

A model for the assessment of the contribution of road traffic to air pollution in the Brussels urban area

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Abstract

As part of the « Sustainable mobility in the Brussels-Capital Region » project, the Centre for Economic and Social Studies on the Environment is currently developing a methodology for the assessment of the physical effects and external costs caused by air pollution generated by road traffic in an urban area. The approach considers a sequence that follows the five following main steps: human activities, emissions, immissions, physical impact and external costs. This paper describes specifically the relationships between the first three steps of the sequence.

As the first step, we present a module that allows the assessment of the contribution to air pollutant emissions of traffic, domestic and office heating as the main urban sources. Road traffic emissions are assessed using both the COPERT methodology and traffic data for the Brussels-Capital Region. Emissions from other activities are taken into account on the basis of statistical data and suitable emission factors in relation with economic and meteorological data. Three pollutants - nitrogen oxides, particulate matter and sulphur dioxide - are considered.

As the second step, we describe a model that establishes the relationship between the emissions previously calculated and the pollutant concentrations in the ambient air. This relationship uses an empirical model based on a hybrid statistical-deterministic distribution. The model is designed as a statistical relation between economic, meteorological and environmental variables given in the form of daily data series for the period 1994-1996. The type of relations used in order to represent the dependence between these variables is also discussed.

The results make it possible to determine the responsibility of each sector of activity in the overall immissions measured in the Brussels area. A comparison is presented between the values measured by the monitoring network and those evaluated by the model. The impact of road traffic in the air pollution in Brussels is discussed for the period considered.

Keywords: road traffic emissions, air pollution modelling, urban air quality.

1. Introduction

Road traffic in the Brussels-Capital Region has continuously increased during the last decade. The reasons of this trend lie mainly in the urban exodus, the employment increase in the Brussels area and its peripheral region, and the continuously increasing population motorization rate. Recent studies (IRIS, 1993) predict the complete saturation of the road network before the year 2005 in the Belgian capital.

The assessment of the impacts of this road traffic increase on the environment in general and on air quality in particular forms one of the major issues of this end of century. In that context, the need for methodologies allowing the assessment of the contribution of road traffic to air pollution has become

greater and greater in order not only to evaluate the actual situation but also to assess the possible effects of measures towards a more sustainable transport system.

As part of the “Sustainable mobility in the Brussels-Capital region” project financed by the Federal Office for Scientific, Technical and Cultural Affairs (OSTC), the Centre for Economic and Social Studies on the Environment (CESSE) is currently developing an accounting framework for the environmental externalities related to the traffic in the Brussels-Capital region. While considering the impacts of air pollution (e.g. in term of building deterioration, health effects, climate change,...), the general approach associates to traffic a sequence based on the five following steps: human activities, emissions, immissions, physical impacts and external costs. This is the classical approach namely used in major studies such as ExternE (European Commission, 1995) for the assessment of externalities in the energy sector and which has recently been updated for its application to the transport sector.

This paper deals specifically with the three first steps of this sequence by presenting a model that makes possible the determination of the share of responsibility that can be attributed to road traffic in order to explain the pollutant concentrations measured in the Brussels-Capital region. The model is divided in two specific modules. The first one links the economic activities with the emissions levels. The second one determines the resulting immissions by modelling the relationship between the previously calculated emissions and different pertinent meteorological variables.

The model works at an aggregated level by considering an average pollution level for the area studied. It estimates the emissions and the resulting immissions for that area on a daily basis for the period 1994-1996. The pollutants considered are: nitrogen oxides, nitrogen dioxides, particulate matter and sulphur dioxide.

2. Basic approach

Some authors demonstrated that there are statistical correlation between concentrations of pollutants in the urban atmosphere, pollutant emission and some meteorological parameters like wind speed or temperature (Benarie, 1980). On the basis of this conclusion, Cross & Lacey (1981) developed a simple model to forecast sulphur dioxide and black smoke concentration levels in urban environments. This model produced good results in London even though it was less sophisticated than most of the forecast-oriented models usually mentioned in the literature. The idea behind this approach is that only some predominating variables, carefully selected on the basis of a statistical approach, determine pollutant concentrations in an urban atmosphere. This type of approach has also been used by other authors (Hallez *et al.*, 1989; Meurrens *et al.*, 1983; Hallez *et al.* 1982) to develop another type of model where the influence of different meteorological factors is taken into account in the form of multiplying functions.

On the basis of these findings, the CESSE developed an econometric type model based on a non-linear multiple regression analysis. This model has been constructed after having studied the influence of various parameters related to pollutant concentrations in an urban atmosphere (Hecq *et al.*, 1992; Hecq and Taminiaux, 1993; Hecq *et al.*, 1994; Hecq *et al.*, 1995).

The model is designed as a statistical relation between a dependent variable - the pollutant concentrations measured at different monitoring sites in the Brussels urban area - and the two following types of explanatory variables:

1. *Economic variables*: emissions related to the main economic activities in the urban area (traffic, indoor heating, industry...);
2. *Meteorological data*: wind velocity, mixing height, precipitation, temperature, daily period of sunshine...

The most pertinent meteorological data have been selected on the basis of statistical analysis. Whereas these data are directly available from the routine measurements performed in the region, the economic data have to be evaluated on a daily basis for the period considered. The specific module described in the next section performs this.

3. Module : Economic activity – Emissions

As major economic activity related variables, the model uses the daily emissions caused both by the indoor heating and the road traffic. Emissions from local industry is not specifically evaluated since it is virtually non-existent in the Brussels urban area while it could be non-negligible for some pollutants (e.g. particulate matter generated in the direct neighbourhood of the region). Its impact is integrated as external import together with the background level considered in the model formulation.

We describe here the specific methodologies used to assess these emissions for the following pollutants: nitrogen oxides (NO_x), particulate matter (PM) and sulphur dioxide (SO₂).

3.1. Indoor heating

The annual emissions of atmospheric pollutants due to indoor heating are calculated by multiplying the consumption of each fossil fuel by its emission factor leading to the following formulation:

$$AEH_i = \sum_j EF_{i,j} \cdot AC_j \quad (1)$$

Where,

- i pollutant index (NO_x, PM, SO₂);
- j fuel index (fuel oil, coal or natural gas);
- AEH_i annual emission of pollutant i due to indoor heating;
- $EF_{i,j}$ emission factors of pollutant i for indoor heating using fuel j ;
- AC_j annual consumption of fuel j used for indoor heating purposes.

The annual emissions related to the domestic heating and to the heating in the tertiary sector have been evaluated separately.

The resulting annual emissions are then converted into daily emissions in order to be integrated in the model. This conversion is performed using the concept of degree-day DD that is defined as follows:

$$DD = 16.5^\circ\text{C} - Te \quad \text{with } DD \geq 0 \quad (2)$$

$$Te = 0.6T_m + 0.3T_{m-1} + 0.1T_{m-2} \quad (3)$$

With,

T_m = average temperature of day m in °C.

The annual emissions are thus distributed according to a daily equivalent temperature Te that actually integrates the temperatures of the two previous days.

The concept of degree-day lies on the assumption that economic agents begin to heat below the threshold of 16.5°C. It is also assumed that, below this threshold, the relation between “energy consumption” and “temperature” is linear. Such relations have in fact been observed on the basis of daily measurements related to the distribution of natural gas by the Brussels regional network (Coussement *et al.*, 1989).

By using an equivalent temperature Te that integrates a sort of lag term rather than the actual daily average temperature, we assume that the heating behaviour is partly influenced by the temperature of the previous days. This relation has actually been proposed by the Belgian Federation of Gas Industry in its statistical yearbook to explain the gas consumption in Belgium (FIGAZ, 1996).

The method of estimating daily emissions consists of two stages: first, to add up the number of degree day over the year and divide the annual emissions from indoor heating in the Brussels-Capital region by this number in order to obtain an emission by degree day; second, to calculate the daily emissions from indoor heating by multiplying the emissions per degree day by the number of degree day for the day considered.

3.2 Traffic

The calculation of the annual emissions from road traffic is based on two types of data. First, the volume of traffic has to be estimated, e.g. in the form of vehicle-kilometres driven by the different vehicle categories within the area considered. We used the regional statistics that provide the number of kilometres driven on the road network each year. Second, suitable emission factors are required for the different vehicle categories circulating in the Brussels area. Average speed dependent emission factors proposed in the COPERT II methodology (Ahlvik *et al.*, 1997) have been used.

COPERT distinguishes for each vehicle category (passengers cars, light duty vehicles, heavy duty vehicles...) different sub-categories defined on the base of the successive emission legislation and the technological concept (cylinder capacity, catalyst, fuel...). For the period considered, the Belgian vehicle fleet has been distributed according to these sub-categories on the base of the available statistics. Effective traffic composition in the Brussels-Capital region on the different road classes (motorway, national road and urban street) has been deduced from federal statistics.

For each road class, a representative average speed has been attributed to the main vehicle categories (passenger cars, light duty vehicle, heavy duty vehicle, bus and coach).

Using the yearly mileage and the representative average speed of each vehicle category on each road class, the methodology developed provides the annual emissions generated by road traffic in the Brussels-Capital region. Hot emissions and cold start emissions are distinguished. Cold start emissions represent the additional emissions resulting from vehicles while they are warming up or with a catalyst below its light-off temperature. The ratio of cold to hot emissions and the fraction of kilometres driven with cold engines are calculated using the yearly average temperature and an estimate of the average trip length following the COPERT methodology.

The overall calculation can be summarised as follows:

$$AET_i = AET_{i,hot} + AET_{i,cold} \quad (4)$$

$$AET_i = \sum_j \sum_k EF_{i,j,k,hot} \cdot AVM_{j,k,hot} + \sum_j \sum_k EF_{i,j,k,cold} \cdot AVM_{j,k,cold} \quad (5)$$

Where,

i	pollutant index;
j	vehicle category index;
k	road class index;
AET_i	annual emission of pollutant i due to road traffic;
$AET_{i,hot}$	annual emission of pollutant i due to road traffic with hot engines;

$AET_{i,cold}$	annual emission of pollutant i due to road traffic with cold engines;
$EF_{i,j,k,hot}$	emission factors of pollutant i for vehicle category j driven on road class k with hot engines;
$EF_{i,j,k,cold}$	emission factors of pollutant i for vehicle category j driven on road class k with cold engines;
$AVM_{j,k,hot}$	annual vehicle mileage for vehicle category j driven on road class k with hot engines;
$AVM_{j,k,cold}$	annual vehicle mileage for vehicle category j driven on road class k with cold engines.

Daily emissions required by the model are obtained using suitable traffic indices. Two indices are combined: a daily index - defined as a function of the day in the week - and a monthly index – defined as a function of the month in the year. These indices were constructed from traffic counts at representative sites in the Brussels urban area in order to account accurately for the variations in the traffic intensity all along the year. Daily emissions are then obtained by multiplying the average daily emission (i.e. global annual emission divided by the number of days in the year) by both indices.

4. Module: Emissions – Immissions

Each pollutant – particulate matter (PM), sulphur dioxide (SO_2), nitrogen monoxide (NO) and nitrogen dioxide (NO_2) - is modelled separately leading to four sets of equations. Each set of equations contains as many equations as daily observations in the time period considered.

The general form of the equations constituting the model establishes a statistical relationship between the three variable categories described above - pollutant concentrations, meteorological data and economic variables - and lies on two types of relation between the time series:

- linear relation between the pollutant concentrations observed and the emissions from indoor heating and road traffic;
- exponential relation between the pollutant concentrations observed and meteorological variables such as wind-speed, precipitation, mixing height and daily period of sunshine.

Note that the daily average temperature is linearly related to the pollutant concentration by way of the degree day concept mentioned above.

The original feature of this formulation is that it simultaneously takes account of the different influences, economic as well as meteorological, on the level of pollutant concentration in the ambient air. Furthermore, in the general equation, the “emission term” and the “meteorological term” are multiplied by each other rather than simply added. This last feature makes the model highly non-linear both in its variables and its parameters.

The resulting equations to be solved are the following (index j relative to the j^{th} daily observation has been omitted to simplify the notation):

$$[PM] = [a_1 \cdot deh_1 + b_1 \cdot det_1 + g] \cdot \left(\frac{1}{vel}\right) d \cdot e^{(e_1 \cdot preci)} \cdot e^{(V_1 \cdot mixh)} \quad (6)$$

$$[SO_2] = [a_2 \cdot deh_2 + b_2 \cdot det_2 + g] \cdot \left(\frac{1}{vel}\right) d \cdot e^{(e_2 \cdot preci)} \cdot e^{(V_2 \cdot mixh)} \quad (7)$$

$$[\text{NO}] = [\mathbf{a}_3 \cdot \text{deh}_3 + \mathbf{b}_3 \cdot \text{det}_3] \cdot \left(\frac{1}{\text{vel}}\right) \mathbf{d} \cdot e^{(\mathbf{V}_3 \cdot \text{mixh})} \quad (8)$$

$$[\text{NO}_2] = [\mathbf{a}_4 \cdot \text{deh}_4 + \mathbf{b}_4 \cdot \text{det}_4 + \mathbf{g}] \cdot \left(\frac{1}{\text{vel}}\right) \mathbf{d} \cdot e^{(\mathbf{V}_4 \cdot \text{mixh})} \cdot e^{(\mathbf{h}_4 \cdot \text{sun})} \quad (9)$$

$[\text{PM}]$, $[\text{SO}_2]$, $[\text{NO}]$, $[\text{NO}_2]$ are the daily average pollutant concentrations given in ($\mu\text{g}/\text{m}^3$). These concentrations are average values for the concentrations measured at the different monitoring stations in the urban area considered.

deh_i and det_i are the economic variables: deh_i represents the daily emission of pollutant i due to indoor heating; det_i represents the daily emission of pollutant i due to transport.

vel , preci , mixh , sun are meteorological variables:

- ◇ vel : daily average wind velocity (m/s);
- ◇ preci : daily average precipitation (mm);
- ◇ mixh : mixing height at midday (m);
- ◇ sun : daily period of sunshine expressed in % (100% = 24 hours).

\mathbf{a}_i , \mathbf{b}_i , \mathbf{g} , \mathbf{d} , \mathbf{e} , \mathbf{z}_i , \mathbf{h}_i are the regression coefficients. These coefficients are determined by means of a multiple non-linear regression analysis. Coefficients that have not been estimated significant were removed in the final form of the equation.

In the equation (6) to (9), the contribution of the different economic activity to the overall immissions can easily be determined. The share of responsibility of indoor heating for the daily immissions of pollutant i is given by the relation:

$$\text{Immission attributed to indoor heating} = [\mathbf{a}_i \cdot \text{deh}_i] \cdot \left(\frac{1}{\text{vel}}\right) \mathbf{d} \cdot e^{(\mathbf{e}_i \cdot \text{preci})} \cdot e^{(\mathbf{V}_i \cdot \text{mixh})} \quad (10)$$

The share of responsibility of traffic for the daily immissions of pollutant i is given by the relation:

$$\text{Immission attributed to road traffic} = [\mathbf{b}_i \cdot \text{det}_i] \cdot \left(\frac{1}{\text{vel}}\right) \mathbf{d} \cdot e^{(\mathbf{e}_i \cdot \text{preci})} \cdot e^{(\mathbf{V}_i \cdot \text{mixh})} \quad (11)$$

The "background level + industry" term describes immissions other than those from traffic and indoor heating. The resulting immission therefore corresponds to the natural background level plus the input from industry both inside and outside the urban area considered. The model does not enable any distinction to be made between these components. The share of responsibility of "background level + industry" for daily immissions of pollutant i is given by the relation:

$$\text{Immission attributed to "background level + industry"} = [\mathbf{g}] \cdot \left(\frac{1}{\text{vel}}\right) \mathbf{d} \cdot e^{(\mathbf{e}_i \cdot \text{preci})} \cdot e^{(\mathbf{V}_i \cdot \text{mixh})} \quad (12)$$

5. Results and discussion

The approach developed enables a relationship to be established, first, between economic activities and emissions and, second, between emission and immissions in the ambient air. The methodology has been applied to the current situation in the Brussels-Capital region. The following sections summarise the most notable results with respect to emissions assessment, emissions-immissions relationship modelling and share of responsibility of the main economic activities in the overall pollution concentrations.

5.1 Pollutant emissions

First, the model assesses the amount of pollutants emitted by road traffic and indoor heating for the period 1990-1996. Its application gives the results presented in Figure 1 for particulate matter, Figure 2 for sulphur dioxide and Figure 3 for nitrogen oxides. In these figures the part of the emissions due to indoor heating can be distinguished from those due to traffic, and so on for each of the three pollutants considered.

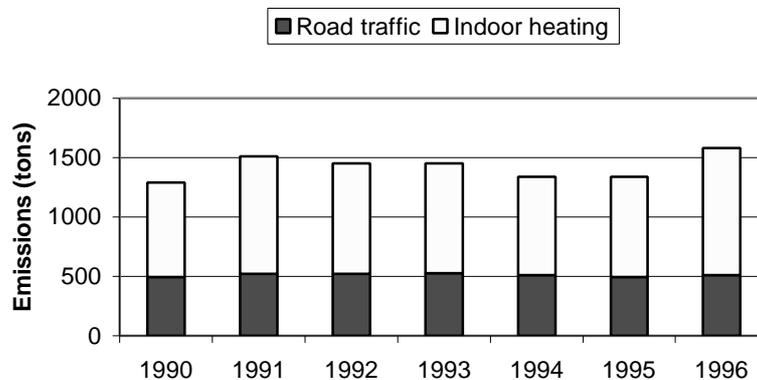


Figure 1: Particulate matter emissions from indoor heating and road traffic in the Brussels-Capital region.

In Figure 1, we can notice that over the period analysed the particulate matter emissions from road traffic have a nearly constant level of about 500 tons per year, while those from indoor heating fluctuate around a mean value of about 900 tons per year. These fluctuations can easily be explained by the variations in the annual average temperature. Cold years result in higher fuel consumption and consequently higher pollutant emissions. On an average for the period 1990-1996, the contributions of the two sectors of activity to the yearly particulate matter emissions in the Brussels-Capital region are estimated at 36% for the road traffic and 64% for the indoor heating.

While considering the SO₂ yearly emissions in the Brussels-Capital region, the Figure 2 shows that for road traffic the emissions have slightly increased between 1990 and 1993 to reach a value of 819 tons per year. Between 1993 and 1996, the SO₂ emissions from traffic have decreased of about 35%. That can be explained by the introduction of new standards for the reduction of the diesel fuel sulphur content, first in 1994 and second by the end of 1996. SO₂ emissions from indoor heating fluctuate around the average value of 1809 tons per year with the same remark as for PM emissions regarding the year to year variations. The contributions of road traffic and indoor heating to the SO₂ emissions are estimated at 29% and 71% respectively.

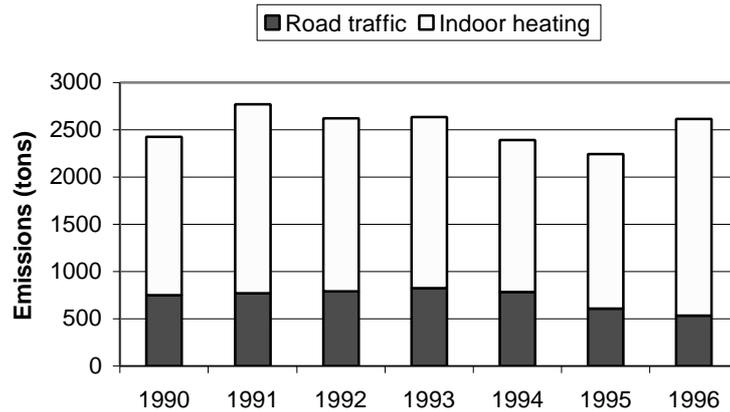


Figure 2: SO₂ emissions from indoor heating and road traffic in the Brussels-Capital region.

Finally, we can see at the Figure 3 that road traffic is mainly responsible for the annual nitrogen oxides emissions in the Brussels urban area with up to 71% of the total emissions on an average for the period 1990-1996. We can noticed also the continuous decrease in the absolute emissions of NO_x from traffic during this period, from about 6300 tons in 1990 to about 5100 tons in 1996. Considering the continuous increase of the overall mileage driven in the area during this period, this decrease can only be explained by the driving fleet characteristics evolution as a consequence of the introduction of more stringent emission standards during the last years.

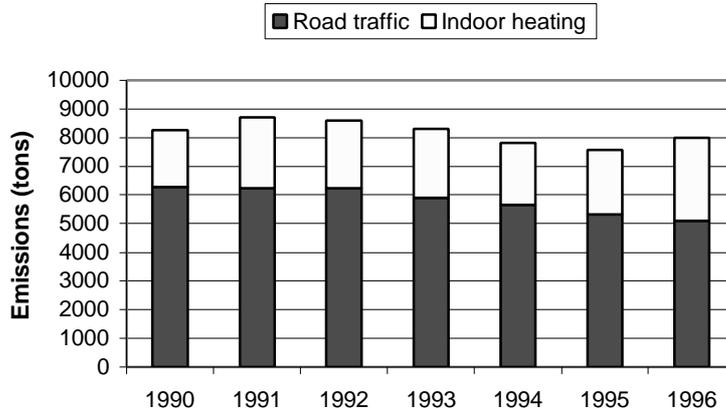


Figure 3: NO_x emissions from indoor heating and road traffic in the Brussels-Capital region.

5.2 Pollutant immissions

While considering the pollutant concentration in the Brussels urban area, the resolution of equation (6) to (9) makes it possible to estimate the daily evolution of the concentrations of particulate matter, sulphur dioxide, nitrogen oxide and nitrogen dioxide. Due to gaps in the pollution data available, we restricted our analysis to the period 1994-1996. Figures 4 to 7 present a comparison between the concentrations measured and those estimated by the model for the four pollutants considered during the year 1996. We can noticed a good agreement between the two time series which demonstrates the model ability to reproduce the daily evolution of pollutant concentration in the Brussels area on the base of the daily emissions previously calculated and some pertinent meteorological parameters obtained from routine measurements in the region.

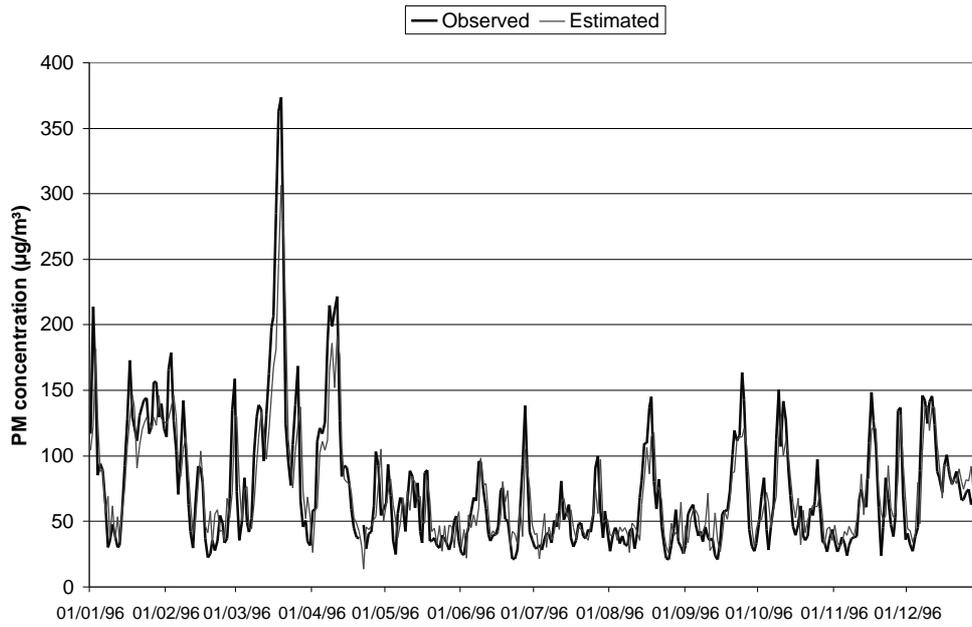


Figure 4: Comparison between observed and estimated daily average PM concentrations in the Brussels-Capital region.

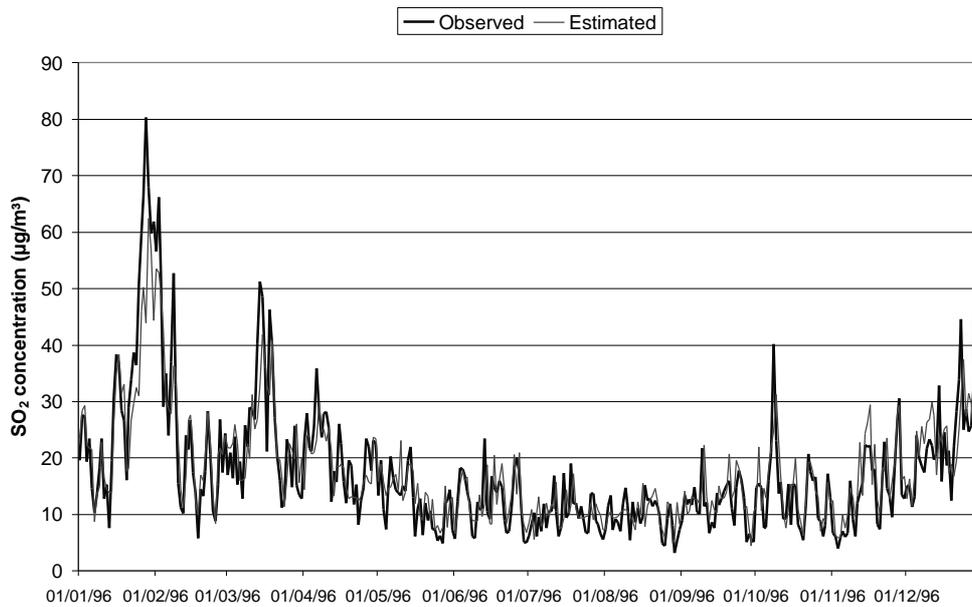


Figure 5: Comparison between observed and estimated daily average SO₂ concentrations in the Brussels-Capital region.

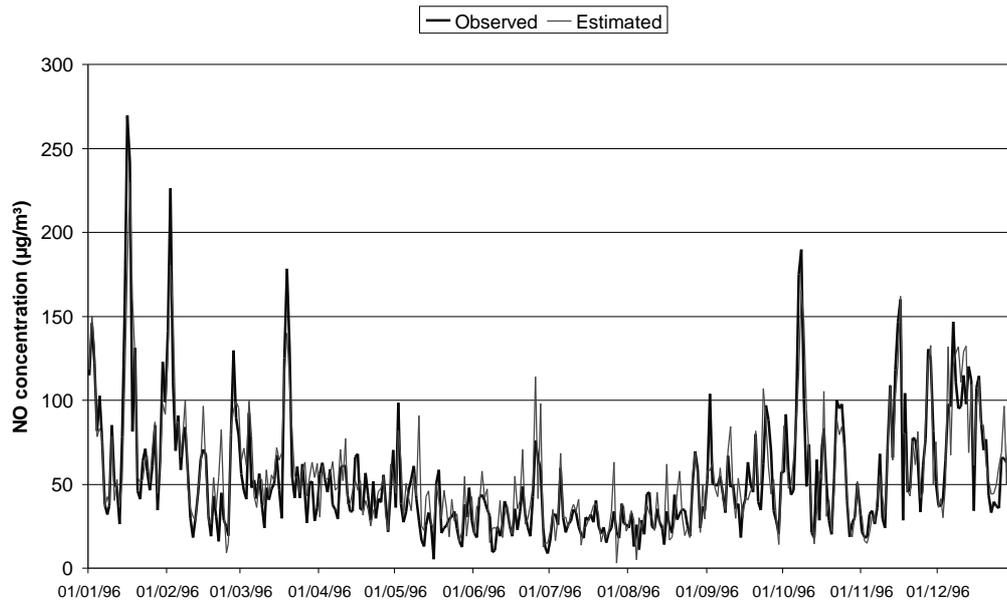


Figure 6: Comparison between observed and estimated daily average NO concentrations in the Brussels-Capital region.

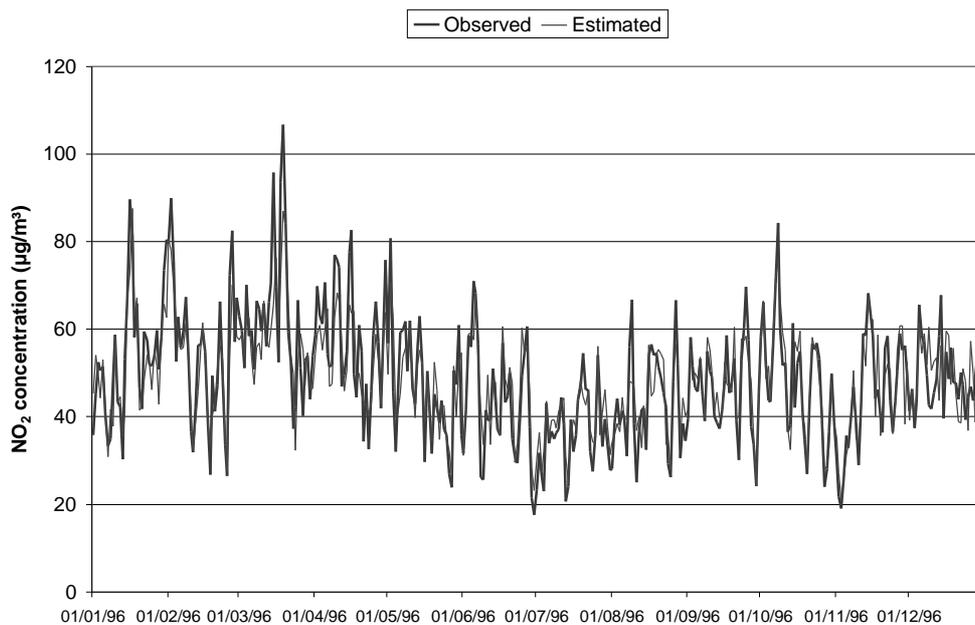


Figure 7: Comparison between observed and estimated daily average NO₂ concentrations in the Brussels-Capital region.

The model developed allows the share of responsibility of the different economic activities in the overall immissions to be assessed according to the relation (10) to (12). For the period 1994-1996, the results are presented in the Figures 8 to 11 where the concentrations are expressed on a monthly average.

In Figure 8, where is presented the particulate matter concentrations over the 1994-1996 period, the share of responsibility of indoor heating and traffic can be clearly seen, as well as the impact of background pollution, imported pollution and industry in the Brussels region. We can notice the typical peaks of pollution caused by indoor heating during the winter months.

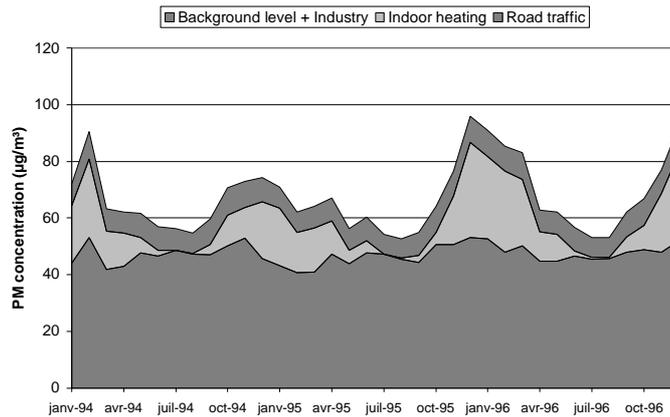


Figure 8 : Contributions of the different economic activities to the PM concentrations in the Brussels-Capital region (concentration expressed on a monthly average).

A remark has to be done while considering the important contribution of the “background level+Industry” term in the overall immissions and the relative low share of particulate concentration attributed to road traffic. This is due to the fact that we actually based our model on the total suspended particles concentration measurements available in the urban area while road traffic is mainly responsible for the emission of low diameter particles (PM_{2,5} to PM₁₀). The measurement network is currently being extended in order to measure such fine particles concentration in the Brussels-Capital region. This will provide us with a more reliable tool for the assessment of the actual responsibility of road traffic. Black smoke measuring network in Brussels has also been modified these last years so that only very short time series are available for the moment. Nevertheless, as a first approach, we modelled the immissions for a specific site where black smoke concentration is measured since 1995, the Berchem-Sainte-Agathe measuring station located in a suburban zone. In a first approximation, the measured concentrations can be considered as representative of an average level for the region studied. A simulation for the year 1996 has demonstrated a good agreement between the observed and estimated values. The share between the main sources gives the following distribution: 6% for the “background level+Industry” term, 28% for the indoor heating, and 66% for road traffic. These percentages have to be compared respectively to the 68%, 20% and 12% obtained for the same year when we consider the total suspended particles. The share of road traffic seems thus to be much more important when we consider the black smoke immissions which are actually more relevant for the assessment of the impacts of road traffic in term of damage to public health and buildings.

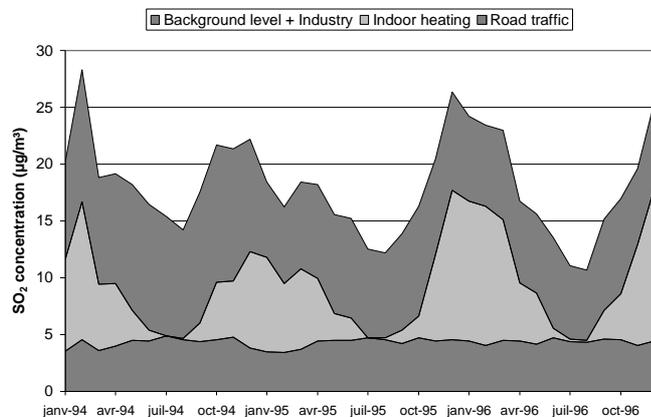


Figure 9 : Contributions of the different economic activities to the SO₂ concentrations in the Brussels-Capital region (concentration expressed on a monthly average).

While considering the SO₂ immissions presented in the Figure 9, the same remark as for the particulate matter can be done regarding the predominant contribution of indoor heating during the winter months while road traffic is mainly responsible for the SO₂ pollution in summer. The seasonal nature of economic activities is therefore reflected in the levels of responsibility. As far as immissions are concerned, the responsibility borne by traffic for SO₂ pollution falls from about 60% in summer to about 30% in winter when indoor heating contributes to more than 50% of the immissions in the region. During the period 1994-1996, the share of responsibility of indoor heating passed from 23% in 1994 to 35% in 1996, while that of road traffic passed from 54% to 41% during the same period.

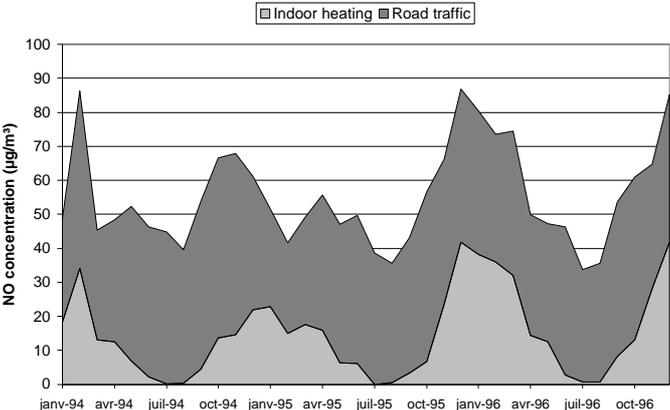


Figure 10 : Contributions of the different economic activities to the NO concentrations in the Brussels-Capital region (concentration expressed on a monthly average).

Results for nitrogen oxides are presented separately for NO and NO₂ in the Figures 10 and 11 respectively. The immissions of these two pollutants are dominated by the road traffic contribution. Indoor heating contributes only during the winter months and mainly for the NO immissions. The share of background pollution is important for NO₂. However, traffic is the economic activity most responsible for this type of pollution, a factor that reduces its seasonal character. The peaks of pollution always occur in the winter, but their intensity is much less apparent than in the case of sulphur dioxide pollution. For the period analysed, we notice an increasing contribution of indoor heating that can be explained by the increase in the annual emissions from indoor heating combined with a decrease in those from road traffic. On an average for the period 1994-1996, the contribution of road traffic has been of 73% for NO and 53% for NO₂ while that of indoor heating has been of 27% for NO and 5% for NO₂.

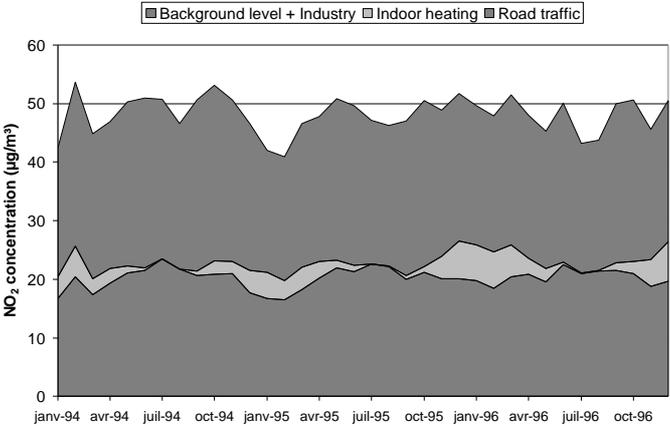


Figure 11 : Contributions of the different economic activities to the NO₂ concentrations in the Brussels-Capital region (concentration expressed on a monthly average).

6. Conclusions

The approach developed allowed both to assess the emissions from the main human activities responsible for the urban air pollution and to determine the share of responsibility of these activities in the pollutant concentrations measured in the Brussels urban area.

The results demonstrated a good agreement between the concentrations observed and those estimated by the model.

On the base of the model, the contribution of road traffic to the pollutant immissions in the Brussels-Capital region has been determined. Road traffic appears to play a very important role in the nitrogen oxides pollution with a contribution of 73% for NO and 53% for NO₂ on an average for the period 1994-1996. In relation with particulate matter pollution, simulation based on the total suspended particles measurement in the area has demonstrated a relative small contribution of road traffic, while a simulation based on local measurements of black smoke established the contribution of road traffic to 66%. While considering sulphur dioxide, the contribution of road traffic appears to be important mainly during the summer months while winter immissions are dominated by the indoor heating seasonal influence. The contribution of road traffic to SO₂ immissions has continuously decreased these last years.

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