to the index for the workplace microenvironment compared to the residence microenvironment. The uncertainty on the exposure index for the residence and workplace microenvironments indoors will be even higher considering the uncertainties on the I/O-ratios. For the street microenvironment the uncertainty on the simple exposure index is relatively low as it is depending on the air pollution, and the potential number of road user at a road segment (ADT times vehicle occupancy). The strength of the simple exposure index is in the relative comparison between locations within a microenvironment and not between microenvironments.

Table 5.1 Estimated Uncertainties on Input and Output of Exposure Model.

	Uncertainty		
Type:	Low	Moderate	Substantial
Input data:			
Average Daily Traffic and temporal variation	x		
Street configuration data	x		
Background concentrations		x	
Meteorological parameters	x		
Indoor/outdoor-ratios		x	
Population data:			
at residence addresses	x		
at workplace addresses		x	x
Time-activity patterns:			
at residence microenvironment		x	
at workplace microenvironment		x	x
Vehicle occupancy	x		
Intermediate output data:			
Air pollution:			
outdoors	x	x	
indoors		x	x
Presence of:			
people at home		x	
people at workplace		x	x
road users in street	x		
Output data:			
Simple exposure indices			
Outdoors:			
at home	x	x	
at workplace		x	x
in street	x		
Indoors:			
at home		x	
at workplace			x
Exposure estimates using standard time profiles			
Outdoors:			
at home	x	x	
at workplace		x	x
in street	x		
Indoors:			
at home		x	x
at workplace			x

Residence and workplace microenvironments

The exposure estimate using time profiles considers the temporal variation in air pollution and presence of people and will naturally inherit the uncertainty on these two variables. The uncertainty on the exposure estimate will be low for long averaging times and increase for shorter averaging times because the temporal variation in air pollution and the presence of people have these characteristics. The profiles of presence represent the average presence and they do not account for time-activity conditions that differ from the normal routines like visit, vacation etc. However, since the time profiles are based on Dutch data it adds considerable uncertainty to the exposure estimates when applied to a specific Danish conditions. Furthermore, since the uncertainty on the number of people present in the workplace microenvironment is expected to be higher than for the residence microenvironment this will add further uncertainty to the exposure estimate for the workplace microenvironment. The uncertainty on the exposure estimate for the indoor residence and workplace microenvironments will be even higher considering the uncertainties on the I/O-ratios. The strength of the time profile exposure estimate is that it takes into account the correlation between the variation in concentrations and the variation in presence. The exposure estimate makes it possible to carry out a reasonable comparison between exposures in the residence and the workplace microenvironments since the time spent in these microenvironments are considered. Therefore, the time profile exposure estimate is a better indicator of personal exposure related to a microenvironment than the simple exposure index.

Street microenvironment

The uncertainty of the time profile exposure estimates in the street microenvironment is relatively low because the temporal variation in traffic loads and the vehicle occupancies are relatively well characterised. Within the street microenvironment the time profile exposure estimate makes it possible to compare different streets from an exposure point of view that takes into account the correlation between the variation in concentrations and the variation in presence of road-users in the streets. It is not possible to compare the time profile exposure in the street environment with the residence and workplace environments since exposures in a street are not associated to the same individuals but to all the people who pass through the street and only spend a short time in the street.

5.11 Performance of Exposure Model

Street configuration data and exposure model

The generation of street configuration data was quite time consuming, about 13-18 seconds per address or about 38 hours for the entire Municipality of Middelfart on a PC 200 MHz Pentium for running the street configuration Avenue program in ArcView. The processing of Avenue code is rather slow because it is an uncompiled programming language. However, once the static street configuration data were established the calculations of time profile exposure estimates took about 9 seconds per address or about 20 hours for the entire municipality with 8,054 addresses using a FORTRAN program.

6 Model Results for Case Study Area

In this chapter, selected data and results from the Municipality of Middelfart are presented to demonstrate the methodology of the exposure model. Two approaches to exposure assessment - a geographic and a statistical - are described within the residence, workplace and street microenvironments.

6.1 Geographic Approach to Exposure Assessment

One of the advantages of using GIS for exposure assessment is the visualisation capabilities for displaying data on different scales and aggregations.

Residence microenvironment

Concentration levels

An example of benzene concentrations in 1996, the number of people at residence addresses and the simple exposure index is illustrated in Figure 6.1 as a close-up of the down-town area of Middelfart. The scale is chosen to make it possible to identify the individual addresses and at the same time to overview a larger area.

The upper view displays the calculated annual means of benzene concentrations by the address points. Levels are in the range of 1.3-3.5 $\mu g/m^3$ which is relatively low due to traffic levels below 4,000 ADT. However, the estimated levels still exceed the recommended guidelines of 0.13-0.25 $\mu g/m^3$ ($1*10^{-6}$ lifetime risk of leukaemia) given by the World Health Organisation, see the listing in *Larsen et al.* 1997. In many locations today's levels also exceed the limit value of 2-5 $\mu g/m^3$ for benzene in 2010 under consideration by the EU commission (Skov, private communication). All locations with levels that exceed a certain threshold e.g. a criteria value, a recommended guideline or a limit value could also be visualised to identify the geographic locations that meet these criteria.

Population

The middle view shows the number of people living at each address. The central part of Middelfart mainly consists of 1-2 floor houses and there are only few multi-storey houses.

Exposure

The lower view gives the simple exposure index defined as concentrations times number of people at each address. The addresses with high concentrations and many people will have a high index.

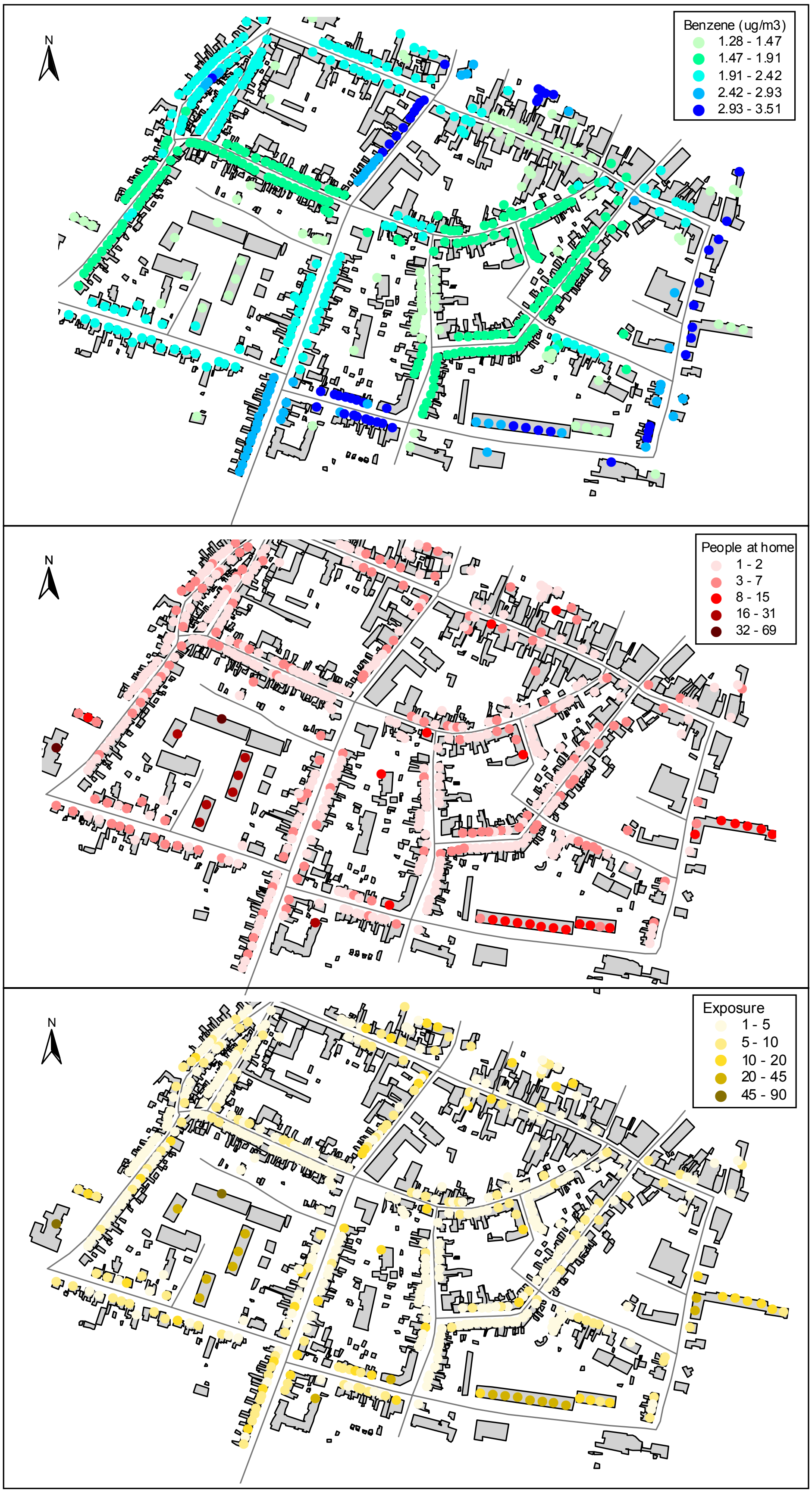


Figure 6.1 *Upper*: Outdoor annual benzene levels (µg/m³) in 1996. *Middle*: No. Of people at residence addresses. *Lower*: Simple exposure index (µg/m³*persons).

Street microenvironment

Exposure of road users

In Figure 6.2, the road user exposure estimate for benzene taking into account the time spent on the road segments are visualised for all road users (passenger cars, vans, lorries and buses). The exposure estimate is visualised as a intensity in order to compare road segments of different length. For practical reasons the exposure estimate was not calculated as outlined in equation 3.6, that states, that concentration levels should refer to street concentrations. Instead street concentrations have been calculated as the average of concentrations at the addresses that belong to a specific road segment. This approach underestimates the levels because the modelled concentrations at the building facades are lower than concentrations in the street. Furthermore, the indoor-outdoor ratio for the different vehicle categories are not taking into account and the exposure of pedestrians and bicyclists are not considered due to lack of data. The figure shows that the highest exposure of road users are at the main roads with the highest traffic loads and highest concentrations. The presentation shifts the focus from the traffic, and related concentrations to the exposure of road users. Two streets that have the same traffic levels and the same concentration levels can have very different road user exposures depending on the distribution of traffic and hence the number of people passing through the street. However, the traffic conditions in Middelfart are entirely dominated by passenger cars and the influence of bus traffic on road user exposures cannot be observed. The road user exposure estimates showed similar results for CO and NO_2 and an opposite pattern for O_3.

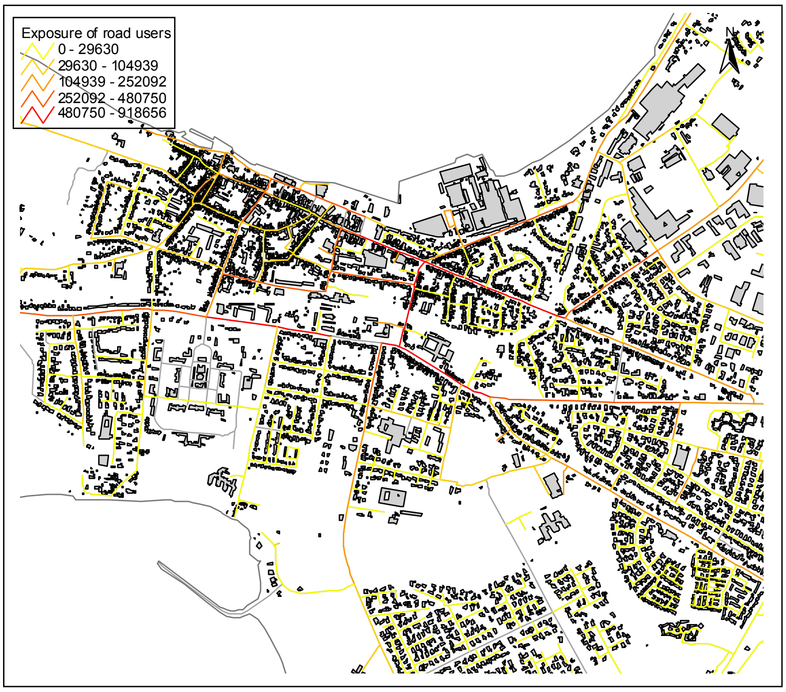


Figure 6.2 Benzene exposure estimate intensity for all road users in 1996 (ppbpersonhours/km).

Workplace microenvironment

Analysis of exposures at specific locations

An example of concentrations at a selection of buildings with a specific use is given in Figure 6.3. Calculations for kindegartens was carried out based on the business number in the CER database.

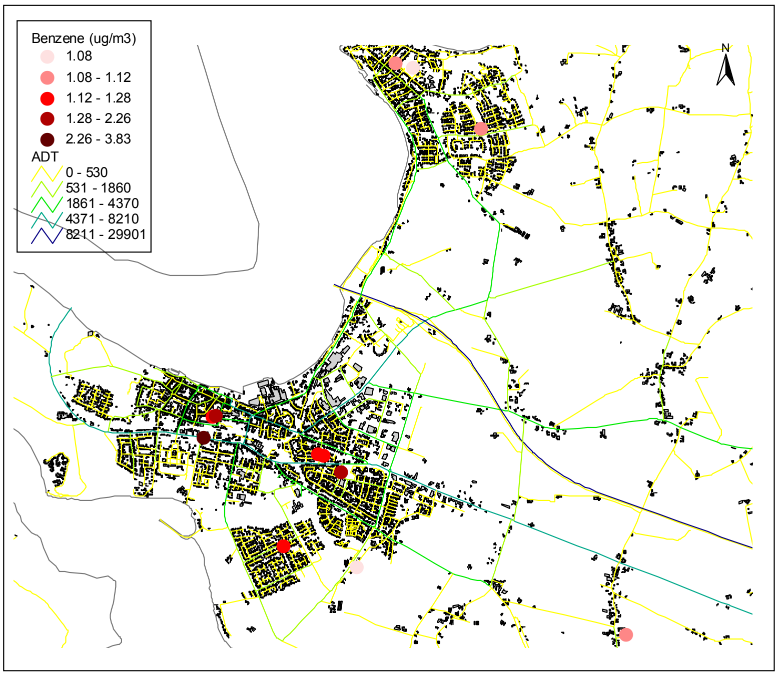


Figure 6.3 Annual benzene levels in 1996 at the locations of kindergartens with children of mainly 3-6 years old.

Grid bases visualisations

Density calculation methods

The previous figures have visualised data according to address points and road segment lines. However, the larger a displayed area the more blurred the view. Therefore, for large areas e.g. the entire municipality a grid based visualisation may be applied. Figure 6.4 shows the population density according to the residence and workplace microenvironments. In Figure 6.5 the benzene concentration density is visualised for the entire municipality and for the city of Middelfart. Figure 6.6 shows the simple exposure index as a density for the residence and workplace microenvironments. The population and exposure densities are calculated for each grid cell by summing the attribute values for each address point found in a user defined search radius and dividing by the area of the search circle. The density of concentration levels have been calculated using the Inverse Distance Weighted (IDW) interpolator method that weights the attribute value of address points closer to the processing grid cell greater than those farther away. All points within a user specified radius have been used in the calculations. A higher power parameter in the IDW interpolation results in less influence from distant points.

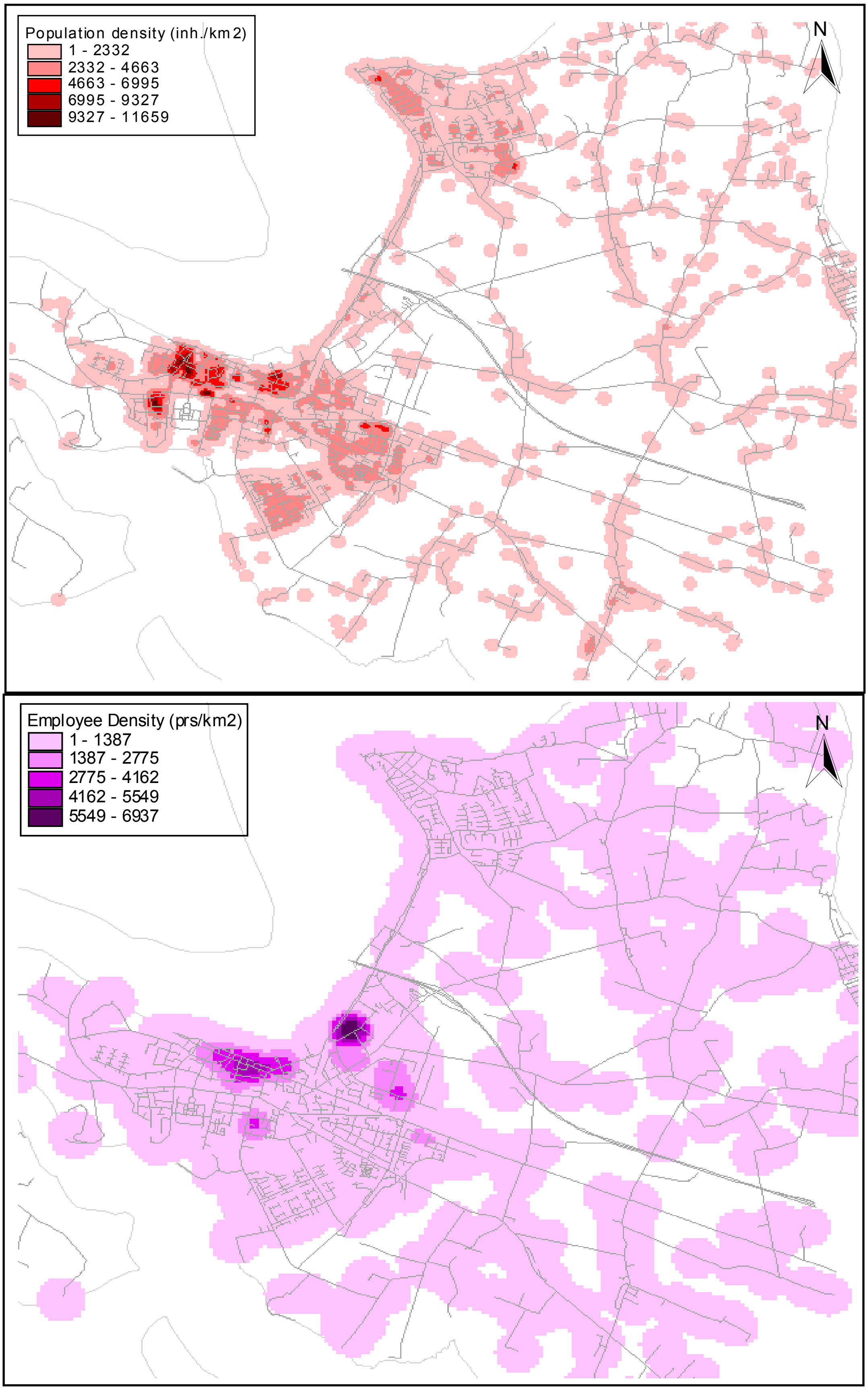


Figure 6.4 *Upper*: Population density based on residence addresses with grid size 25 m and a search radius of 100 m. *Lower*: Density of employees based on workplace addresses with grid size 50 m and a search radius of 350 m. (Units Persons/km^2, 1996).

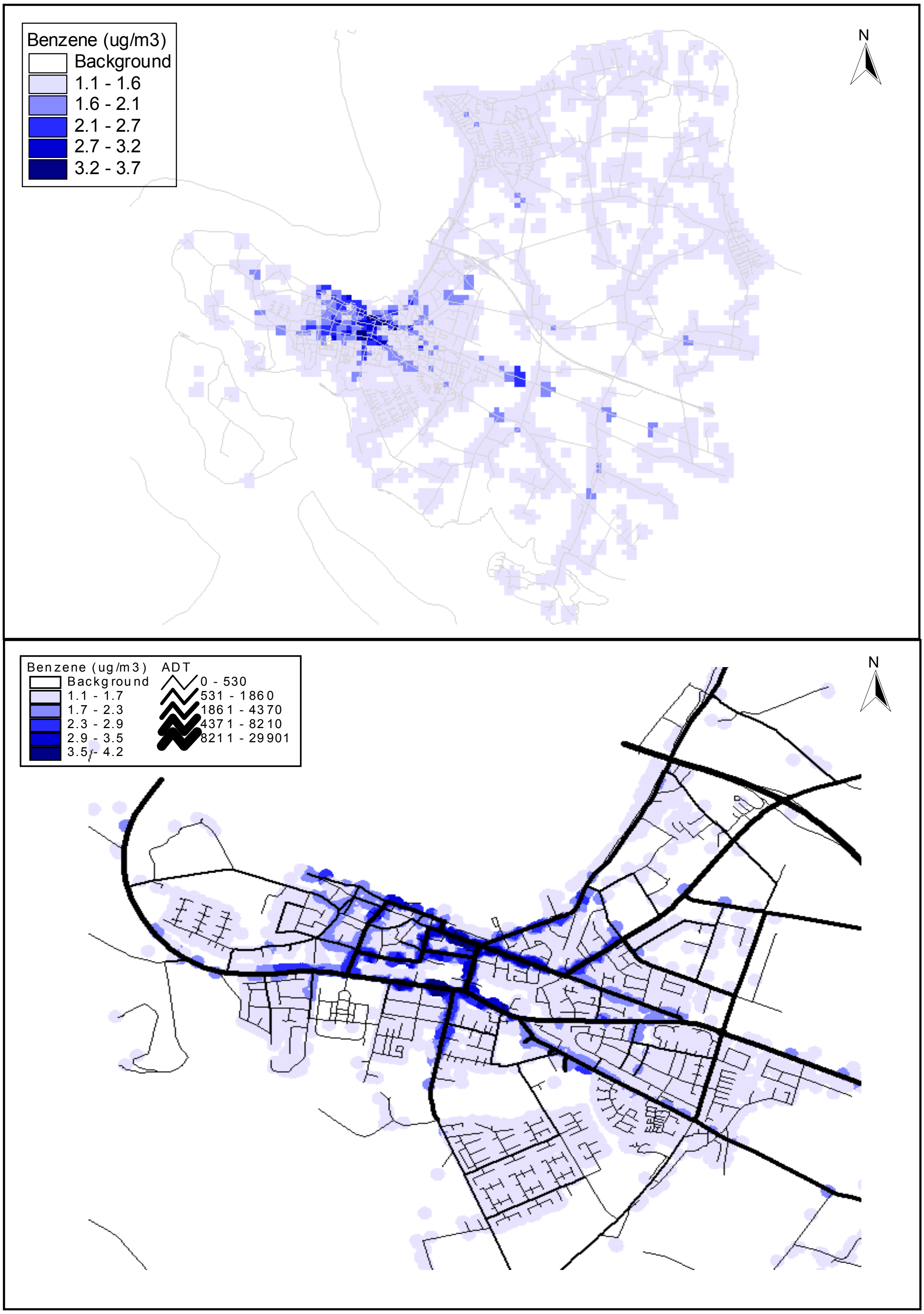


Figure 6.5 *Upper*: Density of benzene concentration levels for the entire municipality with a grid size of 100 m, a search radius of 150 m and a distant power weight of 2. *Lower*: Density of benzene concentration levels for a close-up of the town of Middelfart with a grid size of 5 m, a search radius of 50 m, and a distant power weight of 2. (Units (µg/m^3)/km^2, 1996).

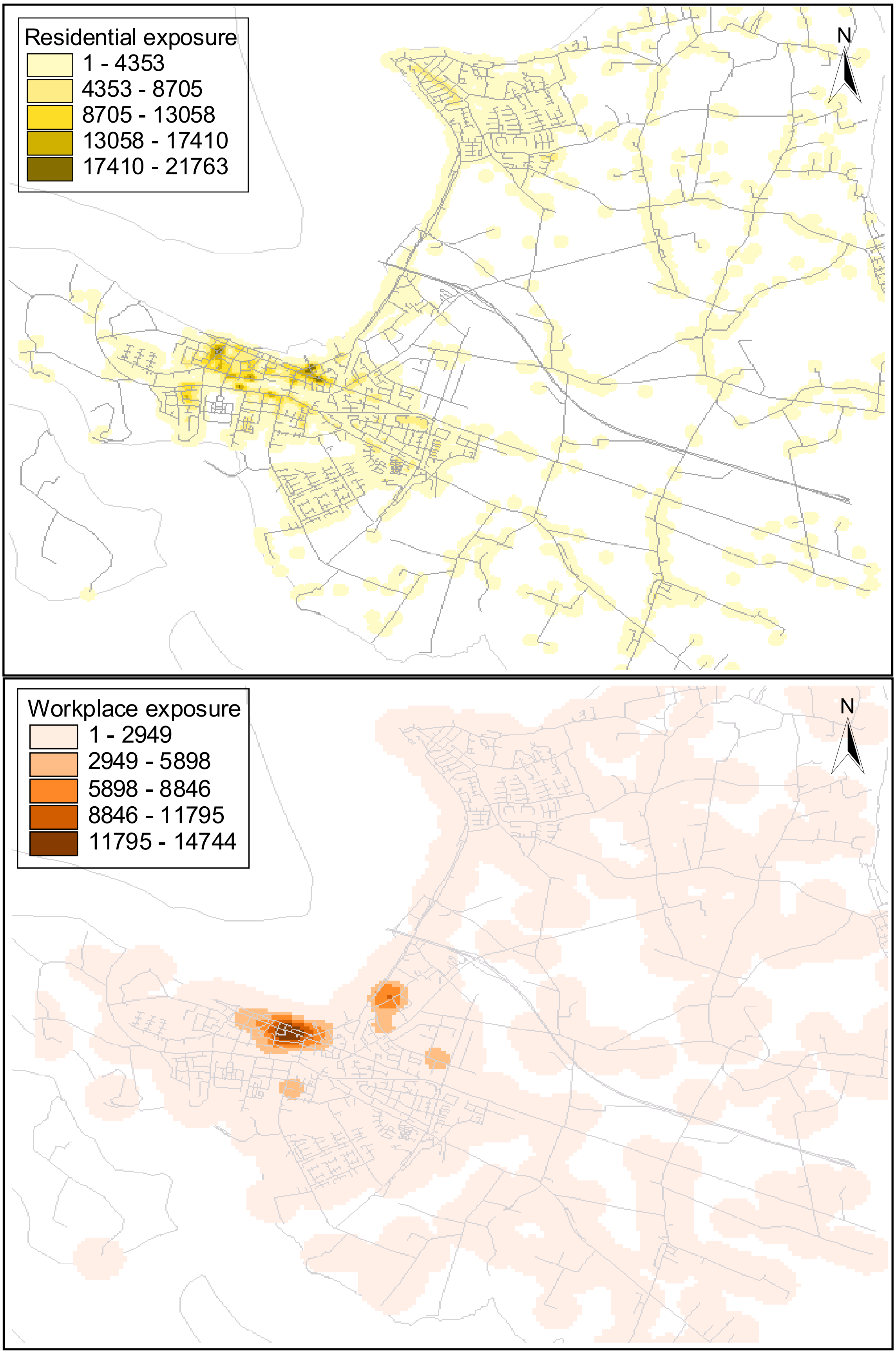


Figure 6.6 *Upper*: Density of simple exposure index for benzene for residence addresses with grid size 25 m and a search radius of 100 m. *Lower*: Density of simple exposure index for benzene for workplace addresses with grid size 50 m and a search radius of 350 m. (Units (µg/m^3*person)/km^2, 1996).

6.2 Statistical Approach to Exposure Assessment

In the following the distribution of exposures will be assessed and the simple exposure index will be compared to the exposure estimate that takes into account the time profiles. Furthermore, the influence on exposures of being indoors and outdoors and the time spent during workings days and weekends will be analysed together with the variation in exposures between age groups. Differences between microenvironments are also discussed. The analysis covers the full extent of the Municipality of Middelfart.

Distribution functions for the residence microenvironment

Figure 6.7 shows accumulated distribution functions for the different pollutants with the residence address as exposure indicator. As expected the distribution is similar for benzene, CO and NO_2. The Municipality of Middelfart is characterised by small towns and large rural areas and under these conditions about 75 per cent of the people live along streets with concentrations close to the background levels. The stepwise increases of the first part of the curves are due to the low trafficked streets which are assigned the same traffic levels. The shape of the accumulated distribution function for O_3 is different compared to the other pollutants because the highest concentrations are found at locations with low NO_x emission outside urban areas. The curve has larger steps because the data have been modelled with only two significant digits.

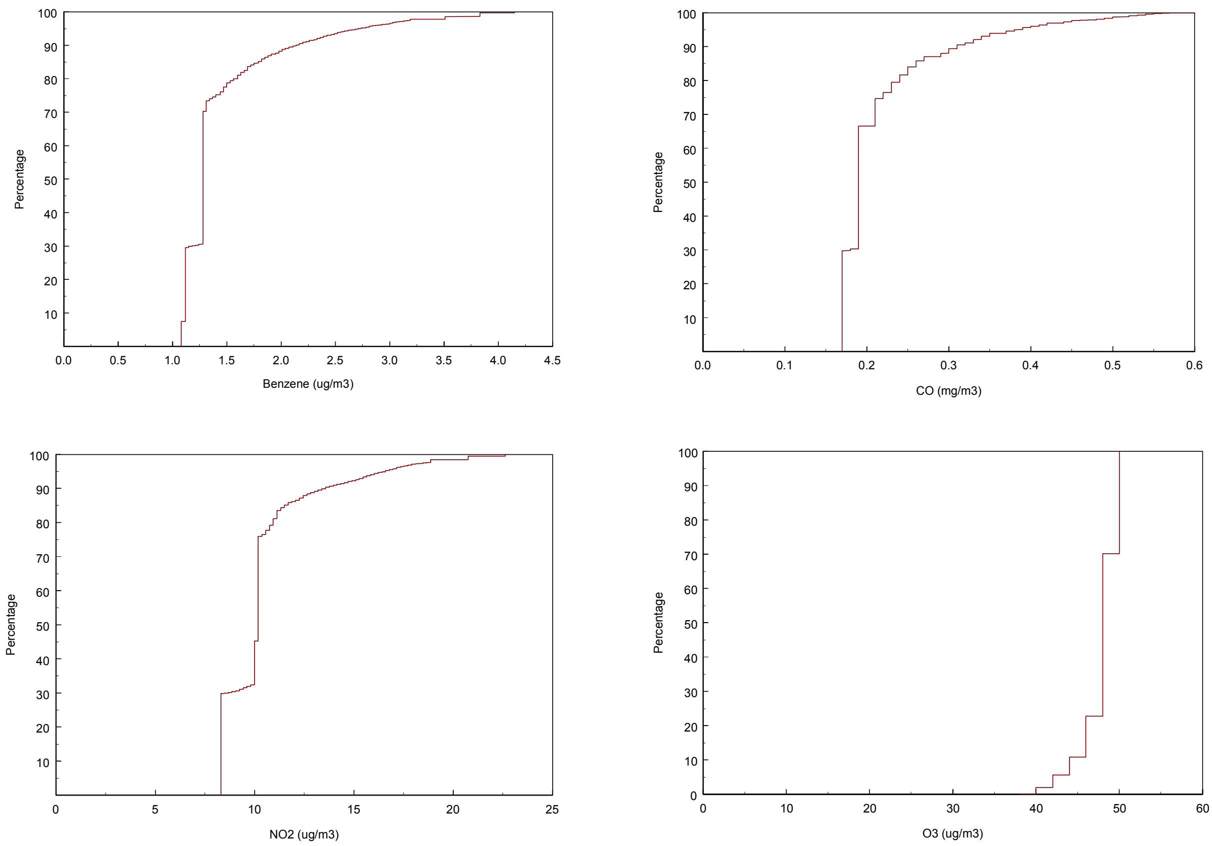


Figure 6.7 Accumulated distribution function of the number of people exposed to annual means of outdoor benzene, CO, NO_2 and O_3 at their residence addresses in the Municipality of Middelfart during 1996. The residence address is assumed to be the exposure indicator and the time-activity pattern are not taking into account. The percentage of people exposed to certain levels of the different pollutants may be derived from the figure.

Simple exposure index versus exposure estimate

Recalling that the time-activity patterns originate from The Netherlands caution should be taking when drawing conclusions for Danish conditions. The intention of the analysis below is first of all to demonstrate the influence of the time-activity patterns on exposures through a number of examples. The simple exposure index and the exposure estimates taking into account standardised time-activity patterns are compared in Figure 6.8. The simple exposure index obviously overestimate the exposure estimate for all the pollutants because the persons are assumed to be at the same location all the time.

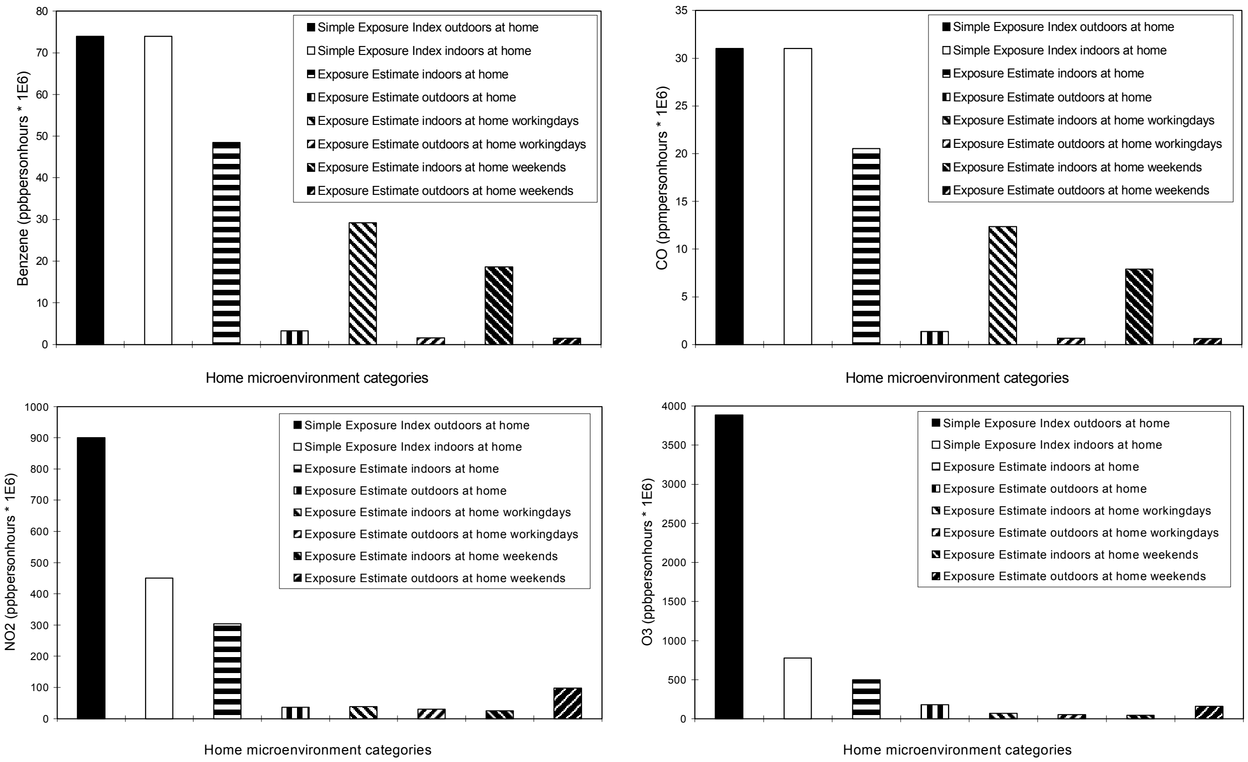


Figure 6.8 Comparison of the simple exposure index and the exposure estimate that takes into account the time-activity patterns for the residence microenvironment during 1996.

For benzene and CO the exposure estimates are about 70 per cent of the simple exposure index, indicating that outdoor concentrations of benzene and CO at the residence addresses are good indicators of the exposures at the residence microenvironment. For NO_2 and O_3 the exposure estimates are about 38 and 18 per cent of the simple exposure index, respectively, indicating that outdoor concentrations of NO_2 and O_3 are less good indicators of the exposures at the residence microenvironment. The reason is that the indoor-outdoor ratios for NO_2 and O_3 are 0.5 and 0.2, respectively, and the time spent indoors is an influential factor in determining exposures. On the other hand, the exposure estimate for NO_2 and O_3 are about 76 and 87 per cent of the simple *indoor* exposure index, respectively, indicating that the indoor concentration of NO_2 and O_3 are good indicators of exposures.

Indoors versus outdoors

About 94 per cent of the exposure estimate for benzene and CO originates from been indoors and only 6 per cent from been outdoors assuming that the indoor-outdoor ratios for benzene and CO are 1.0. The dominating contribution to the exposure estimate from being indoors is due to the fact that most time is spent indoors. According to the Dutch time-activity data about 92-97 per cent of the time being at home is spent indoors depending on the different age groups. The indoor contribution to the exposure estimate is 89 and 73 per cent and the outdoor contribution 11 and 27 per cent for NO_2 and O_3, respectively. The contribution from being indoors is less for NO_2 and O_3 compared to benzene and CO because of the differences in indoor-outdoor ratios.

Working days versus weekends

The exposure estimates for benzene and CO during working days and weekends (incl. the holiday month of July) constitute about 60 and 40 per cent, respectively. Weekends incl. July constitutes about 37 per cent of the time during a year. Weekends have slightly higher exposure estimates compared to their share of the year due to a combination of more time spent at home and generally lower concentrations as compared with working days. The exposure estimates for NO_2 during working days and weekends constitute about 36 and 64 per cent, respectively. For O_3 it is 37 and 63 per cent, respectively. The contribution from the weekends is much higher for NO_2 and O_3 compared with benzene and CO because more time is spent outdoors during weekends and because the contribution from being indoors is of less importance due to the outdoor-indoor ratios for NO_2 and O_3 of 0.5 and 0.2, respectively.

Different age groups

The relation between the exposure estimate and the simple exposure index is compared in Figure 6.9 for the different age groups.

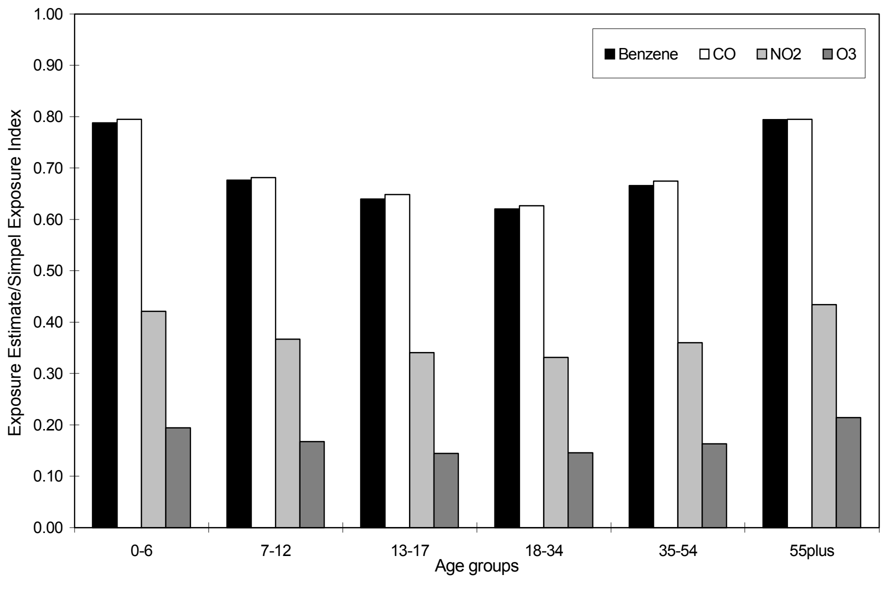


Figure 6.9 Comparison of the relation between the exposure estimate and the simple exposure index for different age groups in 1996.

Relative exposure for the different age groups

In Figure 6.10 the normalised relative exposure is given for the different age groups. The relative exposure is defined as the exposure estimate divided by the number of persons of the specific age group to give the average exposure of a person in an age group. The figure shows that the age groups "0-6" and "persons older than 55" are the groups that have the highest exposure estimates in the residence microenvironment since they spend more time at home than the other age groups.

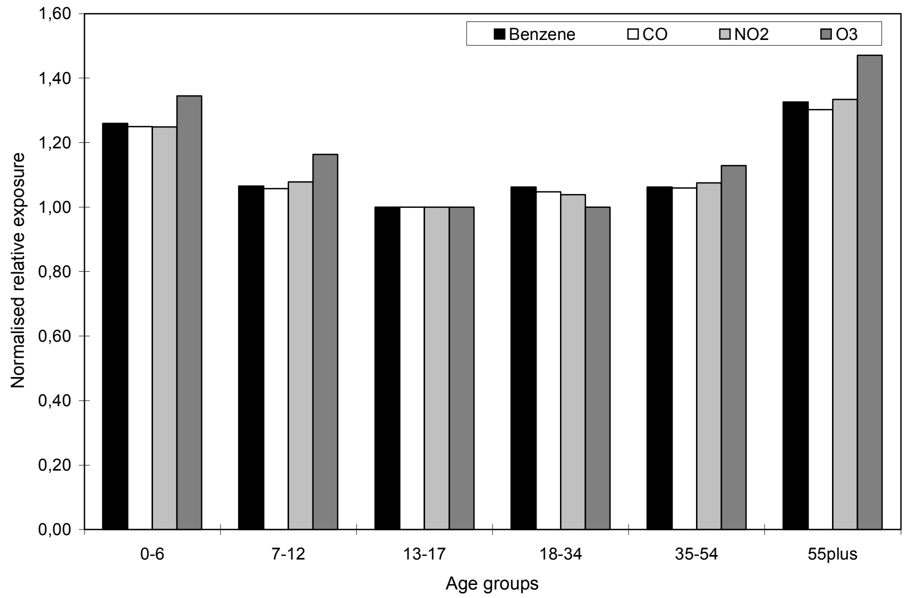


Figure 6.10 Normalised relative exposure for the residence microenvironment for the different age groups in 1996. The data are normalised with reference to the age group 13-17 that had the lowest exposure estimate.

Gender and exposure

The distribution of females and males on age groups is almost similar. Since most Danish adults are engaged in paid employment the difference in time-activity patterns between the genders is expected to be very different from Dutch conditions. Therefore, due to lack of dependable Danish time-activity patterns no analysis of the impact of gender on exposures have been carried out.

Workplace microenvironment

Average concentrations

The average annual concentrations at residence and workplace addresses are given in Table 6.1. Some workplaces are located in the down-town area of Middelfart and along the main roads with relatively high concentrations. Therefore, one might expect that the average concentration levels were higher at workplace addresses compared to residential addresses. However, average levels are quite similar because many small businesses are scattered over the full extent of the municipality where levels are relatively low.

Table 6.1 Average annual outdoor concentrations in 1996.

	Benzene (ppb)	CO (ppm)	NO_2 (ppb)	O_3 (ppb)
Residence addresses	0.46	0.19	5.56	23.8
Workplace addresses	0.47	0.20	5.63	23.8

Accumulated distribution functions

Figure 6.11 shows the accumulated distribution functions for the different pollutants with the workplace address as exposure indicator. The general shape of the curves is almost identical to the residence microenvironment - compare with Figure 6.7 - although the shape is more indented due to fewer addresses and more people at each address.

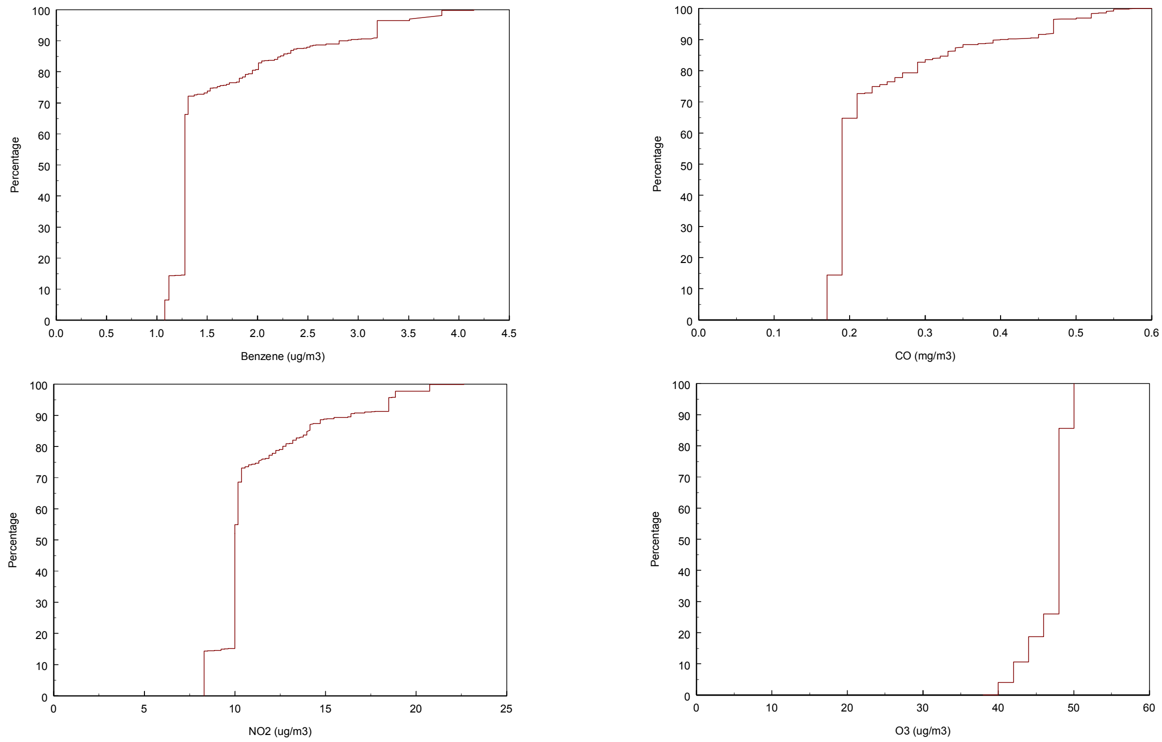


Figure 6.11 Accumulated distribution function of the number of employees exposed to annual means of outdoor benzene, CO, NO_2 and O_3 at their workplace addresses in the Municipality of Middelfart during 1996.

Concentration levels at workplaces

In Figure 6.12 the average outdoor benzene levels at workplace addresses are given according to different employee categories. The workplaces with the least number of employees also have the lowest benzene levels e.g. farms, small businesses in residential areas etc. The benzene levels of the employee categories over 100 only covers a few large workplaces in each category and the average benzene levels are highly influenced by the specific locations of these workplaces.

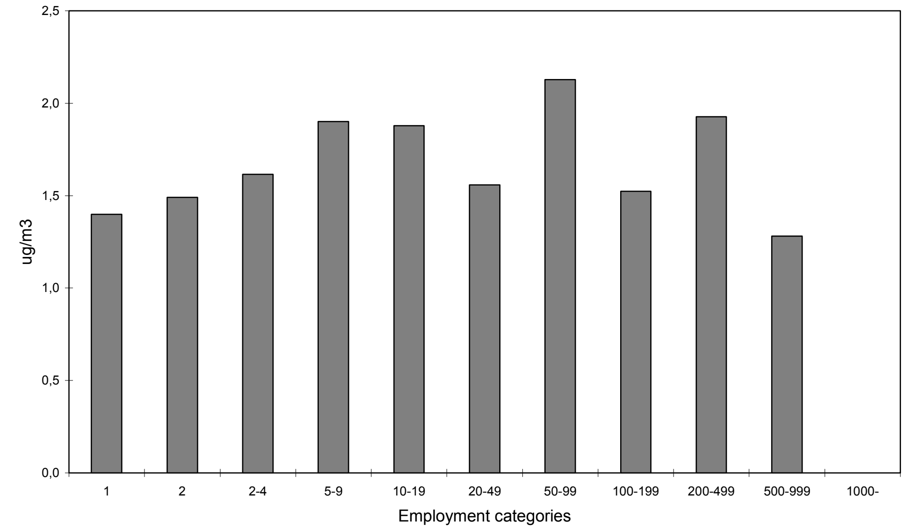


Figure 6.12 Average annual benzene levels at workplace addresses according to employee categories in 1996.

Exposures at workplaces

In Figure 6.13 the simple exposure index for benzene is shown according to the employee categories. The highest exposure indices are found at workplace addresses in the employee categories "10-499" that have relatively high concentrations and also many employees according to chapter 4. The exposure indices are low for the employee categories "1-9" where benzene levels are relatively low and the total number of employees are also relatively low.

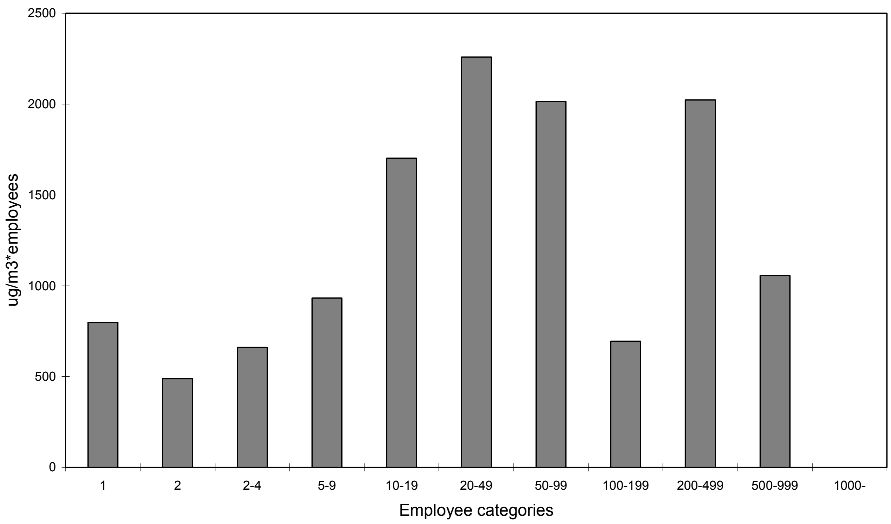


Figure 6.13 Simple benzene exposure index according to employee categories at workplace addresses in 1996.

Age group 18-54

In Figure 6.14, the exposure estimates for the residence and workplace microenvironment are compared for the age group 18-54. For the residence microenvironment the time-activity pattern is well defined for this age group. However, the data on employees do not include information on age groups. Therefore, it is assumed that all the employees are 18-54 years old. This assumption overestimates the exposure because the work microenvironment includes younger or older employees than this age group. It is further assumed that all time spent at work is spent indoors. This assumption underestimates the exposure in the case that there is a difference between outdoor and indoor concentrations because some time is spent outdoors at work.

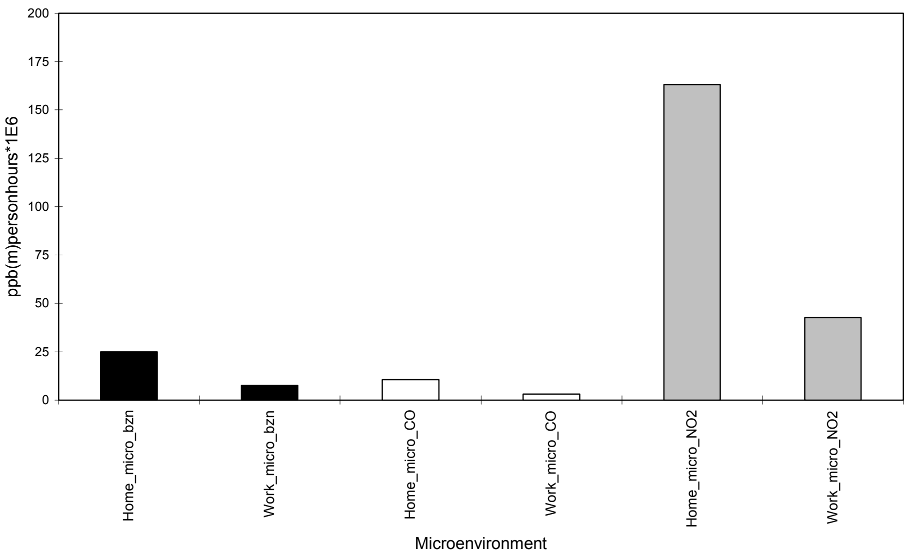


Figure 6.14 Comparison of the exposure estimate for the age group 18-54 between the residence and workplace microenvironment in 1996 assuming that all the time is spent indoors at the workplace microenvironment. For CO the exposure estimate has the unit of ppmpersonhours.

The exposure estimates at the workplace microenvironment are about 26-30 per cent of the residence microenvironment. This estimate seems reasonable since the working time constitute about 31 per cent compared to the time spent at home under the assuming that the working time is 7.2 hours five days a week and the time spent at home is 16.5 hours seven days a week.

Commuting

Note that the comparison between the residence and workplace microenvironments does not include the exact same group of people due to commuting across the municipal boarders. Out of the 9,739 employed people with their workplace in the municipality 2,990 persons (30.7 per cent) have their residence outside the municipality and out of the 9,936 persons with paid work who have their residence in the municipality, 3,190 (32.1 per cent) have their workplace outside the municipality according to *Statistiske Efterretninger* (1996) as per 1st of January 1995. About two third of the exposures in the workplace environment are related to persons living in the municipality and one third is associated to persons from outside the municipality.

Distribution between residence and workplace microenvironments

Table 6.2 shows the distribution of the exposure estimate between the workplace and residence microenvironment as an average for all age groups. For benzene and CO the residence microenvironment constitutes 87 per cent, and 71 and 74 per cent for NO_2 and O_3, respectively. The residence microenvironment constitutes less for NO_2 and O_3 compared with benzene and CO due to differences in indoor-outdoor ratios.

Table 6.2 Distribution of exposure estimate between residence and workplace microenvironments in per cent as an average of all age groups.

Microenvironment	Benzene	CO	NO_2	O_3
Residence	87	87	71	74
Workplace	13	13	29	26
Total	100	100	100	100

Street microenvironment

Figure 6.15 shows the exposure estimate for the different road users taking into account the time spent in the streets. The exposure is entirely dominated by private passenger car road users that constitute 98 per cent of exposures in the street microenvironment.

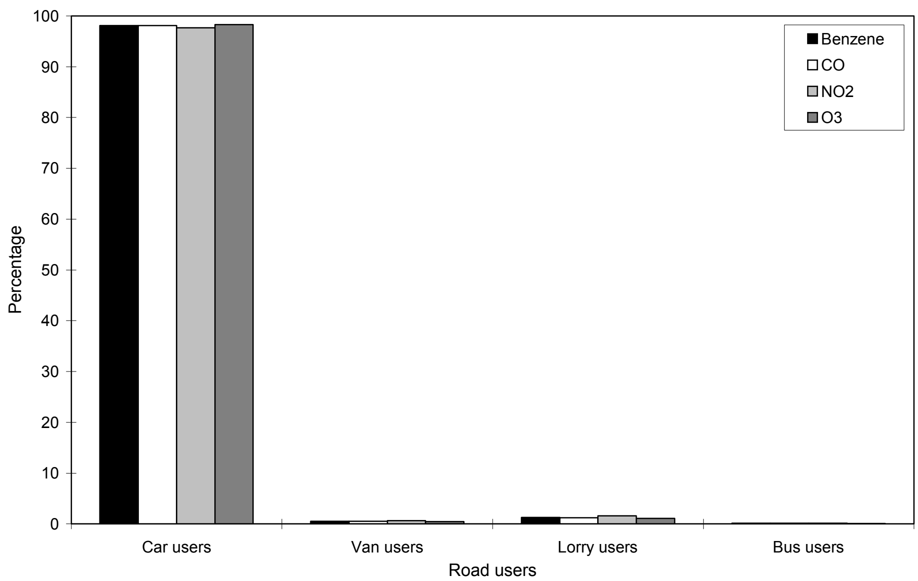


Figure 6.15 Road user exposure estimates in 1996. The outdoor-indoor ratio for all vehicle categories is assumed to be one.

Part III

Potential Model Applications

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7 Application of the Exposure Model in Air Pollution Epidemiology

Introduction

This chapter gives a short introduction to air pollution epidemiology and discusses the different types of epidemiological studies. The choice, relevance and quality of air pollution exposure indicators are essential in air pollution epidemiology and various aspects concerning exposure indicators are discussed. The potentials and limitations of the presented exposure models are discussed in relation to air pollution epidemiology, and future research needs are identified. The application of GIS in air pollution exposure and health studies has also been discussed by the author in an article (Jensen 1998b).

7.1 Types of Epidemiological Studies

Air Pollution Epidemiology

The study of health effects of air pollution is heavily depending on air pollution epidemiology which again requires estimation of human exposure. Air pollution epidemiological studies investigate, the relationship between the distribution of disease in the population and determinants (Williams 1991). Epidemiological methods are often faced with the problem of trying to detect a small signal among a lot of noise to establish associations between health outcomes and exposures to air pollution. Epidemiological methods are based on statistics and an association between air pollution and health outcomes is not necessary causative. An observed association is more likely to be causative if it meets certain criteria like strength, consistency, specificity, coherence, plausibility etc. In *Hill* (1965) nine criteria were identified to assess the likelihood of causation.

Types of epidemiological studies

Beaglehole et al. (1993) classify epidemiological studies in observational and experimental studies which are further divided into subgroups. Below the potential use of air pollution models are briefly discussed in relation to the different types of epidemiological studies.

Observational studies

In observational studies the observer studies the occurrence of a disease in a population (descriptive studies) or analyses the relationships between health status and other variables e.g. air pollution (analytical studies). Descriptive studies do not include exposure assessment but they are often the first step in generation of hypotheses about health status and exposures. Analytical studies are further subdivided into ecological, cross-sectional, case-control and cohort studies.

Ecological studies

Ecological or correlational studies focus on populations or groups usually within larger geographic areas and study the relationship between diseases and possible determinants e.g. exposure or other risk factors. Since the studies are carried out at a high geographic level of aggregation e.g. by country or region the observed relationships may not be applicable at the individual level due to bias. Therefore, the analytic methods that consider individuals rather than groups: cross-sectional, case-control and cohort studies are often used to test hypotheses generated by descriptive or ecological studies.

Cross-sectional

Cross-sectional studies measure the prevalence of disease in a population. These studies are also termed prevalence studies. Assessment of exposures are carried out at the same time as the determination of the effects. Cross-sectional studies are helpful to assess e.g. the health care needs of the population.

Case-control

Case-control studies include a group of persons with a disease and a suitable control group without the disease. A possible relationship between the disease and exposure is examined by comparing the exposure of the two groups. Case-control studies are usually used to investigate rare diseases and they investigate the influence of past exposures before the time of diagnosis. The Danish Childhood Cancer Project headed by the Danish Cancer Society is an example of a case-control study of the relationship between exposure to traffic air pollution and development of childhood cancers. Exposure estimates at the children's home address during their childhood were carried out by NERI using the OSPM model and inputs generated from a questionnaire (Raaschou-Nielsen et al. 1996; Vignati et al. 1997; Jensen 1997b, 1998).

Cohort studies

Cohort studies start out with a group of healthy persons (a cohort) who are classified according to exposures. Exposures are assessed and the cohort is followed in time to detect developments of new cases of diseases. Cohort studies are also called follow-up or incidence studies.

Experimental studies

In experimental studies an intervention is carried out in an attempt to change what is believed to cause the disease e.g. exposure or behaviour, or to influence the disease through treatment. Experimental studies include: randomised clinical trials, field trials involving disease-free people at risk, and community trials similar to field trials but involving whole communities. Examples of experimental studies are testing of vaccines, treatments, or preventive actions reducing the exposures.

Geographic epidemiology

Epidemiological studies with a geographic focus are also termed geographic epidemiology that gives "a description of the spatial patterns of disease incidences and mortality" (English 1996). These studies fall into descriptive studies. However, large-scale descriptive studies consider geography at a high level of aggregation and therefore they are unable to detect environmental factors that are spatially localised e.g. diseases that are affected by the proximity to air pollution from an industrial plant. Geographic epidemiology that considers such smaller geographic areas have been termed small-areas studies (Cuzick and Elliott 1996).

7.2 Air Pollution and Epidemiological Studies

In Table 7.1 the different types of epidemiological studies are listed and related to the geographic extent and time periods they typically cover; and the possibility of using air pollution modelling for exposure assessment in the different types of studies is indicated.

Descriptive and experimental studies

Air pollution modelling is not relevant in descriptive studies since exposure assessment is not included in these kind of studies. Air pollution modelling will probably not be relevant for experimental studies because these intervention studies focus on the change in health status as a consequence of an intervention and not on the exposure itself.

Ecological studies

Large-scale transport models that estimate average concentrations over a coarse grid may be used for ecological studies for larger areas e.g. ozone levels on a 50x50 km grid for studies of differences between health status and exposure in different parts of Europe. On the other hand, small-area studies that consider localised phenomena require a finer scale e.g. a dispersion model like the Danish OML model to study concentration levels and exposures around a point source (Olesen et al. 1992).

Cross-sectional, case-control and cohort studies

Cross-sectional, case-control and cohort studies consider data on health endpoints of individuals together with data on exposures. The presented exposure model may be used in these types of epidemiological studies if exposures to traffic air pollution is under consideration with the residence as exposure indicator (or any address based exposure indicator e.g. the workplace address).

Typical time periods

In Table 7.1 the different epidemiological studies have been grouped into the typical time periods. *Past* indicates that the health effects and exposures are usually considered historically and over a longer time period. *Present* indicates that the health effects and exposures are considered at the same time. *Future* indicates that future health effects and exposures are followed in time from a starting point. Concentration measurements to determine exposures are seldom available when exposures took place in the past. Air pollution modelling may here be the best choice to determine exposures. In the case that the study involves many individuals it is costly and impractical to carry out measurements; and application of models may be the best alternative. Apart from estimating past concentrations the models obviously also have to be able to predict present concentrations and to follow levels in time.

Table 7.1 Types of epidemiological studies by *Beaglehole et al.* (1993). Further elaboration concerning various characteristics in relation to air pollution modelling.

Type of study	Unit of study	Typical geographic extent				Typical time periods			Potential for air pollution modelling
		Int.	Nat.	Reg.	Loc.	Past	Present	Future	
Observational studies:									
Descriptive studies	Population	•	•	•	(•)	•	•		
Analytical studies									
Ecological	Population	•	•	•	(•)	•	•		•
Cross-sectional	Individual		•	•	(•)		•		•
Case-control	Individual		•	•	(•)	•			•
Cohort	Individual		•	•	(•)		•	•	•
Experimental studies:									
Randomised controlled trials	Patients		•	•				•	
Field trials	Healthy people		•	•				•	(•)
Community trials	Communities				•			•	(•)

7.3 Exposure Indicators in Air Pollution Epidemiology

Air pollution epidemiology covers: health effects and exposures; and studies the relationship between these two variables. The methodology for collection of health effect data includes the choice of health effects and their determination and collection (Brunekreef 1992). Health end-points may include data on mortality and morbidity (e.g. lung function measurements, hospital admissions, medicine use). Air pollution epidemiology is a multi-disciplinary co-operation between epidemiologists, and exposure experimentalists and air quality and exposure modellers. The present work focuses on the part of exposure assessment.

Important exposure and dose factors

Important exposure factors are the spatial and temporal variation of concentrations in the microenvironments visited by a person. The dose is closer related to the health effects than the exposure and requires e.g. an estimation of the inhalation rate. The inhalation rate may be assessed from data on physiology and activity level. However, air pollution epidemiology rarely attempts to estimate doses but relies on exposure indicators.

Exposure methods in air pollution epidemiology

In chapter one the different exposure assessment methods were outlined and they are further discussed in *Larsen et al.* (1997). The direct methods include personal and biological monitoring and the indirect methods cover categorical classification, fixed monitors and the microenvironment approach. Below the different exposure indicators are listed with respect to their general accuracy with the most accurate exposure indicator listed first: personal monitoring, microenvironmental approach, fixed monitor stations and categorical classification. Furthermore, measurements will in general be more precise than model results but also more costly and impractical to carry out.

Categorical classification is considered an inadequate method in current air pollution epidemiology where the use of fixed monitors is the most common exposure indicator. In recent year, personal monitoring and the microenvironment approach are increasingly applied, and the application of air pollution models have also increased (Williams 1991).

Ecological studies will typically use indirect exposure methods like fixed monitor stations or maybe categorical classification e.g. city size whereas the studies that consider the individual level: cross-sectional, case-control and cohort studies mainly use fixed monitor stations, or personal monitoring or the microenvironment approach in the case of a small study design. Personal monitoring or the microenvironment approach may also be used for a smaller sample of cases as a validation study of a model that is then used on all the cases included in a study. In recent years, some of the air pollution epidemiological studies that have received most attention are the American cohort studies covering 6 and 151 American cities, respectively, that have showed a highly significant relation between levels of finer particles and mortality and morbidity (Dockery et al. (1993); Pope et al. (1995)). These studies used fixed monitor stations as exposure indicators. The implications of these findings on Danish conditions are discussed in *Larsen et al.* (1997, 1997a).

A short review of the few Danish air pollution epidemiological studies and their use of exposure methods is outlined in *Larsen et al.* (1997).

Biological relevance of exposure indicator

In epidemiological studies it is important to chose relevant air pollutants as exposure indicators that correspond to the health end-points included in the study. This is not a trivial task since people are exposed to a mixture of pollutants and this mixture may involve combination effects. Furthermore, the relationship between exposure and biological response may not be fully understood. Additionally, measurement techniques and availability of air pollution data may pose limitations. The health effects of particles have traditionally been studied with TSP or soot as air pollutant exposure indicators because limit values were defined according to these particle fractions. However, the above mentioned American studies indicate that the finer fractions (PM_{10} and $PM_{2.5}$) are more closely related to the health effects than TSP and even smaller particles fractions may be better air exposure pollutant indicators.

Importance of averaging times

Apart from chosen an air pollutant exposure indicator that is relevant according to the health end-points under study, the averaging times should also correspond to the health end-points. For acute effects associated with NO_2 exposures short-term exposure estimates with short averaging times e.g. one hour or one day should be applied, and long averaging times e.g. monthly or annual means could be used for chronic effects associated with long-term exposures to e.g. a carcinogenic pollutant like benzene.

Errors and confounding

The quality of the exposure indicator is important and may be affected by random and systematic errors. Random errors should be diminished through quality assurance. Apart from the selection of subjects systematic errors or bias may occur in estimation of exposure leading to exposures that in a systematic way differ from the "true value" e.g. in measurements or modelling of exposure. Confounding is a special systematic error that may occur. A confounder is a concurrent variable that can influence the association between the air pollution and health end-points because it is associated both to the exposure and the health outcomes, for example, smoking in a study of lung cancer of ambient air pollution, or variables like temperature and humidity in a study of acute health effects under air pollution episodes. Indoor sources like gas stoves, building materials and consumer products, but also occupational exposures may be confounding factors because these indoor sources may have a significant impact of total exposure since the majority of the time is spent indoors. It is important to exclude the effect of confounders in the study design; or to include the possible confounders in the data collection for control of the effect of confounding in the data analysis (Beaglehole et al. 1993).

7.4 Potentials and Limitations of the Exposure Model

In the following the potentials and limitations of the developed exposure model are discussed in relation to its application in air pollution epidemiology.

Relevance in epidemiological studies

The exposure model is of particular interest in cross-sectional, case-control and cohort studies that consider the individual level, as well as in small-areas studies. The model is not suitable for ecological studies that regard large aggregated geographical areas.

Model estimates versus measurements

The exposure model will be able to estimate exposures where measurements are not available in space or time. The exposure model can also be run for many subjects and for long time periods at a low cost compared to measurements. Furthermore, the exposure model is also able to represent the spatial variation between different locations within a geographic area much better than e.g. a fixed monitor station. The exposure model can predict the temporal variation in air pollution. However, in the cases that predicted street levels are dominated by the contribution from the background levels e.g. in rural areas, the temporal variation may differ due to the standardised way that background levels are generated (Jensen 1998).

The residence as exposure indicator for children and adults

The exposure model estimates exposures at locations. In air pollution epidemiology the residence microenvironment is of primary interest because address based health information already exists for individuals related to the residence address (the Danish Cancer Registry etc.). The workplace microenvironment may also be of interest if traffic is the major source of occupational exposure. The relation between front-door concentrations at the residence address and personal exposures to NO_2 and benzene during 1994 and 1995 was evaluated in the Childhood Cancer Project covering about 100 children in urban areas (Copenhagen) and 100 children in rural areas (outside Copenhagen) (Raaschou-Nielsen et al. 1997a,b). These studies show that the front-door NO_2 concentration is a fairly good indicator of personal exposure ($r^2 = 0.49$) especially in urban areas but also in rural areas ($r^2 = 0.45$) when considering a selection of cases that were exposed to indoor sources in a limited way. Apart from front-door concentrations the personal exposure was also influenced by bedroom concentrations, time spent outdoors, gas appliances used at home, passive smoking and burning candles. The median personal exposure was 8.0 ppb and 3.7 ppb in urban and rural areas, respectively, and the front-door concentrations were 18.6 ppb and 5.2 ppb for urban and rural areas, respectively. The front-door benzene concentration was a less good indicator for personal exposure in urban areas ($r^2 = 0.36$) and in rural areas ($r^2 = 0.43$) when compared to NO_2. The median personal exposure was 1.7 ppb and 1.4 ppb for urban and rural areas, respectively, and the front-door concentrations were 2.8 ppb and 0.6 ppb for urban and rural areas, respectively. Since front-door concentrations were lower than personal exposures in rural areas other sources than the direct street emissions influence the exposure to benzene. Personal exposure of children was also influenced by riding in cars, exposure to gasoline vapours like motocross, moped driving and refuelling of cars.

The recent MACBETH study has also investigated the relationship between front-door benzene concentrations and personal exposure of adults (50 subjects in Copenhagen by passive sampling during 1998). The study showed the same tendency as the Childhood Cancer Project with average outdoor level of 1.3 ppb and personal exposures of 2.4. The data analysis has not yet been finalised (Skov et al. 1998).

The use of standard time profiles

The exposure related to the front-door concentrations at the residence address corresponds to the outdoor simple exposure index. As demonstrated in chapter seven standard time profiles for time-activity patterns for the different age groups may be used to refine the exposure estimate. Provided that standard time profiles are available for air pollution epidemiological studies they may refine the exposure estimate, although, this still has to be validated by comparison between modelled exposure estimates using standard time profiles and exposure measurements.

Urban versus rural areas

As indicated above the residence address is a better indicator for personal exposure in urban areas than in rural areas. The exposure model will also produce the best results in urban areas where the contribution from street emissions dominates (about 50 per cent for NO_2 and about 80-90 per cent for CO and benzene). The impact of background concentrations will be higher for streets with little traffic compared to busy streets. Since most rural areas will be characterised by low traffic levels the impact of background concentrations on predicted street concentrations will generally be higher in rural areas compared to urban areas. There is a higher uncertainty on the predicted background levels due to the standardised way these were constructed than on the estimation of the direct contribution from traffic in the street (Jensen 1998).

Averaging times

A test of the modelled background concentrations was carried out for a busy street in Copenhagen (Vignati et al. (1997)). The relationship between measured and calculated street concentrations was good (r^2=0.84). However, the model underestimates the highest concentrations because the background model is based on average profiles of monthly and monthly diurnal variations that will not account for extreme situations. For monthly means the differences for NO_x and NO_2 between model results and measurements were less than 10 and 15 per cent, respectively. For annual means the differences for NO_x and NO_2 were less than 1 and 3 per cent, respectively. The uncertainty of the model increases for shorter averaging times (annual mean to monthly mean) and the uncertainty would increase further for even shorter averaging times (weeks, diurnal and hourly). The evaluation shows that the background model can be applied in epidemiological studies which considers long-term exposure on at least a monthly basis with the present design of the background model. Long-term exposure assessment in epidemiological studies is mainly suitable for studies of chronic effects e.g. cancer.

Temporal variation

In epidemiological studies two variables are studied at the same time: exposure and health status. Therefore, the ability of the exposure model to estimate the temporal variation is important. The temporal variation of the direct contribution from traffic will be well characterised because traffic levels differ little from the standardised traffic profiles applied in the exposure model (Jensen 1997b). The temporal variation in background concentrations will be more smoothen out as it will not take into account extreme values that may be encountered under an episode due to long distance transport of air pollution.

Pollutants

The traffic air pollutants that raise most health concerns are: fine particles, NO_2, O_3, PAH, benzene, 1,3-butadiene, ethene and propene, and aldehydes (formaldehyde, acrolein, acetaldehyde) (Larsen et al. 1997). At present the exposure model only considers NO_2, O_3, CO and benzene. However, it may be extended with PAH, 1,3-butadiene, ethene, propene, and the aldehydes provided that traffic emission factors and background concentrations were known for these species, and provided that possible chemical transformation in the street environment is known or insignificant.

Fine particles

In terms of health impacts fine particles raise most concern and it is important that a future version of the OSPM model is able to handle fine particles. However, particles pose a challenge because they consist of a mixture of particle sizes that originate from different sources, coagulation and condensation processes are taken place, and particles are also affected by the humidity. Work is carried out to include particles in the OSPM model at NERI (Vignati et al. (1998)).

Confounding

The exposure model does not take into account indoor sources. Data on these sources would have to be provided separately in an epidemiological design and controlled for. Nor does the model take into account other local sources than traffic e.g. a strong industrial point source. To model point sources the exposure model would have be extended with the OML model.

Data requirements

The exposure model requires the following data: cadastral maps as polygons, building theme as polygons, road network as polylines, addresses as points, data from the national databases: CPR, CER and BBR and traffic data.

Other data

The cadastral map is already national, and most municipalities have digital maps on buildings, roads and addresses although the quality varies. TOP10DK that includes buildings and roads covers a large part of the country and will be complete in a few years. A national address database is also on its way and it is expected to be complete in a few years. The databases CPR, CER and BBR are already national. All in all, most of the data required for the exposure model is already available or will be in a few years for any location in Denmark.

Traffic data

For the time being collection of traffic data is the most time consuming task. Most municipalities have traffic data but it may not be linked to the digital road network. However, it is likely that most municipalities will link their traffic data to the road network within the coming years. Therefore, it should be easier to collect traffic data in the future. However, for a larger area that includes several municipalities detailed traffic data would still have to be collected for each municipality individually.

VejNetDk - a national database linked to the road network - is available but it only includes the state roads, most county roads and the major municipal roads. Smaller roads with less traffic are not included. There is no initiative in progress to establish a national road and traffic database that also includes the smaller roads. However, the Danish Road Directorate has been assigned increased road sector responsibility as part of a new Act of Parliament which may lead to increased interest in serving the municipalities e.g. with a national database that also covers all municipal roads.

7.5 Future Research Needs

Future research needs are discussed within three main topics: refinements of the presented exposure model, development of a personal exposure model, and development of a model for national health risk assessment.

Refinements of the presented exposure model

Concentration levels

Estimation of the concentration levels at the address could be further refined. The street configuration data are determined accurately, however, the exposure point may not be representative for the address in the case that the address is associated to a street with low traffic but is located close to a street with heavy traffic e.g. at intersections. Contributions from the main road or from both roads in intersections could be taken into account. Refinements could also be made in estimation of the temporal variation in traffic and cold start as outlined in *Jensen* (1997b). The background model may be refined or alternatively a new more dynamic approach could be developed to improve the determination of the temporal variation in background concentrations that will benefit estimation of street concentrations in rural areas and in urban areas with little traffic where the impact of the background levels on the street levels is significant (Jensen 1998). Activities are undertaken at NERI to develop a more dynamic urban background model.

Indoor-outdoor ratios for Danish conditions may be better investigated to provide for modelling I/O-ratios as a variable.

To be able to estimate the small fraction of particles would also be beneficial in relation to air pollution epidemiological studies.

Population data

The exposure is determined by the concentration levels and the presence of people. Generation of *Danish* standard time profiles for the presence of people at the residence and workplace microenvironments would benefit exposure assessment.

Personal exposure model

Potentials

The presented exposure model does not describe exposure by following a person in space and time as illustrated in Figure 7.1. However, the presented exposure model has a potential for further development into a personal exposure model.

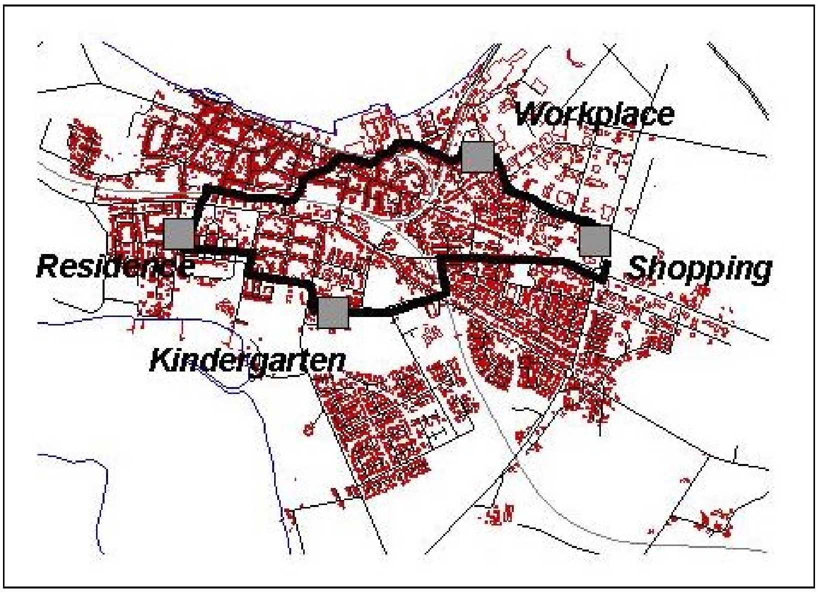

Figure 7.1 Hypothetical example of a person's time-activity pattern in a city during a day that can be used to model personal exposure in GIS.

Benefits

Air pollution epidemiological studies are expected to benefit from a more accurate exposure assessment by using personal exposure assessment that will improve the study of the relation between health status and exposures. Traditionally, time-activity patterns have been collected by questionnaires or by using a personal activity data logger (an electronic diary). GIS, GPS and microenvironment and activity sensors provide new opportunities for collecting time-activity data for personal exposure assessment. However, subjects still have to wear GPS receivers and sensors.

GIS and GPS

Geographic Information Systems are based on co-ordinates. Provided that a time-activity pattern is described by a set of co-ordinates it is possible spatially to describe the time-activity of a person as a polyline. Provided that the time also is recorded at the same time the temporal characteristics of the time-activity pattern can be described (movement, residence time at locations). Using this time-activity data in combination with the concentration levels modelled in the streets and at addresses, the presented exposure model could be further extended to estimate personal exposure. A new extension allows GPS data to be handled in ArcView with Tracking Analyst (http://www.esri.com). Global Positioning System (GPS) receivers are able to provide co-ordinates with an accuracy within 10 m which is sufficient to be able to link a time-activity pattern to a trip in a road network and locations visited. GPS relies on satellites to determine the position at the ground. GPS receivers are becoming less expensive, and are commercially available at low prices for ordinary consumers for navigation of sailboats, route navigation of cars, route and position guidance for hikers, tourists etc.

Microenvironmental and activity sensors

Apart from knowing the spatial and temporal characteristics of time-activity patterns it is important to cover the microenvironments that a person visits. Shadow sensors are available based on the same techniques as applied in an autofocus camera and they are able to differentiate between outdoor, indoor and in-transit microenvironments by measuring the distance from the shoulder to the ceiling. The shadow sensor is not able to differentiate between different types of e.g. indoor microenvironments like home, workplace, shopping. However, the use of buildings may be estimated based on BBR data provided that the GPS data can be associated to the address where the person stays. Alternatively, the addresses that a person visits could be collected separately. Light weight activity sensors are also available e.g. a heart rate sensor that can be used for rough determination of a person's activity level to be able to estimate the inhalation rate for dose estimation. GPS, and microenvironment and activity sensors are further discusses by *Jantunen* (1995) from a time-activity monitoring point of view. These methods should be further validated in pilot studies before they are applied on a larger scale.

Burden and privacy

Compared to traditional ways to collect time-activity data the burden to subjects is low since they only have to wear a few instruments of the size of mobile telephones. The use of GPS, microenvironment and activity sensors may be more invasive to the subject's privacy because very detailed information is collected, although, this should not pose a problem if data are treated anonymously and in an aggregated form.

Time-activity studies

No personal Danish time-activity studies have been carried out of the general population. As part of the Childhood Cancer Project some coarse time-activity data were collected for selected children for model validation purposes (Raaschou-Nielsen et al. 1997a,b). Danish time-activity studies should be carried out in support of exposure assessment, health risk assessment and validation of personal exposure models.

Validation studies

In development of a personal exposure model, validation studies are essential to be able to compare observed and modelled exposure data. Such studies requires measurements of personal exposures, time-activity patterns and indoor-outdoor ratios. *Hertel et al.* (1998) have already showed that the OSPM model is able to reproduce the personal exposures of bus drivers and postmen to traffic air pollution in their working environment.

SMP project

As part of the Danish National Environmental Research Programme (SMP), the National Environmental Research Institute is expected to develop a prototype of a personal exposure model based on the presented exposure model and time-activity data collected e.g. by using GPS receivers (Poulsen et al. 1998).

National health risk assessment

Risk characterization

Health risk assessment involves: hazard identification, effects assessment, exposure assessment and risk characterization as described in chapter two. Risk characterization attempts to quantify the health impacts of air pollution to a population based on a combination of exposure assessment and effect assessment (dose-response).

National exposure assessment

Provided that a national population exposure assessment is available it is possible to carry out risk characterization for pollutants with known dose-response relations. The presented exposure model will be used to establish a national population exposure model based on the residence as exposure indicator. The National Environmental Research Institute has initiated a joint project between the Department of System Analysis and the Department of Atmospheric Environment with the aim to develop a national exposure model by combining the presented exposure model and a prognostic transport behaviour model. The integrated model will be used to assess the population exposure as a consequence of different transport behaviour scenarios. The presented exposure model will be applied for selected urban areas and extrapolated to the national level (Rich et al. 1997).

Risk characterization and economic impact

The national exposure model may in combination with dose-response relations be used to carry out rough estimates of the health impacts of the traffic air pollution and economic impacts provided that the health impacts can be evaluated in monetary terms (Geernaert and Jensen 1997).

8 A Management Tool for Urban Air Quality Planning

In this chapter, current Danish air quality planning and examples of existing GIS based decision-support systems for urban air quality management are briefly discussed. Then the exposure model is discussed in the context of application by local authorities in urban air quality planning and future research needs are identified. The author has also discussed the application of the exposure model as a decision-support tool for urban air quality management in a paper (Jensen 1998a).

8.1 Current Danish Urban Air Quality Planning

Air quality monitoring

Urban air quality monitoring is carried out in three larger Danish cities (Copenhagen, Odense and Aalborg) as part of the National Danish Air Monitoring Programme (LMP) managed by NERI (Kemp et al. (1997)). Air Quality Monitoring in the Greater Copenhagen Area is carried out by the "Hovedstadsregionens Luftovervågnings-enhed (HLU)", at the EPA of the Municipality of Copenhagen (Miljøkontrollen) (HLU 1996). The network includes stations in Copenhagen and other cities in the Greater Copenhagen Area (Køge, Glostrup and Frederiksværk).

Warnings and information

The monitoring networks are also used for smog and ozone warnings of the Danish population under episodes, and for daily information to the Copenhagen public via radio concerning the current air pollution conditions (very high, high, slightly increased, medium, low), and via Text-TV (pages 580-582) and the Internet (www.dmu.dk).

Mapping and action plans

The Municipality of Copenhagen is the only municipality that has carried out a systematic mapping of air pollution levels covering 500 streets in Copenhagen using the simple BLB model (Miljøkontrollen 1995) and the municipality has also prepared a local traffic and environmental plan (Københavns Kommune 1997). The goals for emission reduction are to contribute to the achievement of the national emission reduction goals for the transport sector. For the air quality the long-term goal is that NO_2 levels should be lower than 135 $\mu g/m^3$ (98-percentile) for streets with residences and institutions. A sub-goal during 1995-2010 is to reduce the number of residences exposed to NO_2 levels above 135 $\mu g/m^3$ (98-percentile) by 30 per cent. The goals are expected to be reached through stringent emission standards and local traffic and urban planning measures although the plan does not document that the measures are sufficient to meet stated goals. A number of smaller cities have also carried out a local traffic and environmental plan, and the air quality assessment has been limited to a few busy street canyons using the BLB model for predicting NO_2 and CO levels. The municipalities have had the opportunity to apply for funding of abatement measures from the

Danish EPA provided that they have prepared a local traffic and environmental plan.

Copenhagen

The EPA of the Municipality of Copenhagen has taken part in the development of the "Integrated System for Implementing Sustainability" (ISIS) among three other European cities and regions: Berlin, Kirklees (UK) and Madeira (Kirklees Metropolitan Council 1997). The system was developed during 1994-96 and funded by the EU LIFE Programme. The system aims to guide policy makers, decision-makers and administrators at local authority level regarding road traffic planning and covers air pollution, noise, health and social impacts, and energy. In Madeira, the system was based on a GIS structure (ArcInfo) which organises the data, and feeds the ISIS system. In the case of Copenhagen, GIS was not applied and the system focuses on general information, goals within task areas, mapping of sustainability indicators and suggestions on possible actions for improving the environment. The system did not include tools for scenarios and impact assessment of different abatement measures. The system was primarily an information system for serving general needs of policy makers and not a true decision-support system serving the needs of planners. The system is not in operation at the EPA of the Municipality of Copenhagen, and therefore at present no computerised Decision- Support System (DSS) within urban air quality management is in operation in Denmark.

As indicated above, present Danish urban air quality management mainly consider monitoring, and alert and information systems. Comprehensive emission inventories, mapping of air quality and action plans are almost entirely missing, and decision-support systems are not applied.

8.2 Examples of Existing Urban Air Decision-Support Systems

Other European cities

In a number of larger but also medium-sized Nordic and European cities different urban air quality management systems are in operation based on e.g. AirQuis, EnviMan and AIDAIR as described in chapter 1.

Potentials

These systems are built on a PC client-server platform and consists of a package of sub-models where the customer buys the sub-models needed. The systems have a high quality in user-interface and visual presentation techniques. They incorporate simple GIS functionalities (e.g. zoom, query, editing etc.) and handle vector maps (e.g. roads as lines). The systems may include handling of data from air quality monitoring networks e.g. data collection, quality assurance, report generation. Facilities may also be available to display data on the Internet. Next-day forecasts of pollution levels may also be available requiring accessibility to meteorological forecast data. The systems may include different air quality simulation models for point, area and line sources that facilitates mapping, and scenario and impact assessment for decision-support. Emission inventories that match the requirements of the simulation models are obviously a part of the systems. The AIDAIR system is an example of a system that provides interface with a traffic model (Emme/2).

Limitations

The street air pollution models applied in the above mentioned DDS systems are generally simpler models e.g. empirical-statistical models or line source models. Most systems have incorporated simple GIS functionalities but more advanced spatial and network analyses have to be carried outside the user-interface of the system using a standard GIS. The systems seem to be able to handle detailed vectorised road networks. However, other data like population data seem to be treated on a crude spatial resolution e.g. grids or blocks. The systems may also include simple exposure assessment e.g. concentration levels times population on a crude grid basis but the main focus is on handling monitor data and to predict air quality levels under different assumptions. Address based population data and more detailed street air pollution models for exposure assessment are not part of present decision-support systems.

8.3 Conceptual Urban Air Quality Planning System

In Figure 8.1 a conceptual diagram of the air quality planning process is visualised in relation to the DPSIR and the source-effect concepts. The planning process may be seen as the *response* in the DPSIR concept where elements of the planning process target different components of the DPSIR and source-effect elements.

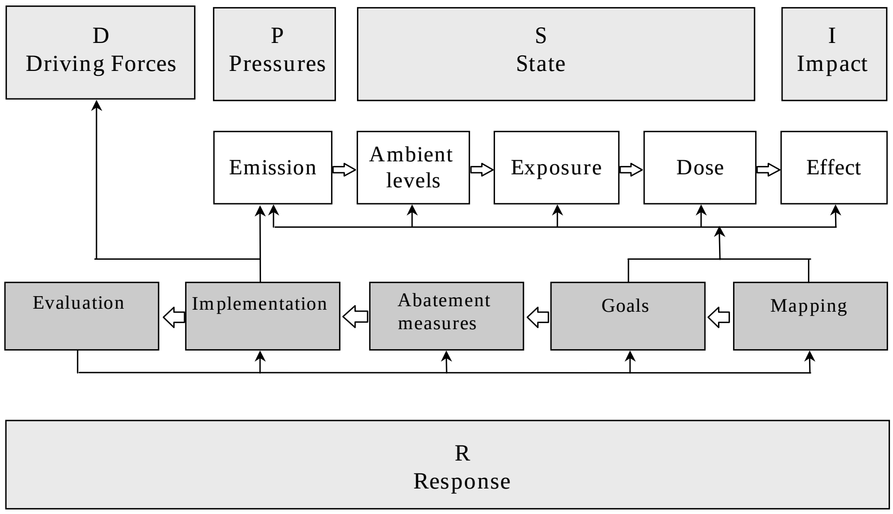

Figure 8.1 A conceptual diagram of the air quality planning process related to the DPSIR and the source-effect concepts.

The planning process

Urban air management is an ongoing process that includes the main elements in the planning process: mapping, goals, abatement measures, implementation and evaluation (Miljøministeriet 1992). Mapping and the subsequent priority of task areas may in principle be directed to any element of the source-effect chain and the same counts for setting of goals. Then abatement measures are identified to meet the goals and an action plan is drawn up for implementation. Recurrent evaluation of the actions taken are also part of the planning procedure to assess whether the goals are met and to carry out possible revisions of goals and/or abatement measures. The possibilities and limitations of an urban air quality management system based on the outlined air quality and exposure model are discussed in further details in the following related to the planning process.

8.4 Target Group of Municipalities

Political and administrative interest is an essential requirement for a municipality to acquire an urban air quality planning system, and determines the potential number of cities interested in such systems.

Health interest

Recent research raise health concerns especially for fine particles but also for other pollutants at levels experienced in Denmark which increase political and public awareness of air pollution.

Legal interest

Cities with more than 250,000 inhabitants or urban areas with a population density where management of the urban air quality is justified are required to monitor and assess (e.g. by modelling) air pollution according to a new EU directive (Rådets Direktiv 96/62/EF). Appropriate actions have to be taken to avoid exceedances of new EU limit values, and information to the public about exceedances of certain threshold values is also required. The four largest Danish cities: Copenhagen (565,000 inh.), Aarhus (215,000 inh.), Odense (145,000 inh.) and Aalborg (120,000 inh.) meet these requirements. Copenhagen, Odense and Aalborg are presently part of the Danish Air Quality Monitoring Programme.

Other interests

Although smaller cities are not required to establish air pollution monitoring and assessment they may benefit from the possibilities to document compliance with limit values, to inform the public and especially sensitive groups of citizens about air pollution, to enhance the urban air quality for health precaution reasons, and to create an improved environmental quality for the benefit of citizens, commerce, business and tourism. Apart from the cities mentioned above, seven Danish cities have a population of more than 40,000 inhabitants where some kind of air pollution assessment system could be a possibility.

Other requirements

The scope of a possible urban air quality planning system will also be determined by the investment and running costs, organisational and knowledge considerations e.g. manpower requirements and skills, availability and accessibility of the required data etc.

Users

The basic idea of decision-support systems is to improve the foundation for policy-makers in the decision-making process by providing a professional tool to assist air quality planning. The day-to-day users are planners and technicians in the municipality. Consultants from consulting companies or NERI may also be users of such systems, and e.g. assist municipalities in the establishment of a decision-support system (DDS) and maybe carry out special purpose analyses.

Transparency

Transparency is a keyword for such systems as decisions should be made by humans not computers. This implies that if value judgement parameters were to be incorporated into the systems e.g. for multi-criteria analysis they should be in control of the user and not hidden in the system.

8.5 Mapping

The first step in the mapping process is to identify relevant environmental indicators, to determine the method for mapping these indicators and to determine the scope of the mapping. The second step is to identify problems based on the mapping and to identity task areas for further action. As indicated in Figure 8.1 any of the components of the source-effect chain: emission, ambient levels, exposure, dose and effect may in principle be a target for mapping.

Mapping Elements of the Source-Effect Chain

Existing air management systems focus on mapping of emissions and ambient levels.

Emission

Emission sources to urban air pollution is dominated by traffic, but other local sources like industry, domestic heating etc. also contribute. From a modelling point of view these sources may be regarded as line sources (e.g. traffic), point sources (e.g. larger industrial stacks) and area sources (e.g. oil-fired central heating systems in a residential area). The data collection for the emission inventories is closely related to the requirements of the different models. Apart from emission inventories the models may require meteorological, urban topographical and background concentration data. A traffic emission inventory of CO, benzene and NO_x can be carried out based on the OSPM emission submodel for past, present and future emissions.

Ambient levels

In urban air management the selection of relevant pollutants will in most cases be based on health considerations. The traffic air pollutants that raise most health concerns are: fine particles, NO_2, O_3, PAH, benzene, 1,3-butadiene, ethene and propene, and aldehydes (formaldehyde, acrolein, acetaldehyde) (Larsen et al. 1997). Obviously, emission data and models have to be available to be able to predict ambient levels of these pollutants. However, at present the OSPM model computes NO_2, O_3, benzene and CO (hourly time-series) and BLB only NO_2 and CO (only as percentile and eight hour running mean, respectively). Although, fine particles may be the most critical pollutant, the complexity of processes that determines the ambient levels of particles makes modelling difficult. To determine the ambient levels of the other pollutants require emission factors and a description of possible chemical reactions that influence the levels. Activities are undertaken at NERI to develop a particle submodel for the OSPM model.

Automatic generation of input data

Collection of street configuration data have been an obstacle for carrying out air quality mapping for large urban areas. The automatic generation of street configuration data for the OSPM model by the urban landscape model is a unique functionality that makes air quality mapping manageable for large urban areas. Development of the methods to generate the temporal variation of traffic and the temporal variation of background concentrations also facilitates mapping of large urban areas.

Air quality assessment

In order to compare predicted levels with air quality limits and guidelines the predicted levels obviously have to be represented in the same way, and the OSPM model is able to met this requirement.

Sustainability indicators

Sustainability indicators may also be used in presentation of mapping results e.g. as an index defined as the ratio between predicted levels and air quality guidelines.

Monitoring

The use of fixed ambient air quality monitoring stations in an urban air management system provides data for air quality assessment, information, warnings and alerts to the public, and provides data for development and validation of models. However, due to the high investment and operation costs of monitoring stations they are not cost effective for mapping purposes. The combination of well equipped monitor stations and models provides a good foundation for mapping. Monitoring is not part of the exposure model.

Next-day forecasts

Next-day forecasts of air quality levels may also be part of urban air quality management and require a prognostic meteorological model and fast computers (workstations). Activities are undertaken at NERI to develop next-day forecasts, and next-day forecasts are not part of the exposure model.

Exposure and dose

The present air management systems may include simple exposure assessment on a crude spatial resolution but non of the systems consider dose assessment. These systems could benefit from improved exposure assessment because human exposure estimates are better indicators for health effects than ambient levels. The high spatial resolution of the simple exposure index and the exposure estimates using time profiles proposed in the exposure model may serve as improved exposure indicators.

Effects

Local effects of air pollution are health problems and annoyance, harm to the vegetation and deterioration of building materials. The urban air pollution is also a source to regional environmental problems e.g. acidification, eutrofication, photochemical pollution, and to global problems like global change (CO_2) and depletion of the ozone layer (CFCs). Although the ultimate objective of an urban air management system is to reduce the effects of air pollution even state of the art management systems do not map the effects explicitly.

Estimation of health effects requires dose-response relationships between human exposures and effects, and an exposure estimation that matches the validity of the dose-response relation. Most dose-response relationships reported in the literature originates from fixed monitor stations and cannot readily be related to other exposure estimations. Quantification of health effects is not part of the exposure model.

The municipalities will tend to focus on local environmental effects as has been the case in most local environmental and traffic action plans. However, the increased focus on CO_2 emissions may force the municipalities to take this into account. CO_2 emissions and energy consumption are not integrated into the exposure model at present.

Present and future conditions

The mapping should describe the present and the future conditions as a foundation for identification of problems and task areas, and setting of goals. The future conditions are described in a reference scenario that predicts the development of air quality levels under current assumptions of developments in traffic loads and emission factors.

Visualisation Techniques in GIS

An advantage of GIS is the built-in display functionalities that provide a geographic dimension to input and output data as illustrated in chapter six. A GIS can not provide a map that could not be made by analogous means but preparation of maps using GIS is easier, faster, more flexible and cost effective, and at the same time it produces high quality maps. The result of a mapping process is selection of maps that may be presented to the public as part of citizens involvement or to the policy-makes as part of a political and administrative decision process. To produce a good map that conveys the message to the target group is not trivial and maps may be both misleading and even manipulating. *Bartels and van Beurden* (1997) discuss the cartographic principles and identify basic elements in making a map that fits the message: map symbology (e.g. size, shape, texture, orientation, colour differences), classes and classbreak (e.g. natural, equal, quantile), use of colours, scale and projection, basic map features (e.g. legend, scalebar, title). Data may be displayed according to the objects in the digital map as: points, polygons (area), and lines.

Points

Points e.g. the concentrations at an address point, the number of people living at the address and the exposure related to the address may be visualised. Visualisation using points is of particular interest for close-ups.

Polygons

Data may be visualised as polygons e.g. data that are related to polygons like buildings. The building height is an example of an attribute that is more obvious to display as a polygon as compared to an address point.

Lines

Street attribute data like traffic loads, traffic emission, width of carriageway and street concentrations may be displays as lines.

Grids and contour plots

ArcView's Spatial Analysts allows the manipulation of the objects' attribute data to make visualisations like grids and contour plots. A grid display contains grid cells where each cell has a single value. Grids are suitable for displaying density data like emission and population densities. The average concentration at all address points within a grid cell could also be displayed to give a crude picture of how concentration densities are highest in city centres and along arterial roads. However, if concentrations are averaged in grid cells, information on the spatial variation within a cell is lost and it makes little sense to compare such estimates with air quality guidelines. Concentrations may be displayed as contour plots. Contour plots consist of iso lines generated by interpolation between e.g. points with concentrations. For the urban environment it is not appropriate to generate contour plots based on street concentrations because contour lines may cross buildings which have no physical meaning, and a contour plot will not represent the high spatial variation of air pollution at ground level. However, modelled urban background concentrations may be visualised as contour plots since they have less spatial variation.

Added GIS functionalities

Most present DDSs are based on simple GIS engines with company developed advanced user-interface on top. The philosophy of the presented air quality and exposure model is to use a standard GIS system. When using a standard GIS as ArcView all the functionalities of this system are available including all the extensions developed for ArcView (e.g. Spatial Analysis, Network Analysis, 3-D Analysis etc.). Furthermore, ArcView is constantly improved and new programmes that work with ArcView provides new opportunities like MapObjects and SDE.

Use of existing data

The municipalities are developing an IT infrastructure of digital maps, databases and GIS for administrative purposes that will serve as a common foundation for a broad spectrum of activities. The presented exposure model has been considered for this IT landscape and takes advantage of existing digital maps and administrative database. Existing state-of-the DDS systems are also open and flexible systems but have been developed for general use to be sold in different countries and they not adjusted to specific Danish conditions neither on the model side (OSPM, OML) nor do they take full advantage of existing digital maps and databases.

8.6 Goals

Emission

Denmark is committed to reduce trans-boundary air pollution according to international conventions for the reduction of national emissions of SO_2, NO_x, VOCs, CFCs and CO_2. The aim of these reductions is primarily to improve the regional and global environment although reductions in SO_2, NO_x, VOCs also have local benefits (Palmgren et al. 1997). National targets for the transport sector have been set for emission reductions of NO_x, VOCs, particles and CO_2 (Trafikministeriet 1990, 1993). Targets for NO_x, VOCs, and particles are likely to be met but the development in CO_2 emissions is in conflict with the targets (Trafikministeriet 1997). The reduction in emissions is almost entirely a result of EU regulation of vehicle emission standards (catalytic converters) but the national regulation of fuel qualities (benzene, sulphur) has also contributed to reduction in benzene (a VOC) and particles (lower content of sulphur reduces particle emission).

Government Agreement

The new Governmental Agreement 1998 states that air pollution from traffic should be halved before 2007 with reference to 1990 (Statsministeriet 1998). The pollutants that are covered by this statement is not mentioned in the Government Agreement but the present goals are a reduction for NO_x and VOCs emission by 60 per cent from 1988 to 2010 and 50 per cent for particles from 1988 to 2010. If the statement covers the same pollutants it represents a minor tightening of existing goals at least for particles as the target year is advanced.

Air quality limits

Denmark has air quality limit values for NO_2, SO_2 and particles (TSP), and thresholds values for O_3 for public information and alerts under episodes. The EU Commission has proposed stringent air quality limits for NO_2, SO_2 particles (PM_{10}, $PM_{2.5}$), and proposals will follow for a selection of other pollutants e.g. benzene, PAH, CO. The EU directive will be implemented in Danish legislation. These air quality limits are based on WHO assessments. Present monitored levels of NO_2 and particles are higher than the proposed limits and compliance may be reached for NO_2 in 2010 but it may not be reached for particles in 2005 and 2010 (Palmgren et al. 1997). Scenario calculations with the OSPM model for selected streets in Copenhagen also shows that the proposed limit value for benzene of 2-5 $\mu g/m^3$ in 2010 may be exceeded (Bercowicz and Palmgren 1998). This suggests that the largest cities may need to take local actions to meet the new limit values.

Municipal goals

The municipalities have to be in compliance with the new stringent air quality limits, and the largest cities also have to manage a monitoring and assessment system as discussed above. A minimum goal for a municipality is to be in compliance with the new air quality limits. A municipality is a source to regional and global air pollution, and has a responsibility to assist in meeting the national emission reduction targets. Local targets that at least match the national targets could be set. Although the new air quality limits to a large degree are health based lower guideline values will further increase the safety margin and will therefore further decrease the risk for especially sensitive people. The Danish EPA has discussed such air quality criteria for traffic related pollutants that are more stringent than the proposed EU air quality limits (Larsen et al. 1997). Municipalities may consider these air quality criteria as long-term objectives as there is a higher certainty for no or very low health effects if these targets are met taken into account the present knowledge of health effects of air pollution. Municipalities may also have a broader perspective on air pollution that may lead to air quality targets that are more stringent that the proposed EU limits, and may view the air quality of a city as a competitive parameter to enhance the urban air quality for health precaution reasons, and to create an improved environmental quality to keep and further attract citizens, commerce, business and tourism. These targets may be set for specific geographic areas as environmental zones e.g. in areas with relatively high levels and high population density. The long-term political commitment to a sustainable development is likely to imply that emissions ultimately have to be reduced to comply with the principles of environmental space and critical loads for the global and regional environment, and that the principles of critical loads may also be applied for local city environments stated as no adverse effect levels for health and annoyance, vegetation and building materials. Apart from quality statements, goals should be expressed as quantifiable goals in order to be evaluated.

Setting of goals is a political process. The exposure model may be used to support this process by evaluation of mapping and scenario results against stated goals.

8.7 Abatement Measures

An assessment of different abatement measures is appropriate in the case that stated goals are violated and it is necessary to be able to draw up a plan of action to met stated goals.

Strategies

There are three basic strategies to reduce the impact of air pollution: emission reduction, dilution, and separation of source and receptor.

Emission reduction

Emission reduction is a source-oriented strategy to reduce the impact of air pollution and may involve reduction of the activity that pollutes, stringent emission standards and cleaner fuels etc. Modern environmental regulation focuses on emission reduction that is the most effective way to reduce the impact of air pollution.

Dilution

A higher degree of dilution of pollutants will improve the local air quality but the total emission load is unchanged and may affect the regional and global environment. The regulation of industrial and power plant point sources is an example where the strategy of dilution is applied in combination with emission reduction. In Denmark, the OML model is used to calculate the height of stacks to meet air quality guidelines for ground level concentrations. Contemporary environmental policy does not recognise that “the solution to pollution is dilution”.

Separation of source and receptor

Separation of source and receptor will reduce the impact of air pollution but not the total emission loads. A recommendation to sensitive people to stay indoors under e.g. ozone episodes is an example. Another example, is the location of sensitive urban functions like kindergartens away from busy streets to lower human exposure.

Permanent and episodic control

The above mentioned strategies can be implemented as part of a permanent and/or episodic control strategy. The arguments put forward for episodic control is that it is a very cost effective supplement to permanent control and that most air pollution episodes occur under special meteorological conditions (e.g. no winds, hot sunny weather, inversion) that can be predicted. Important factors for the success of episodic control is the ability to accurately forecast episodes, to disseminate information to the public, and the willingness of polluters to implement control (Jorquera 1997). Episodic control has e.g. been practised in USA, and recently in Paris during an air pollution episode in 1997 where vehicles were prohibited to enter central parts of the city. Danish regulation of air pollution is based on permanent control, and episodic control is not an option at present because the legal foundation for municipalities to e.g. prohibit vehicles to enter urban areas under episodes is lacking. However, the new Government Agreement states that the Government will prepare the legal framework for further traffic regulation options for the local authorities (Statsministeriet 1998). Although, the legal changes primarily are aimed at options like different types of road pricing systems and environmental zones, they may also open up for episodic air pollution control.

Traffic Air Pollution Abatement Measures

In the following a discussing of abatement measures directed towards traffic air pollution will be given because traffic air pollution is the dominant source in urban areas. The potential and limitations of the municipalities to apply these measures are also briefly discussed in the context of air quality planning.

Abatement measures can be classified as: cleaner technology, recurrent environmental control of vehicles, urban planning, traffic planning, and shift in transport modes.

Cleaner technology

Cleaner technology reduces the emission from a vehicle and may be a consequence of stringent emission standards and standards for fuel quality e.g. catalytic converters and petrol with lower content of benzene. Electric vehicles and alternative fuels are also examples of cleaner technology.

Recurrent Environmental control of vehicles in use

The aim of recurrent environmental control of vehicles in use is to reduce emissions through better maintenance of existing vehicles. The periodic control of cars that will be implemented during 1998 is an example of recurrent environmental control that should be able to identify malfunctioning catalyst converters and poorly tuned engines. On Board Diagnostic Systems (OBD) on vehicles may be a requirement for future cars. More comprehensive and preventive systems are recall systems where a random sample of a car mark and year is tested for compliance with emission standards and a recall is carried out at the expense of the car marker to make necessary adjustments (Palmgren et al. 1997). The regulation of cleaner technology and control of vehicles in use is carried out by primarily EU and national authorities, and Danish municipalities have very limited direct influence on these regulations. However, within these areas municipalities may help promote e.g. electric vehicles, alternative fuels in busses, improved maintenance of municipal vehicles etc.

Urban planning

Urban planning influences the urban structure and land-use, that further affects the traffic performance (km travelled) and the choice of transportation mode. The integration of urban functions, location of offices close to rail way and bus stations, maintaining a decentralised public and private service structure to increase accessibility, and avoiding urban sprawl are examples of measures to reduce distances between city functions and to reduce traffic performance and thereby traffic emissions.

Traffic planning

Traffic planning can reduce emissions and the geographic distribution of emissions by reducing traffic loads, changing vehicle compositions and speeds using various traffic planning measures e.g. speed control, vehicle load restrictions, parking restrictions, bus lanes, bicycle paths, pedestrian zones, information campaigns to changes road users' transport and driving behaviour etc. Among others, the emission factors are depending on the travel speed and the lowest emissions are in range of 50-80 km/h depending on the pollutant in question. Go and stop traffic under congestion condition (low travel speed) also increases emissions compared to a steady traffic flow (Jensen 1992, 1995). The optimal travel speed from an air pollution point of view is in most cases in conflict with traffic safety considerations in urban areas where lower speeds reduce the frequency and severity of traffic accidents. New measures like road pricing promises to be able to regulate traffic temporally and spatially, and environmental zones in central parts of larger cities may regulate traffic by imposing certain restrictions to enter the zones.

Shift in transport modes

Emission reductions will generally be gained if passenger and goods transport are shifted from individual motorised transport to public transportation e.g. from passenger cars to public transportation. However, the emission benefits are highly depending on the transport technologies, vehicle occupancies and pollutants considered e.g. particle emissions may increase with a shift from passenger cars to diesel powered busses (Krawack 1991).

The municipalities have strong influence on public bus transportation as they own the bus companies operating in cities. However, they have less influence on the state owned train and subway transportation systems. They also have strong influence on traffic planning measures as well as urban planning.

Assessment of Abatement Measures

Impact assessment

The exposure model is suitable to assess the impacts of different abatement measures on emissions, ambient levels and exposures.

Scenarios

Assessment of different abatement measures may be carried out to evaluate impacts and compare with stated goals. Scenarios are important elements of assessment of abatement measures.

Emission models

The exposure model has the ability to assess the abatement measures provided that the consequences to e.g. traffic loads and vehicle composition on the road network and emission factors are known.

Traffic models

Urban and traffic planning initiatives may change traffic loads and vehicle compositions in a road network. These changes have to be provided as inputs to assess the consequences to emissions, air quality levels and exposures. A traffic model may be operated to predict traffic changes in a road network due to planning initiatives. A management tool should be able to easily import data from a traffic model or provide an interface with a traffic model as is the case of the AIDAIR system (Emme/2) where a schematic road network was defined in Emme/2 and redrawn to fit the exact streets on the GIS map to allow for a more precise superposition of information layers in the GIS. However, this is still a simple interface that does not make a dynamic linkage between the road network of the traffic model and a vectorised road network in GIS. A more advanced approach is to fully integrate traffic models into the GIS environment and take advantage of GIS functionalities like improved zone aggregation and enhanced opportunities for data quality assurance as pointed out by *Nielsen and Rehfeld* (1995).

The present exposure model is not dynamicly linked to a traffic model but it is obviously able to assess emissions, air quality levels and exposures based on outputs from a traffic model, and it has potential for application of GIS based traffic models.

Monetary evaluation

A monetary evaluation of abatement measures may be carried out applying different approaches. A *cost-benefit* analysis may be used to study various actions to e.g. rank different measures. It is easier to estimate costs of abatement measures than benefits of e.g. reduced health effects. A further discussion of the problems of determining the health benefits and economics of urban air pollution is given in *Geernaert and Jensen* (1997). Two very different approaches have be used to estimate the cost of air pollution: the *willingness to pay* and the *direct costs* based on dose-response principles. Cost estimates based on the willingness to pay principle may be provided by e.g. questionnaires, assessment of how property values are affected by air pollution or the cost of reducing air pollution (e.g. catalytic converters). However, it will not reflect the "true" costs of air pollution and therefore estimation of the direct costs seems more plausible. On the other hand, estimation of direct costs of air pollution requires reliable dose-response relations and exposure estimations which are difficult to establish as discussed through out this report. Crude overall cost estimates of air pollution may be given for a city based on analysis of monitor data and dose-response literature values. Such estimates give an idea of the scope of the present air pollution problem and the potential benefits of reducing air pollution. However, to associate such relationships to specific abatement measures imply large uncertainties, and such features are not part of existing air quality management system at present. Another monetary evaluation method of abatement measures is to use the *cost-effectiveness* approach where the aim is to identify the least costs among different alternatives to achieve specific targets e.g. to reduce air pollution levels to a certain level. This approach is operational in the context of urban air management and emphases a goal-oriented approach to planning. Cost estimates of proposed abatement measures are needed in any case to be able to draw up an implementation plan.

Monetary evaluation of abatement measures is not integrated into existing urban air quality management systems nor the exposure model but sub-models for monetary evaluation may be part of future management tools.

8.8 Implementation

A municipality may prepare an air quality action plan to sum up the key results of the mapping, state the identified problems and task areas, describe the goals and the abatement measures to achieve these goals, and give a time table and budget for implementation of the plan. An air quality action plan could be prepared as a thematic topic of a municipal development scheme and the key results could be incorporated into the municipal development scheme as has been the case in many municipalities that have prepared local traffic and environment plans. An air quality action plan may be prepared within the framework of Local Agenda 21 (Miljø- og Energiministeriet et al. 1995). Local Agenda 21 is a local authority's strategy and action plan to contribute to a sustainable development in the 21st century.

8.9 Evaluation

Systematic and recurrent evaluation

A systematic evaluation of the effects of an action plan is an important element in the planning process and should address the progress in achieving goals and provide a foundation for possible revision of goals and / or abatement measures. The evaluation should preferable differentiate between the effects of: municipal actions (e.g. various traffic regulations), national actions (e.g. stringent emission standards) and changes in the assumptions of the action plan (e.g. higher traffic growth than expected). The exposure model provides for such recurrent evaluation.

Monitoring

Mapping and impact assessment of various abatement measures are heavily depended on suitable models. However, monitoring of air pollution levels at a few selected locations is important to obtain detailed and accurate information about trends and temporal variation of air pollution levels. To evaluate trends and temporal variation in levels it is important simultaneously to monitor the factors that influence air pollution levels: traffic, meteorological parameters and background concentrations as was the case of one well-equipped monitor station in the LMP programme (Jagtvej). Meteorological parameters and background concentrations are measured in the LMP programme but traffic is no longer on a continuous basis. HLU manages a street air pollution monitor station in Copenhagen (Bredgade) where a traffic counting station is operated by the Danish Road Directorate. Monitoring and air quality management systems supplement one another.

8.10 Potentials and Future Research Needs of the Exposure Model as a DDS

In Table 8.1 the current potentials of the exposure model as a tool for urban air quality management are summed up together with future development options described in the following.

Table 8.1 Current Potentials and Future Development Options of the Exposure Model as a Tool for Urban Air Quality Management.

Functionalities:	Current Potential	Future Potential
Mapping:		
Automatic generation of street configuration using digital maps, MR, BBR and GIS	X	
Emission (NO_x, CO, benzene)	X	
Air Quality (NO_2, NO, O_3, CO, benzene)	X	
Exposures at address using CPR (number, age, gender) and CER (number)	X	
High geographical and temporal resolution	X	
GIS visualisation and analysis	X	
Improved user-friendliness, user-manual and documentation		X
Default inputs (emission factors, traffic variation, background levels, meteorological data)		X
Pre-processing of input and output (assign traffic, repres. addresses, statistical analyses)		X
Enhanced performance (MapObject, SDE)		X
More pollutants (especially fine particles)		X
More environmental parameters (energy consumption, CO_2, traffic noise, barrier effect)		X
Crude health effect estimation (exposure-response)		X
Monetary evaluation of health effects		X
Interactive Internet information		X
Link to next-day forecasts		X
Integration of modelling of industrial point sources (OML)		X
Goals:		
Evaluation of mapping and scenario results against air quality limits and guidelines	X	
Impact Assessment of Traffic Air Pollution Abatement Measures:		
Changes in traffic emissions	X	
Changes in traffic loads and vehicle composition	X	
Link or integration with traffic models		X
Change in street configuration data	X	
Implementation:		
Preparation of action plan	X	
Evaluation:		
Recurrent evaluation of goals and abatement measures	X	

Future research and development needs

At present, the exposure model is a prototype that will need further refinements before use by a municipality or consultant.

User-friendly improvements

The model must be easy to use. At present, air quality and exposure calculations are carried out outside the GIS environment. However, to improve the user-friendliness of the model all operations should be carried out from inside ArcView, and integrated into ArcView as menus via a DLL structure as discussed previously. A user-manual should also be drawn up, and further documentation of the sensitivity of the model results to inaccuracies in the inputs parameters should be outlined to give the user an idea of the sensitivity of the model.

Default inputs

It should be easy to provide the needed input data as accurate as possible. This data should be provided as default values with the possibility for assigning user-specified values. The following sub-models should be established.

The present emission module of the OSPM model should be refined with updated emission factors for the different vehicle categories to predict past, present and future emissions. Activities are undertaken at NERI to use emission factors from the Computer Programme to Calculate Emissions from Road Transport (COPERT II) that is used by member countries for compilation of CORINAIR emission inventories to be reported to the European Environmental Agency (EEA) (Ahlvik, P. et al. (1997)). The temporal variation of traffic and cold starts should also be provided as default values based on *Jensen* (1997b).

The temporal variation of background concentrations for different years should be available in the form of files with data from the nearest meteorological mast in the LMP programme (Copenhagen, Aalborg and Odense) or alternatively from a nearby airport. The standardised temporal variation of background concentrations from 1960-95 presented in *Jensen* (1998) could also be provided for cities without urban background measurements. Meteorological files for a number of years should be available including “Kastrup 1976” that is considered a standard meteorological year used for regulation of stack height with the OML model.

Desirable tools

A number of desirable tools may be added as menus to the ArcView interface to ease data collection and analysis. Various tools for pre-processing of data from CPR, BBR and CER may be developed to ease the establishment of input data for ArcView. As outlined in chapter four there may be different sources of traffic data that have to be assigned to the digital road network e.g. street based data from a spreadsheet/database or “to-from node” based data from a traffic model. Tools may be developed for ArcView to facilitate this process. There is no need for calculations for every single address for mapping purposes because addresses close to one another usually have similar pollution levels, and addresses with very low traffic levels could be assigned background levels. A procedure could be developed to identify representative addresses and addresses where calculations were required. This approach could probably reduce the air quality and exposure calculation time by a factor of 10. Various tools for statistical analysis of data could be added e.g. for air quality data (percentiles, mean, max., min.) and for exposure data (accumulated distribution function).

Further model developments

Apart from providing a more user-friendly interface through default input parameters and various tools further developments could be considered. The model should be able to handle the air pollutants that have been identified as critical from a health point of view: fine particles is of primary concern. Air pollution is one impact among a number of environmental impacts that originates from traffic. Traffic noise, traffic safety and barrier effects are other important impacts. Since traffic and environmental planners handle all these environmental impacts in e.g. local traffic and environmental planning they request one integrated system that incorporates all of these environmental parameters (Skaarup, Terp, Lorenzen from Municipality of Copenhagen, private communication). Such integrated systems are under development (Nielsen and Rehfeld 1995). Parameters like energy consumption and CO_2 emission as well as traffic noise and barrier effect may easily be integrated into the exposure model.

The Internet offers an opportunity to inform the public about the air pollution in new ways. With the MapObjects or ArcView Internet Map Server technology it is possible to display maps of e.g. concentrations on a home page and let people interactively retrieve their own address to get to know about air pollution levels where they live (http://www.esri.com). A link to next-day forecasts may also provide next-day concentrations.

Municipalities have on-line access to the CPR and BBR databases. Tools could be developed for recurrent updating of data from CPR and BBR. For the CER database similar systems could be set up. However, for planning purposes it may not be necessary to establish such automatic systems. For planning purposes it would probably be sufficient to receive data from CPR, BBR and CER once a year, and update air pollution and exposure data where changes have taken place.

The performance of the urban landscape model may be increased by maybe a factor of 100 if it is reprogrammed in MapObjects, and in order to handle very large datasets in an effective way the SDE database could be applied.

9 Summary and Conclusions

Background

Change in sources and new air quality limit values

Over the last few decades road transport has become the dominant source to air pollution especially in larger urban areas. Present Danish air quality limits values are not violated but future more stringent EU limit values will be violated at the time of introduction and may be exceeded at the year of compliance in 2010 for particles.

Critical air pollutants

People are exposed to a mixture of pollutants that are believed to cause combination effects. The traffic air pollutants that raise most health concerns are: fine particles, NO_2, O_3, PAH, benzene, 1,3-butadiene, ethene and propene, and aldehydes (formaldehyde, acrolein, acetaldehyde). Fine particles pose the greatest health impact on mortality and morbidity especially to highly exposed and sensitive persons. Although the uncertainty is large on attempts to quantify the health impact, it is estimated that the health impact of air pollution may be at the magnitude of traffic accidents (about 500 annual deaths).

Exposure the missing link

In a Danish context the processes that determine emission and ambient levels have been studied intensively over the years whereas exposure and health effect studies have been limited in numbers. Exposure assessment may be seen as the "missing link" in the source - effect chain. Personal exposure is influenced by the person's time-activity pattern, microenvironments visited, and indoor-outdoor relationships of the microenvironment including indoor sources.

Air pollution epidemiology

Air pollution epidemiology studies the relationship between diseases in a population and exposures to establish exposure-response relationships. Exposure assessment is obviously an important part of air pollution epidemiology, and application of air quality models and GIS are increasing and promising tools in this field.

Health risk assessment and risk management

Exposure assessment is also an integrated part of health risk assessment and management. Health risk assessment involves hazard identification, exposure assessment and effect assessment. An exposure assessment is required to be able to quantify the health risk when a hazard has been identified and an effect assessment (exposure-response relation) has been established based on e.g. epidemiological findings. Health risk management focuses on actions to reduce risks and may involve impact assessment of different control strategies.

Exposure model

Various exposure models have been developed abroad in support of health risk assessment and management (e.g. NEM, AirPEx, SHAPE). However, no Danish exposure models are available at present, and none of the above mentioned models take advantages of the favourite conditions in Denmark for use of GIS and administrative databases. An exposure model may be set up at a national, regional or local scale. Such a model should be able to estimate: who and how many are exposed, where the exposure takes place, the time duration of exposures, exposures to critical air pollutants, and the impact of various control measures on exposures in support of management.

Urban air quality management system

At the local scale, exposure assessment may be seen as part of a decision-support tool for local authorities for improving air quality management in larger Danish cities. An urban air quality management system should encompass: air quality monitoring, emission inventories, air quality and exposure mapping, air quality and exposure impact assessment of various traffic control strategies in support of evaluation of action plans, information to the public about past and present air quality levels but also forecasts for next-day levels.

Exposure model criteria

The exposure assessment in air pollution epidemiology and in health risk assessment and management including local urban air quality management require estimation of air pollution levels in space and time and people's contact to these levels to determine exposures. To solve this core problem is the foundation for application in epidemiological studies and in health risk assessment and management. In health risk assessment and management, the capability of impact assessment of control measures are also important to consider management issues. Hence, the overall exposure model criteria can be stated in the following way. The model approach should:

- reflect the high spatial and temporal variation of ambient air pollution found especially in urban areas
- be able to estimate past, present and future exposures to health related traffic air pollutants
- characterise the exposed population
- be able to be applied for any location in Denmark
- take advantage of existing air quality models and minimise input data generation by relying on available data sources to the extent possible
- support air pollution epidemiological studies
- support health risk assessment and management e.g. national exposure assessment and local urban air quality management.

Exposure model

Characteristics of developed exposure model

The developed exposure model is a physical, single media (air) and single source (traffic) microenvironmental exposure model that estimates exposures geographically with the postal address as exposure indicator. The residence, workplace and street microenvironments can be considered. The model estimates outdoor levels for selected ambient air pollutants (benzene, CO, NO_2 and O_3). The influence of outdoor air pollution on indoor levels can be estimated using average I/O-ratios. The model has a very high spatial resolution (the address), a high temporal resolution (one hour) and may be used to predict past, present and future exposures. A simple exposure index has been defined that assumes that the person is present at the address all the time, and an exposure estimate is also defined that takes into account the time the person spends at the address assuming standardised time-profiles depending on age groups. The Municipality of Middelfart has been used as a case study area to develop and demonstrate the exposure model. The exposure model takes advantage of standard GIS (ArcView and Avenue) for generation of inputs, and for visualisation of input and output, and uses available digital maps, national and local databases, and the Danish Operational Street Pollution Model (OSPM). The OSPM model computes hourly air quality levels based on hourly traffic emissions, street configuration data, hourly urban background concentrations and hourly meteorological parameters.

Comparison with other exposure models

The presented exposure model takes a new geographic approach to modelling human exposure compared to existing exposure models (e.g. NEM, AirPEx, SHAPE) that do not take advantage of GIS. It is also a new approach to take advantage of available administrative databases for exposure assessment.

Inputs

Input requirements are:

- digital maps including buildings, geocoded addresses, geocoded roads, geocoded cadastres
- data from the Building and Dwelling Register (BBR) for building height estimation
- traffic data (ADT of passenger cars, van, lorries and busses) for linking to a segmented road network
- population data on gender and age from the Central Population Register (CPR), and the number of employees from the Central Business Register (CER)
- standardised time-activity profiles for the different age groups in the residence and workplace microenvironment.
- meteorological parameters (hourly).

GIS for exposure modelling

GIS has been chosen as the tool for establishment of the exposure model because the GIS technology is developing fast becoming more user-friendly and expanding and improving its analytic functionalities. The digital maps and databases that can be linked to geographic features are developing fast in geographic coverage and data quality and will be available for any location in Denmark within a few years. Furthermore, Denmark has very detailed national administrative databases on population, health etc.

Traffic data

At present the most demanding task is to link traffic data from local sources to the digital road network. However, the municipalities are likely to organise their traffic data according to their digital road network in the near future. A simple approach was developed to assign traffic data from a spreadsheet obtained from the municipality to a segmented digital road network.

Time-activity data

Time-activity data are not available at present for Danish conditions for generation of standard time profiles, therefore, Dutch data have been used to demonstrate the model approach

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New methods

Different new methods (pre-processors) have been developed to generate the required input parameters for the OSPM model. Avenue applications in GIS (ArcView) have been developed for geocoding of buildings using cadastral maps (MR), and an urban landscape model has been developed for automatic generation of street configuration data based on digital maps and the Building and Dwelling Register (BBR) and GIS. To the knowledge of the author the use of GIS for generation of street configuration data for an air quality model has not been reported before in the literature. Since the OSPM model requires hourly traffic emissions, a method for generation of standardised time profiles for the temporal variation in traffic including the temporal variation in cold starts has been developed. The temporal variation in vehicle occupancies has also been described (Jensen 1997b). A semi-empirical background model has also been developed to provide hourly background concentrations levels for the OSPM model (Jensen 1998).

Exposure model evaluation

Sensitivity analysis and validation

It has not been possible to carry out a comprehensive sensitivity analysis of the exposure model due to time constraints nor to validate the predicted exposure estimates against exposure measurements because such data are not available for the Municipality of Middelfart. Instead the exposure model has been evaluated by discussing the validity of the input data and the impact on exposure estimates of possible uncertainties in the input data.

Outdoor air pollution

Validation studies of the OSPM model shows that it predicts ambient levels and the temporal variation very well. The uncertainty on outdoor air pollution is low for long averaging times (year, month, week) and moderate for short averaging times (day, hour). The background concentration model that was developed for long-term exposure contributes to the uncertainty on the short averaging times. The uncertainty of street concentrations will be lowest in urban areas with heavy traffic since the background levels play a minor role under these conditions.

Indoor air pollution

Although the uncertainty is low to moderate on outdoor air pollution the uncertainty on indoor air pollution levels will be moderate to substantial because the applied constant I/O-ratios are uncertain since indoor sources may be present, and because the relation between indoor and outdoor levels varies in space and time depending on various factors.

Presence of people in microenvironments

The uncertainty on the presence of people in microenvironments are primarily determined by the uncertainty on the standard time profiles.

Simple exposure index

The simple exposure index only considers the air pollution and the potential number of people present at a location determined by population data for the residence and workplace microenvironment. The strength of the simple exposure index is in the relative comparison between locations within a microenvironment not between microenvironments.

Exposure estimates using standard time profiles

The strength of the time profile exposure estimate is that it takes into account the correlation between the variation in concentrations and presence. The time profile exposure estimate makes it possible to carry out a reasonable comparison between exposures in the residence and the workplace microenvironments since the time spent in these microenvironments are considered. Therefore, the time profile exposure estimate is a better indicator of personal exposure related to a microenvironment than the exposure index since it takes into account the time spent in the microenvironment and the concentrations exposed to during that time.

Street microenvironment

Within the street microenvironment the time profile exposure estimate makes it possible to compare different streets from an exposure point of view that takes into account the correlation between the variation in concentrations and presence of road-users in the streets.

Inter microenvironment comparisons

It is not possible to compare the time profile exposure in the street environment with the residence and workplace environments since exposures in a street are not associated to the same individuals but to all the people passing through the street who only spend a short time in the street.

Exposure model results

For the case study area the exposure model was demonstrated for geographical and statistical exposure assessment.

Geographic exposure assessment

Geographic exposure assessment enables visualisation of air quality levels for e.g. comparison with air quality guidelines, identification of “hot spots”, evaluation of exposure conditions at specific locations like kindergartens, and takes advantages of GIS visualisation features for both vector based and grid based displays of input and output. The analysis showed that although today’s levels were generally low, many locations exceeded the limit value of 2-5 $\mu g/m^3$ for benzene in 2010 under consideration by the EU Commission. However, the estimated levels still exceed the recommended guidelines of 0.13-0.25 $\mu g/m^3$ ($1*10^{-6}$ lifetime risk of leukaemia) given by the World Health Organisation.

Statistical exposure assessment

Statistical exposure assessment may include accumulated distribution functions of the different microenvironments, and comparison of the exposure of different age groups and between females and males. The analysis showed that about 75 per cent of the people live along streets with concentrations close to the background levels in the Municipality of Middelfart that is characterised by small towns and large rural areas. The distribution of outdoor levels were very similar for the residence and workplace microenvironments. An analysis of the simple exposure index for benzene showed that the highest exposure are found at workplace addresses in the employee categories “10-499” that have relatively high concentrations and also many employees. For the working people in the age group 18-54, the integrated exposure was dominated by the residence microenvironment when comparing the residence and the workplace microenvironments because most time is spent at home. The age groups "0-6" and "persons older than 55" are the groups that have the highest exposure estimates in the residence microenvironment since they spend more time at home than the other age groups. The difference between females and males was not analysed due to lack of reliable time-activity data related to gender.

Simple index versus exposure estimate

Comparison of the simple exposure index and the exposure estimate taking into account standardised time-activity patterns showed that the simple exposure index obviously overestimate the exposure because it is assumed that the persons are present at the same location all the time. On the other hand, the exposure estimate is a better exposure indicator because it takes into account the time spent at the location. Ambient levels of benzene and CO were better indicators for the absolute exposure level at the residence microenvironment than NO_2 and O_3. The reason is that the indoor-outdoor ratios for NO_2 and O_3 are 0.5 and 0.2, respectively, and the time spent indoors is an influential factor in determining exposures.

Indoors versus outdoors

About 94 per cent of the exposure estimate for benzene and CO originates from been indoors and only 6 per cent from been outdoors assuming that the indoor-outdoor ratios for benzene and CO are 1.0. The dominating contribution to the exposure estimate from being indoors is due to the fact that most time is spent indoors. According to the Dutch time-activity data about 92-97 per cent of the time being at home is spent indoors depending on the different age groups. The indoor contribution to the exposure estimate is 89 and 73 per cent, and the outdoor contribution 11 and 27 per cent for NO_2 and O_3, respectively. The contribution from being indoors is less for NO_2 and O_3 compared to benzene and CO because of the differences in indoor-outdoor ratios.

Working days versus weekends

The exposure estimates for benzene and CO during working days and weekends (incl. the holiday month of July) constitute about 60 and 40 per cent, respectively. Weekends incl. July constitutes about 37 per cent of the time during a year. The reason why weekends have slightly higher exposure estimates compared to their share of the year is a combination of more time spent at home during weekends and generally lower concentrations during weekends as compared to working days. On the contrary, the exposure estimates for NO_2 during working days and weekends constitute about 36 and 64 per cent, respectively. For O_3 it is 37 and 63 per cent, respectively. The contribution from the weekends is much higher for NO_2 and O_3 compared to benzene and CO because more time is spent outdoors during weekends and because the contribution from being indoors is of less importance due to the outdoor-indoor ratios for NO_2 and O_3.

Commuting

Commuting plays a role for assessing exposures geographically. About two third of the exposures in the workplace environment can be related to persons who also lives in the municipality and one third of the exposures at the workplaces are associated to persons from outside the municipality.

Street microenvironment

The exposure in the street environment is entirely dominated by private passenger car road users that constitutes 98 per cent since public transportation by busses plays an insignificant role in a small town like Middelfart.

Application of exposure model for urban air quality management

Current Danish urban air quality management

Current Danish urban air quality management mainly consider monitoring, and alert and information systems. Comprehensive emission inventories, mapping of air quality and action plans are almost entirely missing. Decision-support systems (DDS) are not applied in Denmark, although such systems are in operation in other Nordic and European middle-sized and larger cities. However, present systems often have a low spatial resolution, crude exposure assessment if any, and do not take full advantage of GIS and administrative databases.

New requirements and developments

The municipalities with the largest Danish cities may apply urban air quality management systems in the future for a number of reasons. New EU regulation requires monitoring and assessment of air quality and information to the public in large cities with more than 250,000 inhabitants. Furthermore, recent research raise health concerns especially for fine particles but also for other pollutants at levels experienced in Denmark, and the development within GIS and communication technologies (Internet) provides new opportunities.

Potentials of present model

Compared to existing DDSs the potentials of the exposure model are within: use of advanced street pollution model (OSPM) with high spatial and temporal resolution, use of available digital maps and administrative databases for automatic generation of street configuration data, added GIS functionalities using standard GIS and extensions, and improved exposure assessment. The exposure model may be used as a tool for urban air quality management, and the application of the model has been discussed in relation to the planning process: mapping, setting of goals, abatement measures, implementation and recurrent evaluation. The model may be used for traffic emission inventories (NO_x, CO, benzene), mapping of air quality (NO_2, O_3, CO, benzene) and exposures at residence addresses (total numbers, age, gender), at workplaces (total number of employees) and in streets (road users). The functionalities of GIS are available for visualisation and analysis of data. A number of new methods have been developed to facilitate mapping of air pollution with the OSPM model concerning generation of street configuration data, the temporal variation of traffic emissions and urban background concentrations. Evaluation of mapping and scenario results may be compared with air quality limits and guidelines to support setting of goals. The model may also be used for impact assessment of traffic air pollution abatement measures provided that the changes in traffic emissions factors; traffic loads and vehicle composition in the road network, and street configuration data are available.

Further improvements

At present, the exposure model is a prototype that will need further refinements before it is ready for use by a municipality or consultant: improve user-friendliness by running all operations from within ArcView, preparation of user-manual and further documentation, provision of default inputs parameters for emissions factors

(COPERT II), temporal variation of traffic and background concentrations, as well as meteorological parameters.

A number of desirable tools may be added as menus to the ArcView interface to ease data collection and analysis like: various tools for pre-processing of data from CPR, BBR and CER, assignment of traffic to road network, generation of a limited number of representative addresses, and statistical analysis of air quality and exposure data.

Further model developments

Further model developments may include: more air pollutants especially fine particles, more environmental parameters like energy consumption and CO_2 emission as well as traffic noise and barrier effect, crude health effect estimations, integration of modelling of industrial sources (OML), link to or integration of traffic model, link to next-day forecasts, interactive public information via Internet Map Server Technology, and faster computing performance.

Application of exposure model in air pollution epidemiology

In current air pollution epidemiology, the use of fixed monitors is the most common exposure indicator as categorical classification is considered an inadequate method. In recent years, personal monitoring and the microenvironment approach are increasingly applied, and the application of air pollution models have also increased.

Relevance in epidemiological studies

The exposure model is of interest in analytic epidemiology: cross-sectional, case-control and cohort studies that consider the individual level, as well as, in small-areas studies. The model is not suitable for ecological studies that regard large aggregated geographical areas.

Residence microenvironments

In air pollution epidemiology the residence microenvironment is of primary interest because address based health information already exists for individuals related to the residence address.

Model estimates versus measurements

The use of fixed monitor stations in air pollution epidemiology is limited by the low geographical coverage, the monitored pollutants and the time of operation. The exposure model is able to estimate exposures where measurements are not available in space or time. The exposure model can also be run for many subjects and for long time periods at a low cost compared to measurements. Furthermore, the exposure model is also able to represent the spatial variation between different locations within a geographic area much better than a fixed monitor station. The exposure model will almost predict the temporal variation as good as a fixed monitor stations at least for urban areas.

The residence as exposure indicator

The relation between front-door concentrations at the residence address and personal exposures has been evaluated for children in the Copenhagen area (Childhood Cancer Project). These studies show that the front-door NO_2 concentration is a fairly good indicator of personal exposure especially in urban areas but also in rural areas. The front-door benzene concentration was a less good indicator for personal exposure in urban areas when compared to NO_2 and a poor indicator in rural areas where other sources than traffic dominates exposure. A study of personal benzene exposures of adults in

Copenhagen also indicates similar results (MACBETH study). The exposure model also produces the most accurate predictions under urban conditions where the contribution from background concentrations plays a minor role.

The use of standard time profiles

It has been demonstrated that the standard time profiles for time-activity patterns for the different age groups may be used to refine the exposure assessment, and that the time spent indoors and outdoors is important in exposure assessment.

Mainly long-term exposure assessment

A test of the modelled background concentrations showed that the exposure model may be applied in epidemiological studies which considers long-term exposure on at least a monthly basis with the present design of the background model. Long-term exposure assessment in epidemiological studies is mainly suitable for studies of chronic effects e.g. cancer.

Future research needs

Future research needs have been discussed within three main topics: refinements of the presented exposure model, development of a personal exposure model, and development of a model for national health risk assessment.

Refinements of exposure model

Estimation of the concentrations at the address could be further refined by taken into account possible emission contributions from other roads than the road the address belongs to, and a more dynamic approach to prediction of background concentrations. The knowledge of indoor-outdoor ratios for Danish conditions could also be further improved as well as generation of Danish time-activity data for establishment of standard time profiles.

Personal exposure model

The exposure model does not describe personal exposure in the sense that a person is followed in space and time. However, the presented exposure model has a potential for further development into a personal exposure model for more accurate exposure assessment that will benefit air pollution epidemiological studies. Traditionally, time-activity patterns have been collected by questionnaires or by using a personal activity data logger (an electronic diary). However, the exposure model can be further extended using GIS network functionalities, Global Positioning System (GPS) receivers and activity sensors for collection of individual time-activity data for personal exposure assessment. Activities are expected to be undertaken at NERI to develop a personal exposure assessment based on these principles. The application of such a personal exposure model for an exposure description study or in an epidemiological study would still be limited by the number of GPS receivers and sensors available at the same time. The personal exposure model may be used for short-term exposure determination and studies of e.g. acute health effects. In development of a personal exposure model, validation studies are essential to be able to compare observed and modelled exposure data.

National exposure assessment

The presented exposure model will be used to establish a national population exposure model based on the residence as exposure indicator. NERI has initiated a project with the aim to develop a national exposure model by combining the presented exposure model and a prognostic transport behaviour model. The integrated model will be used to assess the population exposure as a consequence of different transport behaviour scenarios (e.g. increased fuel taxes). The presented exposure model will be applied for selected urban areas and findings extrapolated to the national level.

Risk characterization and Economic impact

The national exposure model may in combination with dose-response relations be used to carry out rough estimates of the health impacts of the traffic air pollution, and the economic impacts of air pollution may also be estimated based on the above health impact assessment provided that the health impacts can be evaluated in monetary terms.

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References

Aarestrup, M., Villadsen, S.S. (1994): Koordinatsystemer i Danmark (Co-ordinate Systems in Denmark). pp. 31-44 *in* Balstrøm, T., Jacobi, O., Sørensen, E.M. (eds.): GIS i Danmark (GIS in Denmark). Publisher Teknisk Forlag, Denmark. 463 p.

Ackermann-Liebrich, U., Viegi, G., Nolan, C. (eds.) (1995): Time-Activity Patterns in Exposure Assessment. EUR 15892 EN. European Commission, 85+4 pp.

Ahlvik, P. et al. (1997): COPERT II Computer Programme to Calculate Emissions from Road Transport - Methodology and Emission Factors - (Final Draft Report), European Environmental Agency, Copenhagen.

Andersen, D. (1988): Danskernes dagligdag 1987 (Daily Life of Danes 1987), Institute of Social Research, Copenhagen, 255 p. (In Danish).

Bartels, C.J., Van Beurden, A.U.C.J (1997): Using Geographic and Cartographic Principles for Environmental Assessment and Risk Mapping *in* Ale, B.J.M., Janssen, M.P.M., Pruppers, M.J.M. (eds.): Book of Papers. Risk 97 Conference, Amsterdam, The Netherlands, 21-24 October 1997.

Beaglehole, R., Bonita, R., Kjellström, T. (1993): Basic epidemiology. WHO. Geneva. 175 p.

Berkowicz, R., Hertel, O., Sørensen, N.N., Michelsen, J.A. (1997a): Modelling Air Pollution from Traffic in Urban Areas. In proceedings from IMA meeting on “Flow and Dispersion Through Obstacles”, Cambridge, England, 28-30 March, 1994 (eds.) Perkins, R.J., Belcher, S.E., pp. 121-142.

Berkowicz, R., Hertel, O., Larsen, S., Sørensen, N.N., Nielsen, M. (1997b): Modelling traffic pollution in streets. NERI-ATMI report, p. 51.

Berkowicz, R., Palmgren, F. (1998): Beregning af luftforurening fra trafik i udvalgte gader i København. Undersøgelser udført af Danmarks Miljøundersøgelser, Afdelingen for Atmosfærisk Miljø for Miljøkontrollen, Københavns Kommune. Danmarks Miljøundersøgelser. 30 s. (Scenarios for the air quality in selected streets in Copenhagen. Study prepared by NERI (ATMI) for the EPA of the Municipality of Copenhagen. NERI report. 30 p.

Bjørnsson, C. (1994): Analysemuligheder i et vektor-GIS (Analytic Functionalities of Vector GIS). pp. 73-82 *in* Balstrøm, T., Jacobi, O., Sørensen, E.M. (eds.): GIS i Danmark (GIS in Denmark). Publisher Teknisk Forlag, Denmark. 463 p.

Bloch, K.S. (1997): Ny metode til støjkortlægning (A new method for traffic noise estimates). Stads- og havneingeniøren (The City and Harbour Engineer). No. 9. pp. 22-26.

Brande-Lavridsen, O. (1994): Digitale tekniske kort (Digital Technical Maps). pp. 113-122 *in* Balstrøm, T., Jacobi, O., Sørensen, E.M. (eds.): GIS i Danmark (GIS in Denmark). Publisher Teknisk Forlag, Denmark. 463 p.

Brunekreef, B. (editor) (1992): Health Effects Assessment. COST 613/2 Report Series on Air Pollution Epidemiology. Report Number 2. EU Commission. EUR 14346 EN. 70 p.

Bøhler, T., Riise, A., Sivertsen, B. (1997): AirQUIS - A Modern Air Quality System in Operation in Oslo. EUROTRAC Newsletter 19/97. pp. 38-39.

Clench-Aas, J., Harstead, A., Aarnes, M.J., Bartonova, A., Braathen, O.A., Grønskei, K.E., Hagen, L.O. (1992): Air Pollution and Short-Term Health Effects in an Industrialized Area in Norway. NILU 28/92. 228 p.

Danish EPA (1992): Industrial Air Pollution Control Guidelines. Guidelines from the Danish EPA No. 9/1992. 123 p.

Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., Speizer, M.D. (1993): An Association between Air Pollution and Mortality in Six U.S. Cities. The New England Journal of Medicine. Vol. 329. No. 24. pp. 1753-1759.

DSFL (1995): Standard for udveksling af digitale kortinformationer. DSFL-format (Standard for exchange of digital map data). Dansk Selskab for fotogrammetri og landmåling (Danish Society for Photogrammetry and Surveying). 145 p.

Duan (1981): Micro-Environment Types: A Model for Human Exposure to Air Pollution. Technical Report No. 47. Department of Statistics, Stanford University. 24 p.

Duan (1982): Models for human exposure to air pollution. Environment International. Vol. 8. pp. 305-309.

Elliott, P., Cuzick, J. (1996): Small-area studies: purpose and methods, pp. 14-21 *in* Elliott, P., Cuzick, J., English, P., Stern, R.: Geographical and Environmental Epidemiology, Methods for Small-Area Studies, Oxford University Press, 382 p.

Enemark, S., Kristensen, A.S. (1994): Digitale Matrikelkort (Digital Cadastral Maps). pp.155-164 *in* Balstrøm, T., Jacobi, O., Sørensen, E.M. (eds.): GIS i Danmark (GIS in Denmark). Publisher Teknisk Forlag, Denmark. 463 p.

English (1996): Geographical epidemiology and ecological studies, pp. 3-13 *in* Elliott, P., Cuzick, J., English, P., Stern, R.: Geographical and Environmental Epidemiology, Methods for Small-Area Studies, Oxford University Press, 382 p.

ESRI (1997): ESRI Shapefile. A Technical Description. An ESRI White Paper. 14 p.

Europe Environment (1997): European Commission: Proposal for a Directive on Pollution Levels in Ambient Air. European Environment. Supplement to Europe Environment No. 513. pp. 1-20.

Fedra, K. (1997): Integrated Risk Assesment and Management: Overview and State-Of-The-Art. *in* Ale, B.J.M., Janssen, M.P.M., Pruppers, M.J.M. (eds.): Book of Papers. Risk 97 Conference, Amsterdam, The Netherlands, 21-24 October 1997.

Freijer, J.I., Bloemen, H.J.Th., De Loos, S., Marra, M., Rombout, P.J.A., Steentjes, G.M., Van Veen, M.P. (1997): AirPEx: Air Pollution Exposure Model. RIVM, The Netherlands. Report no. 650010 005. 77 p.

Fugas, M. (1975): Assessment of the total exposure to an air pollutant. Proc. of the int. conf. on env. monitoring. Las Vegas. Nevada. Institute of Electrical and Electronic Engineers. Inc. New York. 2. pp. 38-45.

Geernaert, G.L., Jensen, S.S. (1997): Health and Economics of Urban Air Pollution Management. Environmental Research Forum 7-8:502-507.

Goodchild, M.F., Parks, B.O., Steyaert, L.T. (1993): Environmental Modelling with GIS. Oxford University Press.

Hall, J.V. (1996): Assessing Health Effects of Air Pollution. Atmospheric Environment. Vol 30. No 5. 743-746.

Hansen, H.S. (1994): GIS-Datamodeller (GIS Data Models). pp. 45-50 *in* Balstrøm, T., Jacobi, O., Sørensen, E.M. (eds.): GIS i Danmark (GIS in Denmark). Publisher Teknisk Forlag, Denmark. 463 p.

Hansen, H.S., Jensen, S.S., Berkowicz, R. (1997): Estimating Street Air Quality Using a 2½ Dimensional Urban Landscape Model. Den Store Nordiske GIS-Konference. (AM/FM-GIS Nordic Conference, Kolding, Denmark, 29-31 October 1997).

Hertel, O., Berkowicz, R. (1989a): Modelling NO_2 concentrations in a street canyon. National Environmental Research Institute, Roskilde NERI Technical report No A-131. 31 p.

Hertel, O., Berkowicz, R. (1989b): Modelling pollution from traffic in a street canyon. Evaluation of data and model development. National Environmental Research Institute, Roskilde, NERI Technical report No A-129. 77 pp.

Hertel, O., Berkowicz, R. (1989c): Operational Street Pollution Model (OSPM). Evaluation of the model on data from St. Olavs Street in Oslo. National Environmental Research Institute, Roskilde, NERI Technical report No A-135. 34 pp.

Hertel, O., Wilhardt, P., Berkowicz, R., Skov, H. (1996): Exposure of Bus Drivers and Postmen to Air Pollution from Traffic in their Working Environment. Paper in the proceedings of NOSA/NORSAC Symposium 1996 (Ed. Poul Hummelshøj), Helsingør, Denmark, 15-17 November 1996. Risø-R-934 (EN). pp 20-22.

Hertel, O., Berkowicz, R., Skov, H., Hansen, Å.M., Wilhardt, P. (1998): Exposure of bus drivers and postmen to traffic air pollution. In preparation for Atmospheric Environment.

Hertel, O., Palmgren, F., Leeuw, F.A.A.M, Gee, D., Herbarth, O., Raaschou-Nielsen, O., Pryor, S., Jensen, S.S., Olsen, E. (1998): Human Exposure to Outdoor Air Pollution. IUPAC Recommendation (In preparation for Pure and Applied Chemistry (PAC)).

Hill, A.B. (1965): The Environment and Disease: Association or Causation. Proc R Soc Med. Vol 58. pp. 295-300.

Hovedstadsregionens Luftforureningsenhed (HLU) (1996): Luftkvalitet i Hovedstadsregionen 1994 (Air Quality Monitoring in Greater Copenhagen Area. In Danish). 138 p.

Høj, J., Studstrup, F. (1998): Trafiksikkerhed med GIS (Traffic Safety using GIS). Dansk Vejtidsskrift 2/98 (Danish Road Periodical). pp. 32-34.

Jacobi, O., Balstrøm, T., Sørensen, E.M. (1994): Indledning (Introduction). pp. 1-7 *in* Balstrøm, T., Jacobi, O., Sørensen, E.M. (eds.): GIS i Danmark (GIS in Denmark). Publisher Teknisk Forlag, Denmark. 463 p.

Jantunen, M.J. (1995): Time Activity Monitoring by Active and Passive Instuments, pp. 63-72 *in* Ackermann-Liebrich, U., Viegi, G., Nolan, C. (eds.): Time-Activity Patterns in Exposure Assessment. EUR 15892 EN. European Commission, 85+4 pp.

Jensen, S.S. (1992): Køremønstre og luftforurening - i provinsen. Rapport 105. Vejdirektoratet. 75 s. + 56 s. (In Danish. Driving Patterns and Emissions. Danish Road Directorate. Report No. 105. In Danish).

Jensen, S.S. (1995): Driving Patterns and Emissions from Different Types of Roads. The Science of the Total Environment 169. pp. 123-128.

Jensen, S.S. (1997a): Mapping Human Exposure to Traffic Air Pollution using GIS. Journal of Hazardous Materials 61/1-3 (1998), pp. 385-392.

Jensen, S.S. (1997b): Standardised Traffic Inputs for Use in the Operational Street Pollution Model (OSPM), NERI Technical Report No. 197. 54 p.

Jensen, S.S. (1998): Background Concentrations for Use in the Operational Street Pollution Model (OSPM), NERI Technical Report No. 234. 109 p.

Jensen, S.S. (1998a): AirGIS - et værktøj til luftkvalitetsplanlægning i større byer (AirGIS - a Tool for Air Quality Planning in Cities). “Trafikdage på Aalborg Universitet 24-25 August 1998” (submitted for proceedings of the Nordic Transport Conference at the University of Aalborg).

Jensen, S.S. (1998b): Application of GIS in Air Pollution Exposure and Health Studies. “Nordisk GIS-konferanse” (submitted for proceedings of the Nordic GIS AM/FM Conference, 28-30 October, Voss, Norway).

Jensen, S.S., Larsen, P.B., Fenger, J. (1997): Sundhedsmæssig vurdering af luftforurening fra vejtrafik - med særlig fokus på partikler. *In* Lahrmann, H., Pedersen, L.H. (red.): Trafikdage på Aalborg Universitet 25-26 August 1997. Konferencerapport 2. Transportrådet og Aalborg Universitet. Trafikforskningsgruppen. - ISP's Skriftserie 209:585-594. (In Danish. Health Impact Assessment of Road Traffic Air Pollution with Focus on Particulate Matter).

Jol, A., Kielland, G. (1997): Air Pollution in Europe 1997. European Environmental Agency. Copenhagen. 107 p.

Jorquera, M.E. (1997): Use of Episodic Controls to Reduce Frequency and Severity of Air Pollution Events. Transportation Research Record No. 1587. pp. 35-43.

Jørgensen, S.E. (1991): Environmental Management Modelling. pp. 377-395 *in* Hansen, P.E., Jørgensen, S.E. (eds.): Introduction to Environmental management. 403 p.

Kemp, K., Palmgren, F., Manscher, O.H. (1997): The Danish Air Quality Monitoring Programme. Annual Report for 1996. NERI Technical Report No. 216. 63 p.

Kirklees Metropolitan Council (1997): Integrated System for Implementing Sustainability (ISIS). Executive summary. Environment Unit Kirklees Metropolitan Council. 46 p.

Kort- og Matrikelstyrelsen (1997): Fynsprojektet. Nyhedsbrev Nr. 4 (Project Funen. Newletter No. 4).

Kronbak, J. (1995): Tilgængelighed i Danmark (Accessibility in Denmark) *In* Lohmann-Hansen, A. (red.): Proceedings of Traffic Conference at the University of Aalborg (Trafikdage på Aalborg Universitet ’95). Vol 2, pp. 701-708.

Københavns Kommune (1997): Trafik- og miljøplan for København. (Local Traffic and Environmental Plan for Copenhagen. The Municipality of Copenhagen). 54 p.

Larsen, P.B., Larsen, J.C., Fenger, J., Jensen, S.S. (1997): Sundhedsmæssig vurdering af luftforurening fra vejtrafik, Miljøprojekt nr. 352, Miljøstyrelsen. (In Danish with English summary. Evaluation of health impacts of air pollution from road traffic, Danish EPA, Report No. 352).

Larsen, P.B., Jensen, S.S., Fenger, J. (1997a): Sundhedsskader fra små partikler i byluft. - Aktuelt Miljø 4(3):12-16. (In Danish. Health Effects of Fine Particles in Urban Air).

Van Leewen, C.J., Hermens, J.L.M. (eds.) (1995): Risk Assessment of Chemicals: An Introduction. Kluwer Academic Publishers. 374 p.

Micallef, A., Deuchar, C.N., Colls, J.J. (1998): Indoor and outdoor measurements of vertical concentration profiles of airborne particulate matter. The Science of the Total Environment 215, pp. 209-216.

Miljøkontrollen (1995): Støj og luftforurening i København. En kortlægning af trafikkens indflydelse på miljøet i byen. Miljøkontrollen, Københavns Kommune. (Noise and Air Pollution in Copenhagen. Mapping of the Environmental Impacts of Traffic. EPA of the Municipality of Copenhagen). 41 p.

Miljøministeriet (1992): Miljø og trafik i kommuneplanlægningen. Information. (Municipal Planning for the Environment and Traffic. In Danish). 153 p.

Miljø- og Energiministeriet, Kommunernes Landsforening, Amtsrådsforeningen (1995): Lokal Agenda 21. En introduction til amter og kommuner (Local Agenda 21. An Introduction to Counties and Municipalities. The Ministry of Environment and Energy, the National Association of Municipalities, and the County Association). 35 p.

Krawack (1991): Luftforurening fra individuel og kollektiv trafik. Undersøgelse i 4 Københavnske bygader. Udarbejdet for Miljøstyrelsen og Vejdatalaboratoriet. Miljøstyrlesens miljøprojekt nr. 165. 153 s. (Air Pollution From Individual and Public Transportation in Four Copenhagen Streets. Prepared for the Danish EPA and the Danish Road Directorate. Danish EPA Environmental Report No. 165).

Miljøstyrelsen (1996): Middelfart støjkortlægning koblet med GIS/BBR. Arbejdsrapport fra Miljøstyrelsen Nr. 76. (Traffic Noise Mapping with BBR/GIS in Middelfart. Report No. 76. Danish EPA).

Moore, D.R.J. (1996): Using Mote Carlo analysis to Quantify Uncertainty in Ecological Risk Assessment: Are We Gilding the Lily or Bronzing the Dandelion?. Human Ecological Risk Assessment: Vol. 2, No. 4, pp. 628-633.

Moseholm, L. (1994): Luftforureningseffekter i København. Effekter på mennesker. Rapport nr.1, Miljøkontrollen, Københavns Kommune. (Health Effects of Air Pollution in Copenhagen. Report No. 1. EPA of the Municipality of Copenhagen. In Danish).

Nielsen, O.A., Rehfeld, C. (1995): Brug af GIS til kommunal trafikplanlægning og beslutningsstøtte. *In* Lohmann-Hansen, A. (red.): Proceedings of Traffic Conference at the University of Aalborg (Trafikdage på Aalborg Universitet ’95). Vol 2, pp. 653-662.

Olesen, H.R., Løfstrøm, P., Berkowicz, R., Jensen, A.B. (1992): An improved dispersion model for regulatory use - the OML model. *In* Air Pollution Modeling and its Application IX, edited by H. van Dop and G. Kallos, Plenum Press, New York, 1992. A brief introduction to the OML model.

OPSIS (1998): EnviMan. The tool of the future for environmental management. CD presentation. OPSIS, Sweden.

Ott, W.R. (1985): Total Human Exposure. Environmental Science and Technology, Vol.19, No.10, 880-886.

Ott, W.R. (1990): Total Human Exposure: Basic Concepts, EPA Field Studies, and Future Research Needs. J. Air Waste Manage. Assoc. Vol. 40. No. 7. pp. 966-975.

Palmgren, F., Berkowicz, R., Jensen, S.S. Kemp, K. (1997): Luftkvalitet i danske byer (Urban Air Quality in Danish Cities). The Ministry of Environment and Energy. The National Environmental Research Institute. No. 16/1997. 63 p.

Pannicelli, C. (editor) (1993): Specifikationer for tekniske kort. Et udvalg under kommunalteknisk chefforening. Udgave marts 1993. 46+14 p. (Specifications for technical maps. A task force under the association of technical directors in the municipalities).

Petersen, J.K. (1994): Topografiske modeller (Topological Models). pp. 51-60 *in* Balstrøm, T., Jacobi, O., Sørensen, E.M. (eds.): GIS i Danmark (GIS in Denmark). Publisher Teknisk Forlag, Denmark. 463 p.

Pope, C.A., Thun, M.J., Namboodiri, M.M., Dockery, D.W., Evans, J.S., Speizer, F.E., Heath, C.W. (1995): Particulate Air Pollution as a Predictor of Mortality in a Prospective Study of U.S. Adults. American Journal of Respiratory and Critical Care Medicine. Vol. 151. pp. 669-674.

Poulsen[1], O.M. Sigsgaard[2], T., Hertel[3], O (1998): Description of research centre under the Danish Environmental Research Programme for 1998-2001 "Environmental and health damaging compounds". Adjuvant effects of plasticizers and detergents – Risk assessment and management[1], Non Infectious Health Effects of Airborne Micro-organisms: NIHAM[2], Human Health Effects of Exposure to Air pollution: HEAP[3].

Raaschou-Nielsen, O., Olsen, J.H., Hertel, O., Berkowicz, R., Skov, H., Hansen, A.M., Lohse, C. (1996): Exposure of Danish children to traffic exhaust fumes. Science of Total Environment 189/190 51-65 pp.

Raaschou-Nielsen, O., Hertel, O., Vignati, E., Berkowicz, R., Jensen, S.S., Larsen, V.B., Lohse, C., Olsen, J.H. (1997): A street pollution model for use in epidemiological studies: evaluation with measured levels of nitrogen dioxide and benzene (In preparation).

Raaschou-Nielsen, O., Skov, H., Lohse, C., Thomsen, B.L., Olsen, J.H. (1997a): Front-door Concentrations and Personal Exposures of Danish Children to Nitrogen Dioxide, Environmental Health Perspectives, Vol. 105, No. 9, pp. 964-970.

Raaschou-Nielsen, O., Lohse, C., Thomsen, B.L., Skov, H., Olsen, J.H. (1997b): Ambient Air Levels and the Exposure of Children to Benzene, Toluene, and Xylenes in Denmark, Environmental Research 75, pp. 149-159.

Refeld, C. (1997): Trafikøkonomiske og miljømæssige konsekvenser ved Havnetunnel-projektet (Transport Economics and Environmental Impacts of the Harbour Tunnel Project). *In* Lahrmann, H., Pedersen, L.H. (red.): Proceedings of Traffic Conference at the University of Aalborg (Trafikdage på Aalborg Universitet '97). Vol 2, pp. 471-478.

Rich, J.H., Jensen, S.S., Hertel, O. (1997): Integrerede Miljøinformationssystemer (IMIS). Bymiljø og trafik - bestemmelse og regulering af befolkningens udsættelse for sundhedsskadelig luftforurening (projektbeskrivelse). (Integrated Environmental Information Systems. Urban Environment and Transport - estimation and regulation of population exposure to traffic air pollutants. Project description). National Environmental Research Institute.

Ryan, P.B. (1991): An Overview of Human Exposure Modeling. J. of Exposure Analysis and Environmental Epidemiology. Vol. 1. No. 4. pp. 453-474.

Rådets Direktiv 96/62/EF (1996) om vurdering og styring af luftkvaliteten. De Europæiske Fællesskabers Tidende. Nr. L 296/55.

Skov, H., Hansen, A.B., Løfstrøm, P., Lorenzen, G. (1998): MACBETH - Danish Part. Benzene exposure of people living and working in Copenhagen. Poster presentation at the Atmospheric Chemistry and Air Pollution 6th FECS Conference on Chemistry and the Environment, 26-28 August 1998, Copenhagen.

Sorenson, S., Schramm, J. (1992): Individual and Public Transportation - Emissions and Energy Consumption Models. Laboratory for Energetics. Technical University of Denmark. Report RE 91-5. 61 p.

Statistics Denmark (1996): Statistisk Årbog 1996 (Statistical Yearbook 1996). Danmarks Statistik. 571 p.

Statistics Denmark (1997): Statistisk Årbog 1996 (Statistical Yearbook 1997). Danmarks Statistik. 558 p.

Statistiske Efterretninger (1996): Arbejdsmarked. 1996:21. (Statistical News. Labour marked. 1996:26).

Statsministeriet (1998): Godt på vej. Denmark i det 21. århundrede. Regeringsgrundlaget marts 1998. (Government Agreement March 1998. The Prime Minister's Office).

Trafikministeriet (1990): Regeringens Transporthandlingsplan for Miljø og Udvikling (Transport Action Plan for Environment and Development of the Danish Goverment. Ministry of Transport). 198 p. (In Danish).

Trafikministeriet (1992): Befolkningens rejsevaner 1992 (Travel Habits of the Danish Population 1992. Ministry of Transport, Copenhagen, 1994, 80 p. (In Danish).

Trafikministeriet (1993): Trafik 2005. Problemstillinger, mål og strategier (Transport 2005. Issues, Goals and Strategies. Ministry of Transport). 109 p. (In Danish).

Trafikministeriet (1997): Trafikredegørelse 1997. (Transport Review. Ministry of Transport). 227 p. (In Danish).

Vejdirektoratet (1997): Personer pr. bil. Belægningsgrader for person- og varebiler. Rapport nr. 137. (Danish Road Directorate. Persons per vehicle. Occupancies for passenger cars and vans. Report No. 137. In Danish).

WHO (1987): Air Quality Guidelines for Europe. Regional Office for Europe. 426 p.

Vignati, E., Hertel, O., Berkowicz, R., Raaschou-Nielsen, O. (1997): Generation of input data for the OSPM. A sensitivity analysis of a method based on a questionnaire. National Environmental Research Institute. NERI Technical Report, No. 188. 52 p.

Vignati, E., Berkowicz, B., Palmgren, F., Lyck, E., Hummelshøj, P. (1998): Transformation of size distributions of emitted particles in streets. (Submitted to the Science of the Total Environment).

Vine, M.F., Degnan, D., Hanchette, C. (1997): Geographic Information Systems: Their Use in Environmental Epidemiologic Research. Environmental HealthPerspectives. Vol 105. No. 6. pp. 598-605.

Williams, M. (editor) (1991): Exposure Assessment. EUR 14345 EN. CEC COST 613/2, European Commission, 98+4 p.

Worboys, M.F. (1995): GIS - A Computing Perspective. Taylor and Francis. 375 p.

Yocom, J.E. (1982): Indoor-Outdoor Air Quality Relations. A Critical Review. Journal of the Air Pollution Control Association, Vol. 32, No. 5, 500-520.

Zartarian, V.G., Ott, W.R., Duan, N. (1997): A Quantitative Definition of Exposure and Related Concepts. J. of Exposure Analysis and Environmental Epidemiology. Vol. 7. No. 4. pp. 411-437.

Appendices

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English-Danish Glossary

Average Daily Traffic (ADT):	Årsdøgntrafik
Building and Dwelling Register:	Bygnings- og Boligregisteret (BBR)
Cadastral district:	Ejerlav
Cadastral map:	Matrikelkort
Cadastral number:	Matrikelnummer
Cadastre:	Matrikel
Central Business Register:	Det Centrale Erhvervsregister (CER)
Central Population Register:	Det Centrale Person Register (CPR)
Cross Reference Register:	Krydsreferenceregisteret (KRR)
Danish Data Protection Agency:	Registertilsynet
Data Processing Company for All Danish Municipalities and Counties):	Kommunedata
Danish Cancer Society:	Kræftens Bekæmpelse
EPA of the Municipality of Copenhagen:	Miljøkontrollen, København
National Environmental Research Institute (NERI):	Danmarks Miljøundersøgelser (DMU)
National Environmental Programme	Det Strategiske Miljøforsknings-program (SMP)
National Survey and Cadastre Denmark:	Kort- og Matrikelstyrelsen (KMS)
DSFL:	Dansk Selskab for Fotogrammetri og Landmåling
Involvement of citizens:	Borgerinddragelse
Island polygon:	Ø-polygon (polygon indeholdt i et andet polygon)
Lot:	Lod (en del af en matrikel)
Map Base Funen:	Grundkort Fyn
Municipal development scheme:	Kommuneplan
Microenvironment:	Mikromiljø eller typemiljø
Office of Central Population Register:	CPR kontoret
Parcel register:	Matrikelregisteret (MR)
Property number:	Ejendomsnummer
Road Safety and Transport Agency:	Færdselsstyrelsen
Slivers:	GIS begreb for de strimler som dannes, når to temaer i et kort overlejres
Spatial join:	Knytter attribut data fra et lag til et andet ved at udnytte den rumlige sammenhæng mellem de to lag
Statistics Denmark:	Danmarks Statistik

GIS and Digital Maps

A short introduction to GIS and digital maps, and the applied GIS software ArcView and the associated program Avenue is given in this appendix.

GIS

Definition of GIS

There is no universally accepted definition of GIS since the systems are used by many different groups and within many professional subjects, and it is also a very dynamic field where definitions of GIS will change in time. However, a geographic information system (GIS) may be defined as "a computer-based information system that enables capture, modelling, manipulation, retrieval, analysis and presentation of geographically referenced data" (Worboys 1995).

Short history of GIS

The concept of a Geographic Information System was first introduced in the late sixties but the history of GIS in Denmark is shorter (Jacobi et al. 1994). In the late seventies the national research institution for plant field experiment (Statens Planteavlsforsøg) was the first to programme their own GIS software. However, it was the establishment of the natural gas companies in the beginning of the eighties that tricked the development of GIS in Denmark as they needed detailed maps of large parts of Denmark to plan the national pipeline network which delivers natural gas to both large and small consumers. In many places the natural gas companies co-operated with the municipalities in the production of digital maps also involving various private and public companies. In the late eighties the establishment of the National Survey and Cadastre Denmark (KMS), by joining various existing institutions, initiated the development of digital national topographical and cadastral maps, and marine charts. A Danish standard exchange of digital map data (DSFL) was established during the eighties (DSFL 1995). The eighties and early nineties were characterised by digitising existing and new geographic data whereas in the late nineties GIS moves to application beyond cartography in various sectors.

In the late nineties a wide variety of geo-data are available and these are still increasing in numbers and quality. An overview of these map and geo-data is given on the homepage of KMS (http://www.kms.dk/). Denmark has a long tradition for computerised national administrative databases e.g. the CPR database which can be linked to the digital maps as attribute data. During the nineties user-friendly desktop GIS also becomes available like the ArcView making GIS a technology that is widely applied in public administration, research institutions and private companies.

Examples of GIS functionalities

In the following is given a brief description of some of the GIS functionalities from an application point of view based on *Worboys*

(1995): Network analysis, terrain analysis, layer-based analysis, location analysis, and spatio-temporal analysis.

Network analysis

Network analysis involves e.g. to find the shortest or the least time demanding route between two locations in a road network to minimise km travelled or transport time.

Terrain analysis

Terrain analysis may be based on a dataset that gives topographical elevations at point locations. Analysis may include to find the paths of least resistance down the slopes of the terrain for example for watershed management. The data model behind terrain analysis is based on fields that are two-dimensional (x,y) with elevation represented as an attribute. Future three-dimensional GIS will represent a point in space in three dimensions (x,y,z) and will include analytic functionalities that builds on this data model.

Layer-based analysis

Layer-based analysis involves analysis of relationships between geographic features using e.g. buffering or overlay functionalities. A buffer may be a circle of a given distance around a point or a corridor of a constant width along a line or around an area that is used to identify features e.g. a buffer zone along a road network may be used to identify adjacent sand and gravel deposits within a certain distance. An overlay analysis may combine two layers of features to create a new layer e.g. identify all publicly owned land that at the same time are sand and gravel deposits within the buffer zone specified above.

Location analysis

Location analysis may involve a study of the location of a factory to minimise the transport costs (transport length and time) of raw materials or to optimise the location of a new place of entertainment to maximise the potential number of customers within a certain car driving distance.

Spatio-temporal analysis

Present GIS handles data in two dimensions: two- dimensional space (x,y) with attributes where time only can be handled as an attribute. However, geographic objects usually change in time and many analyses involve handling of spatio-temporal information. Future temporal GIS may be able to reference data to three kinds of dimensions: two-dimensional space and its attributes and time. Temporal GIS will handle time as a dimension and encompass functionalities that allow for spatio-temporal analysis.

The exposure model falls into the spatio-temporal analysis category. All geographic features (buildings, streets, address points and property limits) are treated as static objects in time whereas the temporal variation in air pollution levels and presence of people at a location used to estimate exposure are handled separately from the GIS in a separate program.

Data Models

Vector and raster models

Spatial data may be presented by two different data models in GIS: the vector or the raster model. The vector model represents objects or entities in real life as points (e.g. a mast), lines (e.g. a street) or polygons (e.g. a building). The raster model consists of a grid of usually square cells (pixels) and each cell is defined by its row and column number. For example, a point object is represented as one cell and a line or polygon object as a group of cells (Hansen 1994). ArcView is a vector GIS.

Simple fundamental spatial objects in vector GIS

The data model of contemporary vector GIS is built on a two-dimensional coordinate frame consisting of a fixed origin and a pair of orthogonal axes (x- and y-axis) intersecting the origin (the Cartesian plane). Geographic objects may be represented as points, polylines or polygons, see Figure 1 (Worboys 1995).

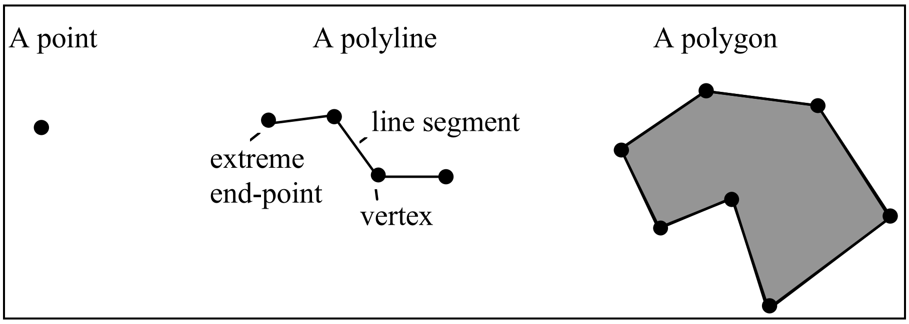

Figure 1 Simple fundamental objects in GIS: points, polylines and polygons.

Point

A point is defined by a unique pair of real numbers (x,y) defining its distance from the origin in the direction of each axis. Points may be viewed as vectors allowing for various operations to be carried out.

Polyline

A straight line is defined as the point set on a line passing through two points. The line segment is given by the line between the two points. A polyline is defined as a finite set of line segments (edges) such that each line segment end-point (vertex) is shared by exactly two line segments, except possible for two points (the two end-points in an open polyline termed the extremes). A polyline is simple when no two line segments intersect and it is closed when it does not have extreme points.

Polygon

A polygon is defined as the area enclosed by a simple closed polyline.

Other objects

Some geographic information systems are also able to represent multipoints (set of points), multipolygons (set of polygons), holes and other shapes like circles, ellipses, splines etc.

Static and Dynamic Spatial operations

Spatial operations on spatial objects may be grouped into static and dynamic operations. Static operations do not alter the object (e.g. calculating the length of a polyline) whereas dynamic operations do (e.g. splitting an object in two objects). A few examples of these operations are given below and the different operations are discussed in further details in *Worboys* (1995).

Static spatial operations

Static operations are subdivided into general, set-oriented, topological and Euclidean operations.

General operation

A general operation is the *equal* operation that tests if two spatial objects e.g. two polygons are identical and return a Boolean result (true, false).

Set-oriented operations

Set-oriented operations are concerned with membership conditions and relationships between sets. A set is a collection of elements (members) and the membership describes the relationship between the elements and the sets to which they belong. An example of a set-based operation is the Boolean test *is a subset of* that returns true if every element of one set is a member of the second set. Other examples are *union* that is an "operation that takes two sets and returns the set of elements that are members of at least one of the original sets" or *intersection* that is an "operation that takes two sets and returns the set of elements that are members of both the original sets".

Topological operations

"Topology is the study of topological transformations and the properties that are left invariant by them". Important concepts of topology are: boundary, interior and exterior as illustrated in Figure 2.

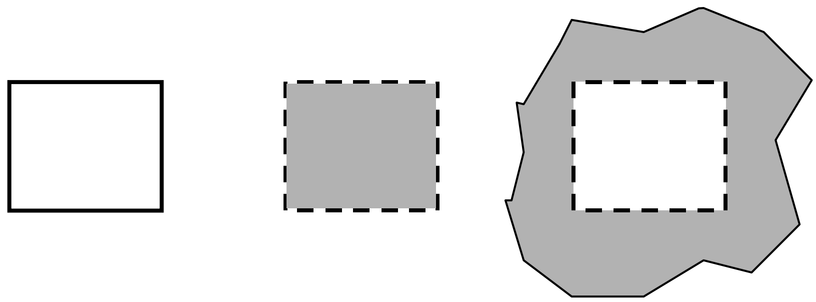

Figure 2 Illustration of the concepts: boundary (*left*), interior (*middle*) and exterior (*right*).

For example, *a point is in the interior of a polygon* is a topological property because any topological transformation (stretching of the plane) maintain this property whereas *the distance between two points* is non-topological (the distance will change when the plane is stretched). In other words, topology is concerned with properties of neighbourhood and connectedness. An example of a topological operation is the Boolean operation *is within* that returns true if the point is enclosed by a simple loop (polygon) which is used for point-in-polygon operations. Other examples of topological operations are *meets* ("two polygons touch externally in a common portion of their boundaries"), *covers* ("one polygon is a subset of another polygon"), *overlaps* ("two polygons impinge into each others' interiors"), *is inside* ("one polygon is a subset of another polygon and the polygons do not share the same boundaries").

Euclidean operations

Examples of Euclidean operations are *distance* between points, *length* of a polyline, *area* and *perimeter* of a polygon.

Dynamic operations

Fundamental dynamic spatial operations are *create*, *destroy* and *update* (e.g. rotate, scale, translate). Other dynamic operations are variations of these fundamental operations like *split* that splits one object into two objects.

Relational Databases and SQL

Relational database

The foundation of a GIS is the database. Different database structures exist but almost all databases used in GIS are based on the simple relational model structure (Worboys 1995). A relational database is defined as "a collection of tabular relations often just called tables. A table has attribute names (labelling of columns) and rows. A row consists of a list of values (data) one for each attribute (column). A relation scheme is a set of attribute names and a mapping from each attribute name to a domain (type of data like string, number, Boolean etc.). and a relation is a finite set of rows associated to a relation scheme in a relational database". The properties of a relational database are: "the ordering of rows in the relation is not significant, rows in a relation are all distinct from one another, columns are ordered so that data items correspond to the attribute in the relation scheme with which they are labelled". A number of operations may be performed on relational databases e.g. *union* (the union of two tables is a new table that holds all the rows of both tables) and *intersection* (the intersection of two tables is a new table that only holds rows shared by both tables). Another example is the useful *join* operation where two tables are merged based on common attribute values.

SQL

Data manipulation of relational databases (data definition, and insert, modify and retrieve data) is carried out by the Structured Query Language (SQL).

Digital Maps

Spaghetti maps

The first digital maps did not account for topology. These maps are often disparagingly called spaghetti maps, and e.g. represent a building as four lines and not as a polygon. However, to calculate the area of the building in GIS the building has to be defined as a polygon (Petersen 1994).

Digital maps

A digital map for vector GIS is a map that may include points, polylines and polygons or more complex spatial objects to represent geographic objects. Technical digital maps used by the municipalities for administrative purposes include objects like buildings, streets, rail ways, wind mills, forest areas etc. A digital map is characterised by the objects included, its scale and accuracy, the production method, the map projection and co-ordinate system.

Map projection and co-ordinate system

A map projection is a projection of points on or close to the surface of the earth to a plain surface often defined by an ellipsoid. A co-ordinate system is then defined for the map projection. In Denmark System34 is used as the co-ordinate system with Hayfords ellipsoid from 1924 as map projection and a co-ordinate system defined in 1934 with a y-axis (north) and a x-axis (west) to get only positive co-ordinate values. UTM (Universal Transversal Mercator) is a global system with another projection and co-ordinate system that gains increasing importants. Converting between these two systems is possible (Aarestrup and Villadsen 1994). All the digital maps used in the present project are based on System34.

Production

Digital technical maps are produced using mainly photogrammetry (ortho photos) supplemented by surveying - theodolite and GPS (Global Positioning System) techniques - and by digitising existing analogous maps. The cadastral map contains property limits, and is produced by digitising existing analogous maps supplemented by surveying techniques and also ortho photos for quality assurance e.g. comparing the location of fences and administrative property limits.

Specifications and exchange formats

Different specifications have been applied in the production of digital maps due to the different interests of map holders. A Danish standard for digital map production does not exist. However, different specifications have been used (Pannicelli 1993; Brande-Lavridsen 1994) and there is also a Danish format for exchange of digital map data named the DSFL-format (DSFL 1995). ArcView does not support the DSFL-format. An expensive commercial software is available for converting of the DSFL-format to ArcView's shape-format. However, NERI has developed its own DSFL converting programme which has been applied in the present project.

Georeference

To link data stored in an administrative database to the digital map requires a unique relationship between the objects in the map and data in the administrative database. This is termed a georeference or that the objects in the map are geocoded. Geocoding refers to the process of establishing a georeference. A geocoded building in a map may e.g. be identified by a unique ident linked to data from e.g. the Building and Dwelling Register. However, if the building is not geocoded it will just appear as a building in the map that can not by identified as a specific building.

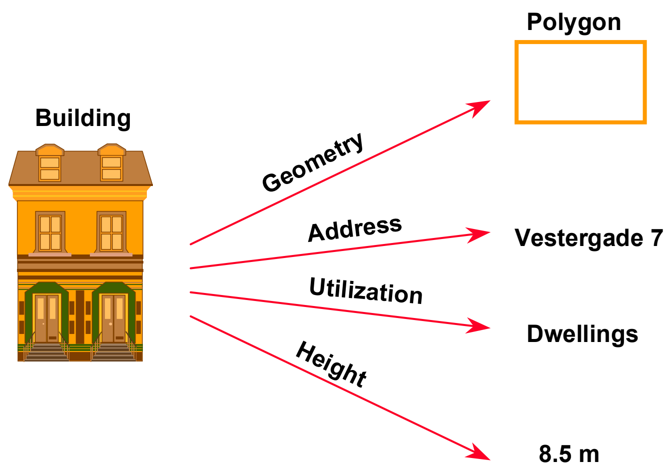

Figure 3 Example of a geo-referenced object and its attribute.

The exposure model requires that the buildings, addresses and streets are geocoded. In the technical map streets and addresses but not buildings are geocoded. Therefore, a method has been developed to geocode buildings using the cadastral map (property limits) and address map. This method is described in further details in chapter 4.

ArcView and Avenue

ArcView

ArcView

The exposure model uses the GIS application ArcView that is an easy-to-use desktop GIS developed by ESRI (ESRI 1997). ArcView is based on a vector data model that supports simple spatial objects: points, polylines, polygons and multi variants of these features but not more complex features like splines. A point is represented as a pair of coordinates in the order X,Y. A polyline is a ordered set of vertices (points) also called an arc. A polygon is represented as an ordered set of vertices where the first vertex has the same location as the last vertex. This is also called a ring or a simple closed polyline that should be a non-self-intersection loop. The interior of the polygon is defined by the order of the vertices (clockwise order) and rings describing holes in a polygon are defined by a counterclockwise vertex order.

Files

ArcView stores these spatial object types (e.g. a road segment as a polyline) in a *shapefile*, the associated attribute information e.g. traffic loads on the road segment in a *dBASE file*. Furthermore, it has an internal *index file*. All files have the same prefix (filename). The shapefile with the suffix "*.shp" describes a spatial object in which each record defines the shape as a list of its co-ordinates (vertices). A shape may be a point, polyline or polygon and a shapefile can only describe one type of spatial objects at a time. Attribute information is held in a standard dBASE format file with the suffix "*.dbf" where each record (row) has a one-to-one relationship with the associated shape record. The index file has the suffix "*.shx". The data structure is nontopological in the sense that topological properties are not recorded explicitly.

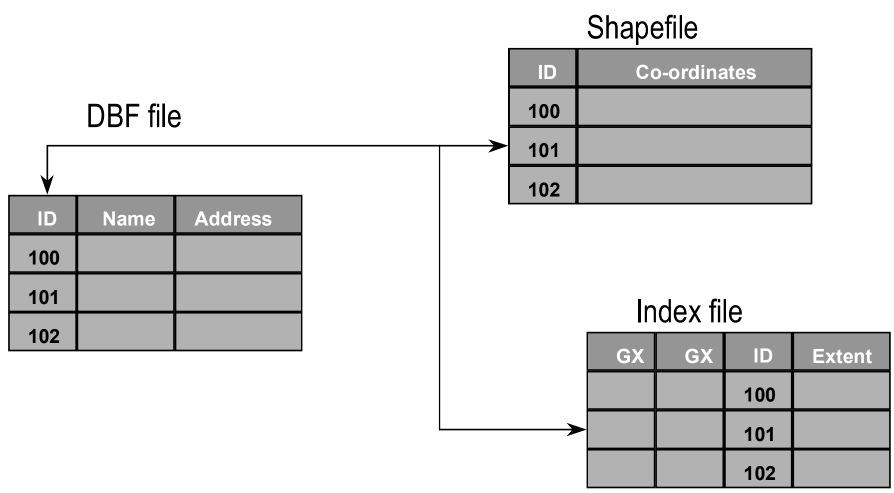

Figure 4 Illustration of the file-based data model of ArcView.

ArcView supports most of the basic static spatial operations: general, set-oriented, topological and Euclidean operations and simple dynamic operations. ArcView does not use SQL for data manipulation but Avenue reguests.

Avenue

Avenue GIS software is an object-oriented programming language for ArcView that makes it possible to extend the basic capabilities of ArcView and to customize ArcView for specific applications. C^{++} is the programming language behind Avenue requests. The interface of ArcView is actually an Avenue application. Avenue programmes termed scripts have been written to e.g. geocode the buildings and generate street configuration data for the OSPM model.

Extensions to ArcView

Various extensions may be obtained to ArcView that expands its analytic capabilities. The add-on "The Network Analyst" extension enables e.g. to find the shortest route in a road network. "The Spatial Analysis" extension extends the spatial analyses operations e.g. to generate contour plots or grids. Spatial Analysis has been used to generate e.g. grid based population density maps.

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National Environmental Research Institute

The National Environmental Research Institute, NERI, is a research institute of the Ministry of Environment and Energy. In Danish, NERI is called *Danmarks Miljøundersøgelser (DMU).*
NERI's tasks are primarily to conduct research, collect data, and give advice on problems related to the environment and nature.

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A new human exposure model has been developed that combines data on traffic air pollution and population data on a high spatial (postal address) and temporal (one hour) resolution. The model system is using a Geographic Information System in combination with available digital maps (buildings, streets, address points, property limits) and administrative databases on people, traffic and buildings. The air pollution is calculated with the Danish Operational Street Pollution Model (OSPM). Simple human exposure estimates are predicted by combining air pollution data with the number of people living or working at a given address during a given time period. The model system may be used for exposure impact assessment of traffic control measures, and exposure assessment in health studies.

Ministry of Environment and Energy
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