An integrated activity-based approach for air quality issues

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Bijdrage aan het Colloquium Vervoersplanologisch Speurwerk
20 en 21 november 2008, Santpoort

Samenvatting

Een geïntegreerde activiteitengebaseerde aanpak voor luchtkwaliteit

Activiteitengebaseerde modellen werden oorspronkelijk ontwikkeld om meer inzicht te geven in het verplaatsingsgedrag van mensen. Ze geven informatie over de activiteiten – en verplaatsingspatronen van individuen in een populatie gedurende de dag. Door de uitgebreide set aan data die door deze transportmodellen gegenereerd wordt, is deze aanpak echter ook nuttig voor andere onderzoeksdoeleinden buiten transport. Activiteitengebaseerde modellen verschaffen immers niet alleen nuttige informatie over de plaats en het tijdstip van een activiteit of verplaatsing, maar door deze informatie te gebruiken als input voor luchtkwaliteitsmodellen, kan deze informatie ook omgezet worden naar emissies, concentraties en zelfs blootstelling. De (theoretische) voordelen van activiteitengebaseerde modellen voor luchtkwaliteit werden slechts door enkele auteurs beschreven en modellen die voor dergelijke toepassingen ontwikkeld zijn, zijn op dit moment echter schaars.

De toepassing die we in deze paper beschrijven, toont aan op welke manier een activiteiten gebaseerd model gebruikt kan worden voor luchtkwaliteitsdoeleinden. Hiervoor werd een operationeel activiteiten gebaseerd model (ALBATROSS) gecombineerd met een emissiemodel (MIMOSA) en een dispersiemodel (AURORA) om emissies, concentraties en blootstelling in Nederland in kaart te brengen. In een eerste onderzoek werd de link tussen het activiteitengebaseerde model en het emissiemodel onder de loep genomen. Goede overeenkomsten werden gevonden tussen de gemodelleerde emissies en gerapporteerde emissiewaardes. Een tweede onderzoek handelde over de conversie van de voorspelde emissies tot concentraties. Hiervoor werd het AURORA dispersiemodel aangewend. Een belangrijk voordeel van dit onderzoek is dat het toelaat om de voorspelde concentratiewaardes te valideren met werkelijk gemeten concentraties (ipv enkel gerapporteerde waardes zoals bij emissies). De statistische analyse op beide concentratiereeksen toonde aan dat de activiteitengebaseerde luchtkwaliteitsketen in staat was om de concentratiepatronen in Nederland met voldoende nauwkeurigheid te voorspellen. In een laatste onderzoek werden de voorspelde concentraties uit de ALBATROSS-MIMOSA-AURORA keten dan gebruikt om de blootstelling van de Nederlandse populatie in kaart te brengen. Hiervoor werd de lokatie-informatie van de individuen uit het activiteitengebaseerde model gecombineerd met de concentraties om zo een dynamische blootstelling te berekenen. Het voordeel hiervan is dat deze blootstellingsbenadering per uur een blootstelling kan berekenen en dus rekening houdt met het feit dat mensen zich verplaatsen gedurende de dag terwijl de traditionele blootstellingsberekening enkel residentiële informatie beschouwd.

Gezien het feit dat het activiteitengebaseerde model in deze studie zowel gebruikt werd om de luchtkwaliteitsvoorspellingen uit te voeren als om de blootstelling te bepalen, wordt door deze aanpak een geïntegreerde benadering van het luchtkwaliteitsprobleem gerealiseerd. Dit laat toe om de impact van allerlei (transport)maatregelen op emissies, concentraties en blootstelling veel gedetailleerder door te kunnen rekenen. Voor zover de kennis van de auteurs reikt, werd dergelijk onderzoek nog nooit uitgevoerd met een activiteiten gebaseerd model.

1. Introduction

The rapid economic development in most Western countries has led to fast growth in the number of vehicle miles traveled since the 1970's (European Commission, 2001). Personal mobility, which increased from 17 km a day in 1970 to 35 km in 1998, is now more or less seen as an acquired right. At the same time, however, traffic is also an important cause of environmental pollution and damage to health. Numerous studies indicate that air pollution increases the risk of development of cancer and allergy or aggravate the condition of people suffering from air ways or heart diseases. Traffic air pollutants that raise most health concerns are fine particles (PM), nitrogendioxide (NO2) and ozone (O3).

Due to the negative effects of transport, one of the key challenges of the modern policy making consists of promoting a sustainable transportation system aiming at the prevention or reduction of the negative effects of the transportation system on health and environment. It is therefore not surprising that governments today are considering several traffic policy measures to reduce the negative effects of the increasing mobility on the environment. While formulating policy measures concerning traffic and transportation, a number of considerations with regard to health, traffic safety, environment, etc. need to be taken into account enabling as such an evaluation of the strategies producing the best net advantages in an integrated manner. However, analytic tools enabling an integrated assessment often lack, or are inadequate and insufficient. Often only direct isolated measures have been taken into account in the past by governments to reduce a specific targeted negative effect. These measures are called direct measures because they are created to contribute directly to solving the problem of road safety or environment. Yet, there also exist a number of general mobility-related policy measures, mostly to influence transportation demand, but whose impact on road safety and/or environment is much less straightforward to determine. In other words, these general road policy measures are expected to have only an indirect effect on road safety and environment. They have a direct influence on the demand for transportation (in fact, this is usually their reason for existence, e.g. to reduce congestion). But since the demand for transportation is the principle driver behind road safety and environment, they hereby also contribute indirectly to road safety, a better environment and ultimately thus also improve public health. Examples of such general policy measures include, for instance, congestion pricing, closing certain highway entries and/or exits, promoting telecommuting activities, stimulating car pooling, changing institutional aspects like shop opening hours, etc.. Therefore an important challenge compromises developing a coherent framework in which a variety of inputs can be joined and their effects can be evaluated.

To give more accurate and complete estimates on the impact of (transport) policies on the environment, the use of an integrated exposure modelling framework, taking into account the different causal links between activities, trips, emissions, concentrations and exposure, is preferred.

2. Scope and Objectives

The overall objective of the work described in this paper is to build an integrated modelling methodology for the assessment of air quality and population exposure to air pollution. To illustrate the feasibility of this concept, an application in The Netherlands is presented.

The specific steps required to meet this overall objective include the following research tasks.

- Calculate and validate the emissions resulting from passenger vehicle trips by using the trip information from an activity-based model
- Calculate and validate the pollutant concentrations by converting the activity-based emissions into ambient pollutant concentrations
- Establish a population exposure model using the time series population information from an activity-based model and temporal air quality data

The basic approach to develop the integrated exposure framework 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. Because the activity-based model is used both for the population modelling as for the travel demand modelling part, the new framework is consistent and enables us to analyze scenarios without overlooking any secondary effects.

3. Methodology and models

The integrated evaluation of population exposure to air pollution requires information on both air quality and population. In this research an integrated model framework was therefore established including the following models: an activity-based model (for information on the population and the travel patterns), an emission model (to convert trips into air emissions) and a dispersion model (to convert the air emissions into concentration levels).

In Figure 1 the general set-up of this research is presented schematically. In this section some general information is provided on each model type and a description is given of the specific model used in the current research.

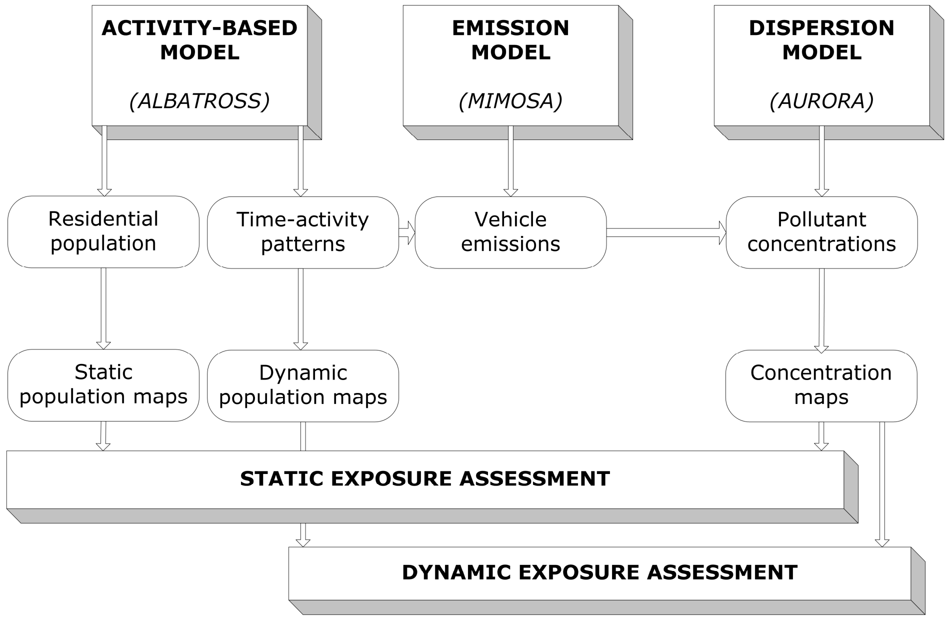

Figure 1: Overview of the model chain used to establish a dynamic assessment of exposure to transport related air pollution.

3.1 The activity-based model ALBATROSS

Introduction to activity-based transport models

The major idea behind activity-based models is that travel demand is derived from the activities that individuals and households need or wish to perform, with travel decisions forming part of the broader activity of scheduling decisions. Travel is merely seen as just one of the attributes. Moreover, decisions with respect to travel are driven by a collection of activities that form an agenda for participation. Travel should therefore be modelled within the context of the entire agenda, or in other words, as a component of an activity scheduling decision. Activity-based approaches aim at predicting which activities are conducted, where, when, for how long, with whom and the transport mode involved.

The most important features of activity-based modelling can be found in McNally (2000), who has listed 5 themes which characterize the activity-based modelling framework:

(i) travel is derived from the demand for activity participation;
(ii) sequences or patterns of behaviour, and not individual trips are the relevant unit of analysis;
(iii) household and other social structures influence travel and activity behaviour;
(iv) spatial, temporal, transportation and interpersonal interdependencies constrain activity/travel behaviour;
(v) activity-based approaches reflect the scheduling of activities in time and space.

ALBATROSS

For use within the exposure modelling framework, the activity-based model ALBATROSS was selected. The activity-based model ALBATROSS, A Learning-Based Transportation Oriented Simulation System, was developed for the Dutch Ministry of Transportation, Public Works and Water Management as a transport demand model for policy impact analysis. ALBATROSS is a computational process model that relies on a set of decision rules, which are extracted from observed activity diary data, and dynamic constraints on scheduling decisions, to predict activity-travel patterns (Arentze and Timmermans, 2000; Arentze et al. 2003). The model is able to predict which activities are conducted, when, where, for how long, with whom, and the transport mode involved. Albatross is unique in that 'decision rules' as opposed to 'principles of utility maximization' underlie the scheduling decisions. Furthermore, the rather detailed classification of activities and inclusion of a full set of space-time and scheduling constraints are distinctive features of the model compared with most other models.

To simulate activity-travel patterns for a whole population, information on both the population characteristics and their activity-travel patterns is required. Other necessary input data include physical information about the study area. Information on the classifications of activities and choice facets used in ALBATROSS and other data sources used to construct the physical database for Albatross are described in Arentze and Timmermans (2005).

The activity scheduling agent of ALBATROSS generates a schedule for each individual and each day and consists of four major components. The first model component generates a work activity pattern consisting of one or two work episodes, their exact start time, the duration of each episode, and their location. It also predicts the transport mode to the work activity. The second component determines the part of the schedule related to secondary fixed activities such as bring/get activities, business and others. It determines which types of activities are conducted that day, the number of episodes of each activity that occur, their start time and duration. Furthermore, it also identifies possible trip-linkage to the work activity and predicts the location of each episode. The third component concerns the scheduling of flexible activities. Almost similar to the previous component, it predicts activity types, the number of episodes of each activity type, the start time and duration of each episode as well as the location of each episode. The additional prediction of sequence of activities and possible trip-chaining links between activities are also part of this stage. Finally the last model component predicts the transport mode used for each tour (except for the work activity where transport mode is known as the outcome of an earlier decision). These main components assume a sequential decision process in which key choices are made and predefined rules delineate choice sets and implement choices made in the current schedule. Interactions between individuals within households are to some extent taken into account by developing the scheduling processes simultaneously and alternating decisions between the persons involved. ALBATROSS does not represent activity schedules of children explicitly. More information about the detailed working of this model and other computational process models can be found in Arentze and Timmermans (2005) and Anggraini et al. (2007). Validation studies of the scheduling process of ALBATROSS are described in Arentze and Timmermans (2000) and Arentze et al. (2003).

3.2 The emission model MIMOSA

The emission selected for the current work, is the extended version of the macroscopic MIMOSA emission model (Lewyckyj et al. (2004) often used to calculate emissions and emission reduction scenarios for larger areas in Belgium.

Model configuration

In order to calculate the vehicle emissions, MIMOSA requires input information on the road network and the traffic situation. Emission factors are used to convert the vehicle distances into emissions. The emission factors used within the MIMOSA model were partially extracted from experimental data collected by on-road measurements as well as from the Copert-III report (Ntziachristos and Samaras, 2000). For missing data (some specific pollutants e.g. PM emissions), emission functions from MEET (1999) were applied.

MIMOSA aims at calculating geographically spread emissions. Therefore, the geographic location of the different traffic links in the study area is required. For every link in the road network the xy coordinates of the start point and endpoint is necessary. Further, information on the road type (highway, national road, main road outside the city, main road inside the city, secondary road) and traffic flows are needed to take into account the variations in the vehicle fleets.

In order to calculate the vehicle emissions for passenger car trips in the Netherlands, as aimed at in this study, MIMOSA version 3.0 was extended with information regarding the Dutch vehicle fleet and road conditions. Further, the settings within the model were altered to benefit maximally from the information provided by a activity-based approach.

3.3 The dispersion model AURORA

Calculating emissions is useful for environmental policy, but it is not sufficient to study exposure to air pollution. Dispersion models are needed to convert the emissions into concentrations at which the population is exposed. AURORA, Air quality modelling in Urban Regions using an Optimal Resolution Approach, is a prognostic 3-dimensional Eulerian box model of the atmosphere (De Ridder et al., 2008). The model assesses how, after being emitted from a source, air pollutants are transported and mixed in the air, undergo physical changes and chemical reactions, generate secondary pollutants, etc. Both air pollutants in the gaseous and the particulate phase are taken into account. The model's outcome are 3-dimensional concentration fields on an hourly basis.

Model configuration

The AURORA air quality modelling system consists of different parts allowing for:

1. meteorological calculations to derive the relevant meteorological parameters (a.o. air temperature, wind speed and direction, humidity, …);
2. the generation of two-dimensional emission fields for air pollutants;
3. the release, chemical transformation, the transport and the deposition of air pollutants.

The actual "heart" of the AURORA model is a number of routines dealing with the transport (advection, diffusion and deposition) and chemical transformation of the air pollutants. They are all indicated in Figure 2. In order to drive these modules AURORA needs meteorological data, emission data and background concentrations.

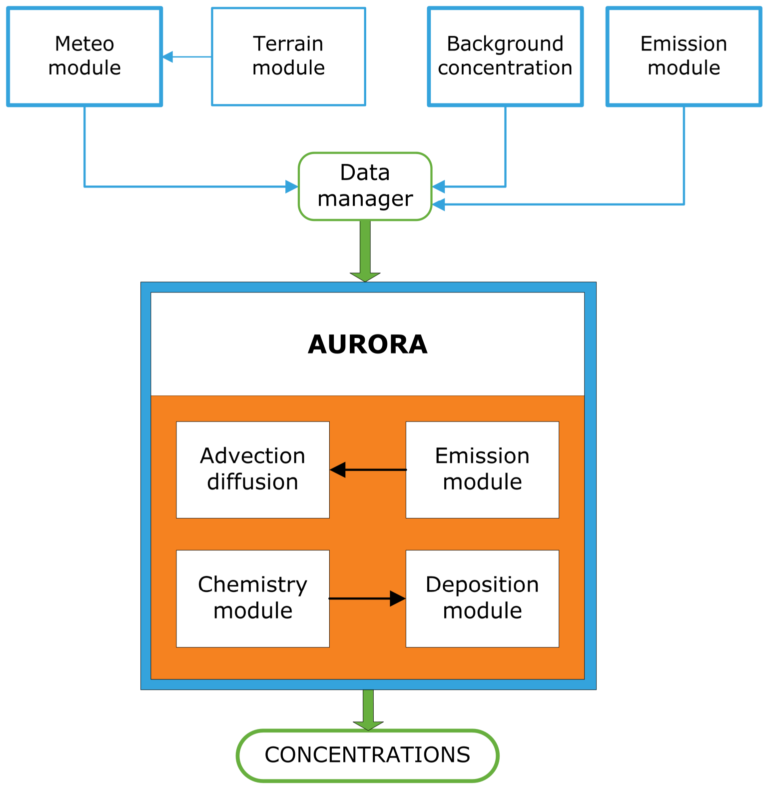

Figure 2: Lay-out of the AURORA modelling system

4. Results

4.1 Activity-based emissions

The predicted results from the activity-based emission modelling approach were compared with travel and emission values from the Dutch Scientific Statistical Agency (CBS) whose data originates from other model simulations.

Regarding the temporal variation in travel behaviour, the activity-based predictions corresponded well with the reported results. Both the timing and the magnitude of the morning traffic peak were predicted with good accuracy by the activity-based model. The prediction for the evening peak on weekdays slightly differed from the NTS values, but the overall picture of the temporal variation turned out very well. The feasibility to model the temporal variation in travelled distance instead of using only peak-hour information is an important improvement compared to most other travel studies who often work with time factors to derive hourly information from one peak-hour value. When the traffic flows fluctuate differently throughout the study area, this activity-based approach will certainly be a better option.

In Table 1 the differences between predicted and reported total emission values for the base year are presented. Relative differences vary between 3 and 26 % for PM and SO_2 respectively. NO_x emissions are overestimated by 17 % and the VOCs are overestimated by 9 %. The CO_2 predictions differ by approximately 11 % from the reported CBS emission values. This can partly be attributed to an slight overestimation of the mileages by the ALBATROSS model.

Table 1. Total vehicle emissions for the year 2000: predicted versus reported values ([a]CBS, 2000)

Emissions (x10^6 kg)	***CO_2***	***NO_x***	***VOC***	***SO_2***	***PM***
Modelled results	19292.25	70.21	43.97	1.59	2.97
Reported results[a]	17346.00	60.10	40.35	1.26	2.88
Relative difference (%)	11.22	16.71	8.98	26.30	3.21

A good agreement between both values does not automatically indicate a good representation of the real situation, and only states the similarity between both models. Ideally, a validation method should comprise the use of measurements instead of simulation values, but the procedure of comparison with other models provides useful cross-validation. More detailed discussion of the travel and emission results can be found in (Beckx et al., in press).

Since travel and emission measurements were not available on a national level (only concentration measurements are available), the values from the Dutch Scientific Statistical Agency were considered as an acceptable alternative for the validation of travel and emission data. In a next step of this modelling framework, pollutant concentrations (based on the emissions presented here) are used for validation purposes by comparing the model results with air quality measurements in the next paragraph.

4.2 Activity-based concentrations

The ALBATROSS-MIMOSA model chain was combined with the AURORA air quality model to estimate concentrations of PM_{10}, O_3 and NO_2 across space and time. By comparing the predicted hourly concentrations with actual measurements we evaluated the ability of the ALBATROSS - AURORA model chain to replicate base year concentration profiles in different areas and time periods.

The results of the statistical analysis demonstrate that the modelling framework is able to predict hourly concentration values for NO_2, PM_{10} and O_3 with sufficient accuracy (Index of Agreement values > 0.5). The best agreement between modelled and observed concentrations was calculated for O_3 (overall IA of 0.75) while the overall agreement for PM_{10} was weaker (IA of 0.57). The statistical results for NO_2, a traffic related air pollutant, are the most important in this study, considering the fact that we wanted to evaluate the use of an alternative transport model to give good estimates of the contribution of traffic sources to ambient pollutant concentration levels. Overall statistics for NO_2 were satisfying with an overall IA value of 0.64. Poor results were reported in stations near the border indicating a possible wrong assessment of the contribution of foreign traffic. The agreement of predicted and measured concentrations of our modelling system was very similar to the statistical results presented in the other papers (e.g. Kousa et al. 2001), indicating that the ALBATROSS - AURORA system is definitely able to simulate both temporal and geographical variations of concentrations with sufficient accuracy. In comparison with other model validation studies however our study included an extended dataset with hourly concentration data from more than 30 measurement stations distributed throughout the Netherlands.

The results in this study demonstrate the ability of the AURORA model to simulate hourly concentrations of NO_2, PM_{10} and O_3 and show that an activity-based model can be used to predict the contribution of traffic sources to local air pollution with sufficient accuracy. This result confirms the usefulness of activity-based transport models for air quality purposes, but demonstrates for the first time their application in pollutant concentration modelling. A more detailed discussion on the concentration results can be found in (Beckx et al., 2009a)

4.3 Activity-based exposure estimates

By combining the concentration information with population data from the activity-based model, both static and dynamic exposure estimates were calculated. With the 'static' approach we mean the 'traditional' exposure approach that considers only residential information and thud implicitly assumes that everybody is always at home. The 'dynamic' approach, on the other hand, takes into account the travel patterns of individuals when calculating the exposure. Results are presented for the Utrecht urban area as a case study. For the Utrecht area, two kinds of exposure analyses were made: a calculation of the total exposure in the study area and an analysis of the exposure hours (i.e. the total number of hours spent in or above a certain concentration).

The first exposure analysis in the Utrecht area concerned the calculation of total hourly exposure estimates by multiplying, for each hour, the number of people in each postcode area (PCA) with the corresponding concentration level. By summing all the exposure values per hour, a total exposure for the Utrecht city centre was calculated both for the static and the dynamic exposure approach. The relative difference in total exposure on weekdays between the static and the dynamic approach is presented in Figure 3. This figure is the same for all pollutants since it actually represents the relative population difference for the two approaches. Hence, Figure 3 also represents the relative in –or outflow in the Utrecht PCA's during an average weekday, compared to the static population. Between 9 a.m. and 16 p.m. the relative difference between static and dynamic estimates amounts more than 100%, meaning that the Utrecht population more than doubles during a weekday compared to the (static) residential information. At night, the number of people estimated by the dynamic exposure method approaches the number of residents used in the static method. Consequently differences between the total exposure estimates are smallest at night.

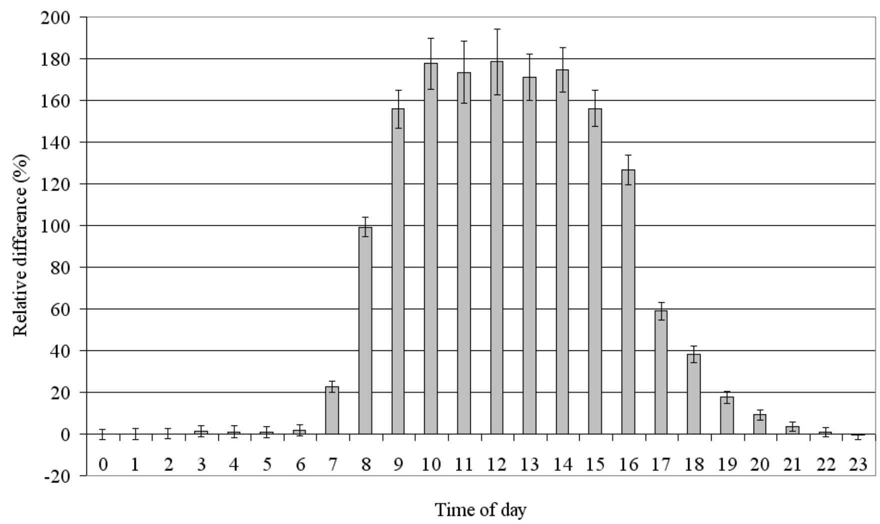

Figure 3. Relative difference between static and dynamic total exposure estimates on weekdays for the city of Utrecht.

The second analysis concerns the amount of hours that people are exposed to certain concentrations. For this analysis, the number of people exposed each hour to a concentration was calculated for both the static and the dynamic approach. Each hour spent by a person at a certain concentration, was expressed as a 'personhour'. In Figure 4 the cumulative number of personhours in the month of April 2005 spent above a certain concentration PM2.5 is shown for both the static and the dynamic approach.

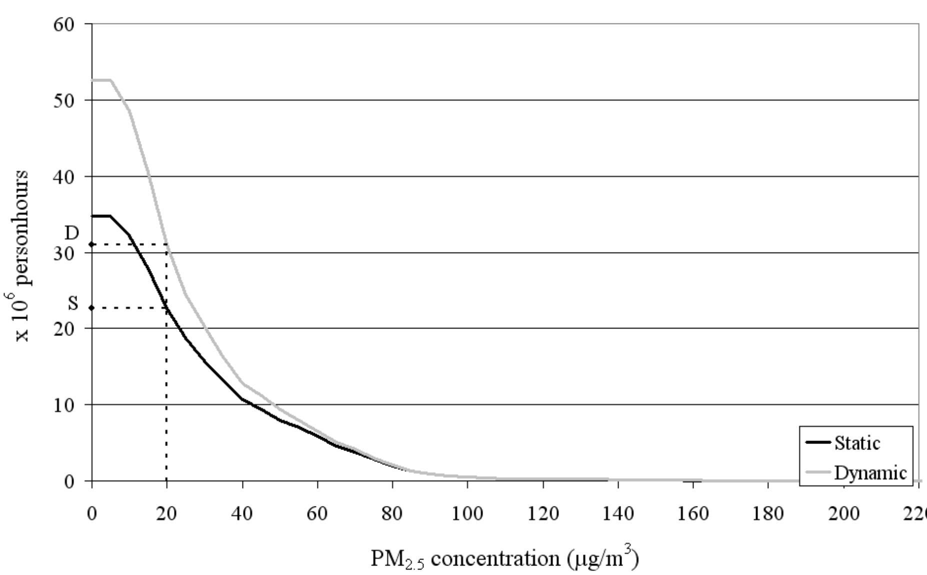

Figure 4. Personhours spent above a certain PM2.5 concentration level in the Utrecht city centre in April 2005 (S-static = 22.60 million personhours and D-dynamic = 30.99 million personhours for PM2.5 concentrations ≥ 20 μg/m3).

It is clear that the total number of hours spent in the Utrecht area is higher for the dynamic approach than for the static approach. According to the static approach approximately 35 million hours are spent in the Utrecht city centre in the month of April. The dynamic approach, on the other hand, simulates approximately 52 million hours spent in the Utrecht city centre. Apparently, the dynamic approach simulates an increase of the population in the study area during the day, confirming the results in Figure 3. According to the new EU air quality directive (2008/50/EC), EU member states are obliged to bring $PM_{2.5}$ exposure levels below 20 µg/m^3 by 2015 in urban areas. Therefore, the exposure above this limit value was also examined. The static exposure approach predicted roughly 22 million hours spent at concentrations above the limit value of 20 µg $PM_{2.5}$/m^3. Using the dynamic approach on the other hand, we estimate that more than 30 million hours were spent at concentrations above 20 µg PM2.5/m3.

More detailed information on the application of activity-based models for exposure analysis can be found in Beckx et al. 2005 and Beckx et al. 2009b.

5. Discussion and conclusion

The kind of integrated modelling approach presented in this paper, using a transport model for air quality purposes, is not only innovative from a scientific and methodological perspective, but it also offers advantages for policy makers. It enables them to take into account that trips both cause transport related emissions and at the same time change the distribution and attributes of the population which will result in different exposure estimates. The availability of activity-based models for exposure analysis therefore opens up a myriad of possibilities for innovative policies and measures. Policy makers will be able to design measures aimed at reducing the exposure at the most important sites, at the most critical times and for selected population groups. These efforts may partly coincide with currently implemented measures to meet general air quality standards. However, in addition to this, we expect that new policies can especially be made more effective in reducing health impacts. In any case, policies in other domains which nowadays risk to offset environmental policies can be screened on their environmental effects before being implemented. In the past the use of different models and policy schemes has often caused one policy in one domain to offset effects of another policy in a different domain because secondary effects could no be taken into account. Enabling to make the link between policies in different policy domains (e.g. mobility, energy and health) is therefore an important advantage of the integrated modelling chain developed in this research.

Further, by applying an activity-based model for the transport modelling part of this framework, instead of a traditional four-step transport model, the range of measures that can be evaluated with this activity-based approach will increase. In an activity-based model each individual is represented as an agent. During simulation, the model simulates the full pattern of activity and travel episodes of each agent and each day of the simulated time period. The pattern of activity and travel episodes, i.e. the schedule, is constructed by a scheduling model or scheduler, which takes personal, household, and environmental attributes as well as constraints into account. These constraints can be situational, institutional, household, spatial, timing, and spatial-temporal constraints. The scenarios corresponding to particular policy measures that can be evaluated with such an activity-based model consist of changes in the personal, household, and environmental attributes and/or in the constraints. In this way, the policy measures that are investigated in the scenarios are taken into account by the scheduler, and thus result in potential changes in the scheduling behaviour. The traffic demand is in its turn derived from the schedules of all the agents in the simulation. Examples of measures or scenarios that can be evaluated by such an approach are changing shop opening hours, ageing of the population, teleworking, etc.…

In summary, this paper demonstrated the advantages of an activity-based approach for air quality purposes by presenting three kinds of applications: the calculation of vehicle emissions, the simulation of pollutant concentration patterns and the assessment of the population exposure to air pollution.

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