Modelling traffic pollution in streets

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Preface

This report summarises some of the results obtained during the project on Air Pollution from Traffic, which was conducted in the frames of the Danish National Environmental Research Programme 1992-1996, within the Centre of Air Pollution Processes and Models. The project was managed by the Danish National Environmental Research Institute and performed in co-operation with the Risø National Laboratory, the Road Directorate and dk-Teknik.

The aim of the project was to obtain a more complete knowledge of air pollution from traffic in urban areas, including not previously measured compounds, such as ozone, volatile organic compounds (VOC) and other photochemical precursors.

The project included several measuring programmes, results from which were used for detailed studies of air pollution processes and model development.

This report concerns mainly the subject related to modelling air pollution from traffic in urban streets. A short overview is presented over the theoretical aspects and examples of most commonly used methods and models are given. Flow and dispersion conditions in street canyons are discussed and the presentation is substantiated with the analysis of the experimental data. The main emphasis is on the modelling methods that are suitable for routine applications and a more detailed presentation is given of the Operational Street Pollution Model (OSPM), which was developed by the National Environmental Research Institute. The model is used for surveillance of air pollution from traffic in Danish cities and also for special air pollution studies.

The result obtained during the National Environmental Research Programme on Air Pollution from traffic have substantially contributed to improvements of the OSPM and a better understanding of the problems related to traffic pollution.

1   Introduction

Automobile transport is now an inherent part of our civilisation, and as it happened with many other technological advancements, the negative aspects are becoming more and more pronounced. One of them is air pollution from car exhaust gases. This pollution has many adverse effects, whose manifestation and character varies depending on e.g. the geographical scale in consideration. On the European scale, and even on the global scale, the road traffic is known to be the major contributor to the anthropogenic emissions of the "greenhouse" gas Carbon Dioxide (CO_2) and it is expected that these emissions will continue to increase with the steadily increasing amount of traffic. On regional scale, the photochemical pollution, formation of smog episodes, are also to a large extend attributed to emissions from traffic. The most severe damaging effects related to pollution from traffic can, however, be found in urban areas. It is here that the traffic density is largest and concentrations of car exhaust gases are often orders of magnitude higher than in rural areas. Urban areas can still not be considered as homogeneous entities; the largest pollution levels occur in street canyons where dilution of car exhaust gases is significantly limited by the presence of buildings flanking the street.

Although, estimation of emissions is an essential part of any study concerning air pollution from traffic, this subject will not be treated here. The main focus is put on the physical processes governing the pollution phenomena and especially on mathematical description of pollution dispersion in urban streets.

Mathematical models which include relationships between emissions and concentration levels are necessary for estimation of e.g. future trends in air quality or evaluation of abatement strategies. There exist many such models, with varying levels of complexity, and they have been used for air quality studies on scales ranging from global to single industrial point sources (see e.g. *Zannetti, 1990; Olesen and Mikkelsen, 1992*). However, the very special dispersion conditions in street canyons imply that the more traditional modelling methods are hardly applicable in this case.

The main features of pollution dispersion in street canyons and the available modelling tools are discussed in this chapter. The reader should, however, not expect a thorough review of street pollution models. The main emphasis is on applied methods which can be used for routine evaluation and analyses of air pollution from traffic in streets, with a focus on the use of the Danish model, the Operational Street Pollution Model (OSPM). The principles behind this model, test results and also limitations of the model will be discussed here.

A multidisciplinary project devoted to studies of air pollution from traffic in urban areas was recently carried out in Denmark in the frames of the Danish Environmental Research Programme, which was initiated in 1992/1993. Some of the project results will be reported here, as they provide new and valuable information on behaviour of pollution in urban streets.

The main characteristics of flow and dispersion conditions in street canyons derived from measurements and model simulations are discussed in Section 2. A short review of available pollution models is given in Section 3. Description of OSPM is presented in Section 4, while results and comparison with measurements are discussed in Sections 5

and 6. Chemical transformations, especially regarding formation of nitrogen dioxide (NO_2), are discussed in Section 7. The treatment of this problem by OSPM is also described here. Finally, some unresolved problems and recommendations for future work are presented and discussed in Section 8.

2 Wind flow in street canyons

The most characteristic feature of the street canyon wind flow is the formation of a wind vortex so that the direction of the wind at street level is opposite to the flow above roof level. The presence of a canyon vortex was already demonstrated by *Albrecht (1933)* and later on verified by *Georgii et al. (1967)*.

Unfortunately, direct field measurements of wind flow in street canyons are rare and results are often not very conclusive. The main reason for this is that as a rule, only few point measurements of wind are usually available and even those can be significantly influenced by very local structures. This makes it difficult to use such measurements for determination of a full three dimensional structure of the wind pattern. Some more elaborated flow visualisation techniques are therefore applied. An example of such an experiment is the work of *DePaul and Sheih (1986)*. The mean wind velocities in a street canyon were determined by analysis of trajectories of tracer balloons that were released in the canyon and photographed in rapid sequence. The balloon trajectories showed the formation of a vortex cell within the canyon, provided the ambient wind velocity exceeds 1.5-2.0 ms^{-1}. An important feature of the flow pattern, demonstrated in this experiment, is that the vertical extent of the cell does not seem to extend beyond the roof level. Velocity vectors at roof level appeared to be nearly parallel to the ambient wind.

Wind measurements in an urban canyon are reported by *Nakamura and Oke (1988)*. Horizontal wind speed and direction were measured both above and within the canyon. One instrument was placed 3.6 m above the roof while the other was mounted 1 m above the floor of the canyon at its midwidth. Their observations confirmed formation of a canyon vortex when the flow was normal to the street axis. The wind direction at the bottom of the canyon was approximately "a mirror reflection" of the above roof wind direction. When roof level wind speeds exceed about 2 ms^{-1}, the street level wind speed was approximately 2/3 of the wind flow above roof top. This is in reasonable agreement with the *DePaul and Sheih (1986)* observations.

Profiles of mean wind speeds and turbulence statistics in and above an urban street canyon were recently presented by *Rotach (1995)*. His observations indicate that the profiles exhibit a strong dependence on atmospheric stability conditions.

2.1 Wind tunnel studies

The most extensive investigations of flow and dispersion regimes in street canyons are performed in wind tunnels. Based on available wind tunnel data, especially the works of *Hussain and Lee (1980)* and *Hosker (1985)*, *Oke (1988)* provided a systematic classification of flow regimes in urban street canyons. The flow types are characterised by three regimes depending on the canyon geometry: isolated roughness flow, wake interference flow and skimming flow. The canyon geometry is defined mainly by the ratio H/W, where H is the average height of the canyon walls and W is the canyon width. The three flow regimes are illustrated in Figure 2.1. For widely spaced buildings (H/W < 0.3), the flow fields associated with the buildings do not interact, which results in the *isolated roughness flow* regime. At closer spacing (0.3 < H/W < 0.7) the wake created by the upwind building

is disturbed by the downwind building creating a downward flow along the windward face of this building. This is the *wake interference flow*. Even closer spacing results in the *skimming flow* regime. In this case a stable circulatory vortex is established in the canyon and the ambient flow is decoupled from the street flow.

Several studies have been undertaken to verify or quantify more precisely the threshold H/W ratios for transition between the different flow regimes. *Hunter et al., (1991, 1992)* have estimated flow regimes in street canyons of varying geometry using a numerical flow model. Their results agreed very well considering transition between wake interference skimming flow regimes but for transition to the isolated roughness flow regime in long canyons they found a H/W ratio significantly smaller than that estimated by *Oke (1988)*. The classification of flow regimes, provided by *Oke (1988)*, should be considered only as a qualitative one. Caution must be taken when wind tunnel results are extrapolated to "real life" conditions.
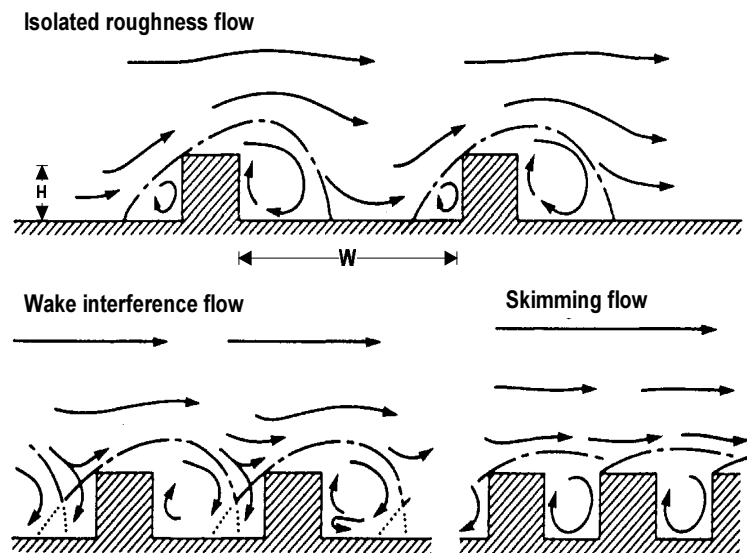

Figure 2.1 Flow regimes associated with different canyon H/W ratios (after Oke, 1988).

2.2   Tracer dispersion experiments

Works by *Hoydysh and Chiu (1971)*, *Jacko (1972)*, *Hoydysh et al. (1974)*, *Wedding et al. (1977)*, *Kennedy and Kent (1977)*, *Hussain and Lee (1980)*, have shown the influence of the street geometry on dispersion conditions. A series of wind tunnel experiments for different street geometries was reported by *Builtjes (1983, 1984)*.

One of the most systematic investigations of dispersion characteristics in a wind tunnel model of urban streets was performed by *Hoydysh and Dabberdt (1988)* using tracer gas and flow visualisation techniques. Three different canyon configurations were considered in this study: a regular long street canyon with equally high buildings on both sides of the street (equal notch configuration); a canyon with the height of the upwind building twice the downwind building (step-down notch) and a canyon with the downwind building

height equal 1.5 upwind building height (step-up notch). Across-street concentration gradients and the vertical profiles were measured for various wind angles. The results of this investigation have confirmed some previous research findings and also provided several new insights. The vertical concentration profiles were well approximated by an exponential function with the maximum at street level. For cross street wind directions the concentration levels were generally a factor of two or more greater for the leeward than the windward side, except for the step-down notch where windward concentrations were slightly greater than the leeward concentrations. For the even notch configuration the street level concentrations on the windward side exhibited significant variation with wind direction. A local maximum was observed for perpendicular wind directions, a shallow minimum for wind direction around 45° and a subsequent increase of concentrations for wind angles approaching parallel directions. A later study by *Dabberdt and Hoydysh (1991)* confirmed these findings.

Wind flow characteristics for wind angles perpendicular to the street axis were observed with the aid of neutrally-buoyant helium-filled soap bubbles whose trajectories were traced to determine wind velocities in the canyon. Most trajectories were nearly circular or elliptical and extended throughout the depth of the canyon. For the even notch configuration the average circumferential velocity was about one-fourth of the ambient wind speed. In the case of the step-up notch, the effective circumferential velocity was about one-half of the ambient wind speed.

The information inferred from wind tunnel experiments is a very useful aid for development of mathematical models.

2.3   Wind flow modelling

The basic equations used for description of the mean flow are (*Busch, 1973; Rodi, 1995*):

the continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2.1}$$

and the steady state momentum conservation equation:

$$u_j \frac{\partial u_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\nu \frac{\partial u_i}{\partial x_j} - \overline{u_i' u_j'} \right] - \frac{1}{\rho} \frac{\partial p}{\partial x_i}; \quad i = 1,2,3 \tag{2.2}$$

where

u_i are the three mean velocity components (i=1,2,3 or x,y,z),

u_i' are the turbulent fluctuation components (deviations from the mean velocity); the overbar means time averaging,

p   is the pressure,

ρ is the air density,

ν is the kinematic molecular viscosity.

In (2.1) and (2.2) as well as in the subsequent equations, the summation convention of repeated indices is implied.

The left-hand-side of (2.2) describes advection of mean momentum, while the right-hand-side represents the diffusion and pressure forces. Equation (2.2) cannot be solved directly as it contains new unknowns, the Reynolds stresses, $\overline{u_i' u_j'}$. The key problem is to define an appropriate parameterization of these stresses - the "closure concept".

Two main categories of modelling concepts have evolved: the eddy-viscosity concept, called also first order closure method, and higher order closure methods involving additional model equations for Reynolds stresses. The latter method is widely used in modelling atmospheric flows (*Launder, 1989*) but so far has not found a broader application for street canyon flows.

The eddy-viscosity concept assumes that in analogy to molecular diffusion the turbulent stresses are proportional to the local velocity gradients, which leads to the following relation:

$$\overline{u_i' u_j'} = -\nu_t \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] \tag{2.3}$$

where ν_t is the eddy-viscosity which now needs to be parameterized.

The eddy-viscosity concept is mainly based on the assumption that

$$\nu_t \propto \hat{u} \cdot L \tag{2.4}$$

where û and L are some appropriate velocity and length scales, specific for the particular flow. The eddy-viscosity should actually be a tensor but in the most engineering applications a scalar formulation is used.

The problem is common for all turbulent flows but treatment of street canyon flows implies specific boundary and initial conditions. Of special interest is here the situation occurring when wind blows perpendicularly to an infinitely long canyon of width W and height H. The wind flow can thus be considered as two-dimensional. Assuming furthermore that the eddy-viscosity is a constant and neglecting the molecular viscosity terms, the simplified transport equations can be written,

$$-u \frac{\partial u}{\partial x} - w \frac{\partial u}{\partial z} + \nu_t \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} \right) - \frac{1}{\rho} \frac{\partial p}{\partial x} = 0 \tag{2.5}$$

$$-u \frac{\partial w}{\partial x} - w \frac{\partial w}{\partial z} + \nu_t \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial z^2} \right) - \frac{1}{\rho} \frac{\partial p}{\partial z} = 0 \tag{2.6}$$

The cross canyon (x-direction) velocity component is denoted by u and the vertical (z-direction) component is w. Equations (2.5) and (2.6) can be written in a more convenient form using the concept of vorticity,

$$\omega = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \tag{2.7}$$

$$-u \frac{\partial \omega}{\partial x} - w \frac{\partial \omega}{\partial z} + \nu_t \left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial z^2} \right) = 0 \tag{2.8}$$

For a vortex-like flows in street canyons it is reasonable to assume that advection of vorticity is small and in this case (2.8) is thus reduced to,

$$\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial z^2} = 0 \tag{2.9}$$

Hotchkiss and Harlow (1973) found that a suitable solution for this equation is (*a sign error appears in the original report*)

$$\omega = \omega_o \left(e^{ky} + \beta\, e^{-ky} \right) \sin(kx) \tag{2.10}$$

The expression for the street canyon velocity components satisfying free-slip boundary conditions for along-walls and canyon bottom components and vanishing normal components, reads,

$$u = \frac{A}{k} \left[e^{ky}(1+ky) - \beta\, e^{-ky}(1-ky) \right] \sin(kx) \tag{2.11}$$

$$w = -Ay \left[e^{ky} - \beta\, e^{-ky} \right] \cos(kx) \tag{2.12}$$

where

$$k = \frac{\pi}{W} \qquad y = z - H$$

$$\beta = e^{-2\,kH} \qquad A = \frac{k\, u_o}{1-\beta}$$

H is the height and W is the width of the street, while u_o is the wind speed above the canyon (the point x=W/2, z=H)

The wind field calculated by (2.11) and (2.12) is shown in Figure 2.2 for canyons with three different H/W ratios. Wind velocities are normalised with respect to u_o.

The Hotchkiss and Harlow model, although being very simplified, reflects the basic properties of wind circulation in street canyons. Comparison with wind measurements in a street with H/W ratio close to one, presented by *Yamartino and Wiegand (1986)*, shows some reasonable agreement. Caution must be shown using the Hotchkiss and Harlow model for other canyon configurations. Referring to the aforementioned work by *Oke (1988)*, the wind flow model by Hotchkiss and Harlow describes only the skimming flow regime and is not suitable for canyons with H/W ratio significantly different from one. It should also be noted that the expression (2.10) for the vorticity field is not a unique solution of the equation (2.9). Any linear combination of terms like (2.10), with k being a multiple of B/W, will satisfy (2.9). The same conclusion is due to the wind field expressions (2.11) and (2.12). The coefficients of the linear combination terms can be calculated requiring appropriate boundary conditions for the top-canyon profile of the u-component. This may result in a more realistic formulation of the wind field for wider canyons. The limitations of the analytical solution proposed by *Hotchkiss and Harlow (1973)* are, however, still determined by the simplified assumptions about constant eddy viscosity, neglecting of the advection terms and also the free-slip boundary conditions. More sophisticated numerical modelling methods must be used in order to avoid these simplifications.
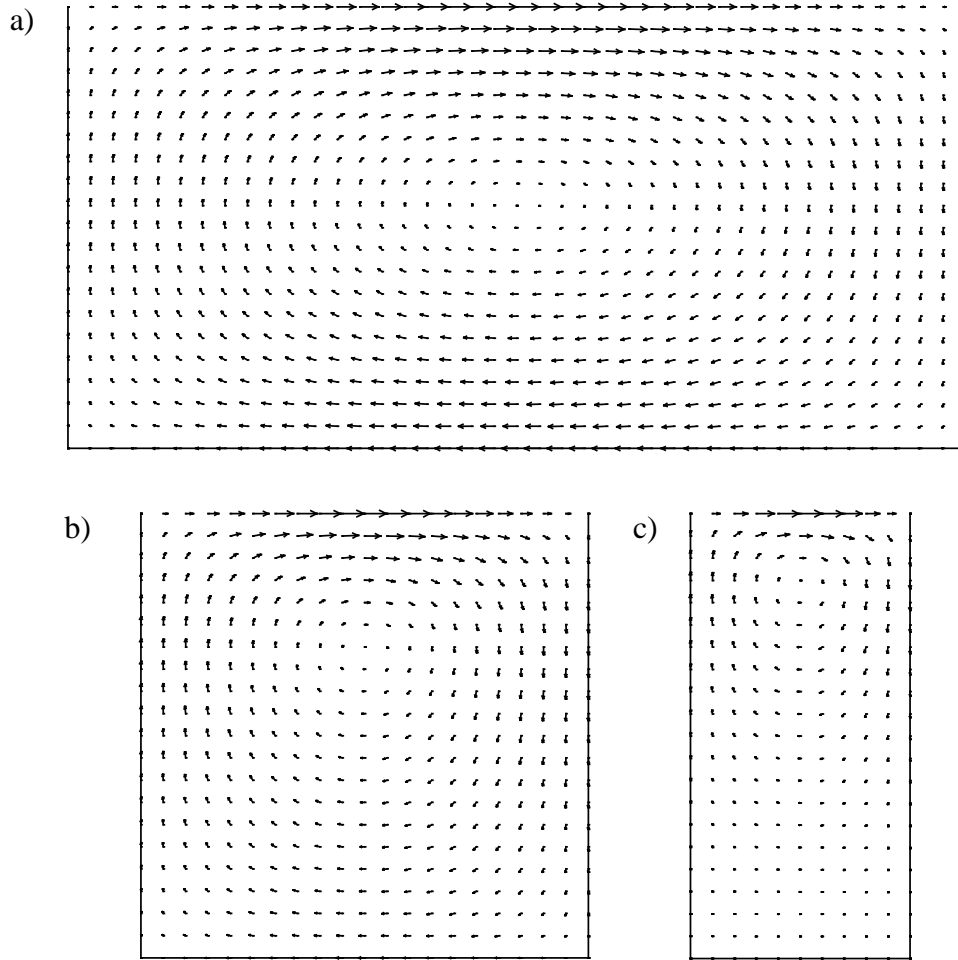
Figure 2.2 Wind flow in street canyons according to Hotchkiss and Harlow (1973) analytical solution.
 a) W/H=2, b) W/H=1, c) W/H=0.5

The method which found the most wide application in modelling flow conditions in street canyons and also in the case of other obstacles is the so called *k-ε* method (*Rodi, 1995*). The velocity and length scales are here determined by the turbulent kinetic energy:

$$k = \frac{1}{2}\overline{u_i^{'} u_i^{'}}$$

(2.13)

and the rate of dissipation of the turbulent kinetic energy:

$$\varepsilon = \nu\overline{\frac{\partial u_i^{'}}{\partial x_j} \frac{\partial u_i^{'}}{\partial x_j}}$$

(2.14)

The eddy-viscosity is modelled by:

$$\nu_t = c_\mu \frac{k^2}{\varepsilon}$$

(2.15)

where c_μ is an empirical proportionality constant.

Beside the momentum conservation equation (2.2), two additional equations are needed to specify ν_t in (2.15): an equation for the turbulent kinetic energy, k, and an equation for the dissipation rate, ε,. The rather lengthy derivation of these equations will not be discussed in detail here. They are obtained from (2.2), and after some manipulation, and parameterization and introduction of three new constants additional to ν_t, these equations now describe the spatial variations of k and ε. Combining these equations with (2.1), (2.2), (2.3) and (2.15) yields a closed set of equations, that can be solved numerically.

The k-ε model has been extensively tested and calibrated for industrial flows around bluff bodies and structures. The tests have focused on regions where flow separation can occur, which is also an important property of the flow in and around street canyons. The constants in the models have been determined from experimental data, considering basic universal flows, and afterwards improved by experimental modelling.

Most of the constants are found to have very similar values for industrial and tunnel flows and for atmospheric flows. The one exhibiting the largest difference is the constant c, that typically varies from 0.09 for industrial flows to 0.03 for atmospheric flows. An important reason for non-universality of the constants in the k-ε model is that the model is not a first principle turbulence closure model, but entails several assumptions and approximations that may result in different coefficients, when important aspects of the flows are different. An important difference between industrial and atmospheric flows is the much larger length-scale interval available to atmospheric flows, which means that for the same dissipation and turbulence stress, the turbulent kinetic energy will usually be much larger in the atmosphere, than in a tunnel simulation. Through (2.3) and (2.15) this is seen to yield correspondingly smaller c for atmospheric flows. The implications of this are not completely understood although the consequences of trying the models with both coefficients often seem small.

Results of wind flow simulations in street canyons by a k-ε model developed at the Risø National Laboratory *(Sørensen et al., 1994; Sørensen, 1995)* are shown in Figure 2.3 for similar conditions as in Figure 2.2. The k-ε model makes larger demands on boundary conditions than does the simple model by *Hotchkiss and Harlow (1973)* and therefore the results are not exactly comparable. Nevertheless, the similarities and differences are worthwhile to notice.

The wind flows given by (2.11) and (2.12) and depicted in Figure 2.2 are all simple and similar. There is only one dominating rotor with a kernel in the centre of the canyon, regardless of the W/H ratio. Although the flows depicted by the k-ε model are superficially similar to the ones shown in Figure 2.2, a number of important differences become clear upon closer inspection. The centre of the rotor is seen to be displaced towards the windward side of the street, and is moving from a rather elevated position for a narrow street down closer to the bottom for a wider street. Finally, secondary vortices are clearly seen in the bottom corners of the street, most clearly in the leeward corner, but for the W/H=1, also in the windward corner. For W/H =2, the windward secondary eddy seems to be overwhelmed by the primary eddy. Furthermore, the simple analytical model does not describe the influence of the canyon geometry on flow conditions above the canyon. The feed back between the canyon flow and the flow aloft is apparent from the results presented in Figure 2.3, although both models predict essentially parallel wind flows at the top of the canyon. Coupling between the canyon flow and the flow aloft allows for estimation of the fluxes between the canyon and the air above.
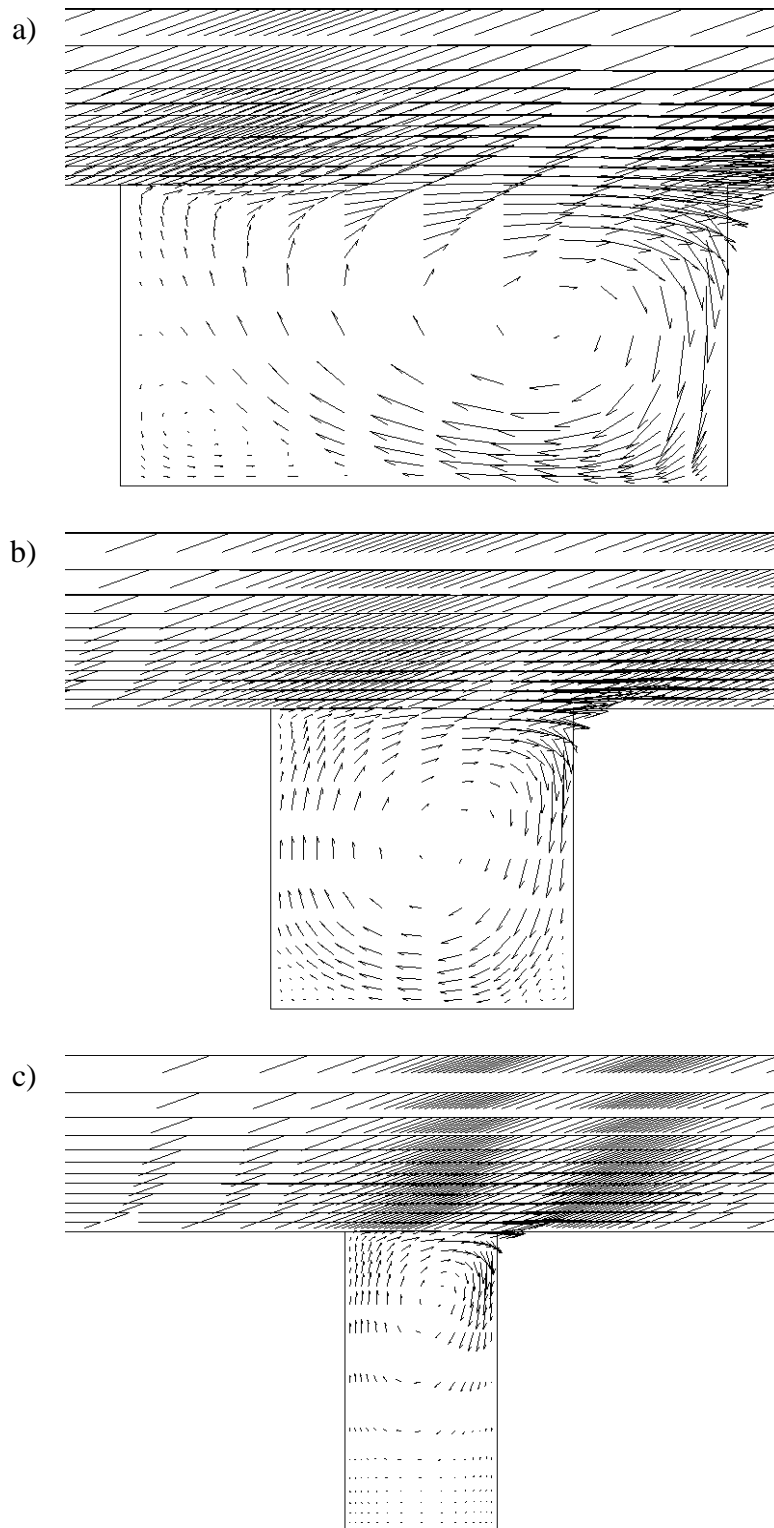
Figure 2.3. Wind flow in street canyons calculated by a k-ε model (Sørensen, 1995). a) W/H=2, b) W/H=1, c) W/H=0.5

It can be concluded that the larger efforts of running a *k*-ε model are paid back by the additional important information about the flow provided by the model. However, more efforts are needed to implement the results of the model in street pollution modelling.

3   Dispersion modelling

Modelling dispersion of pollutants in streets is inevitably connected with wind flow modelling. The mathematical principles are basically the same, i.e. the governing equation is the steady state mass conservation equation for a scalar,

$$u_j \frac{\partial c}{\partial x_j} = - \frac{\partial}{\partial x_j} \overline{c' u'_j} + S$$

(3.1)

where c denotes the mean concentration and c' is the deviation from the mean value. S represents here all possible sources and sink terms, as e.g. emission or chemical reactions.

The key problem is again determining the parameterization of the turbulent flux term $\overline{c' u'_j}$ and the most common approach is based on the eddy diffusivity concept,

$$\overline{c' u'_j} = - K_t \frac{\partial c}{\partial x_j}$$

(3.2)

where K_t is the eddy diffusivity coefficient, usually assumed to be equal to the eddy viscosity ν_t.

The mean wind fields and diffusivity coefficients can be supplied by a particular flow model and equation (3.1) solved numerically subject to appropriate boundary conditions. Modern numerical methods and availability of powerful computers have resulted in several such models which have been developed. The diffusivity coefficients are estimated either making use of the mixing length concept (*Sievers and Zdunkowski, 1986; Moriguchi and Uehara, 1993; Lee and Park, 1994; Kamenetsky and Vieru, 1995*) or the *k-ε* method (*Johnson and Hunter, 1995; Mestayer and Anquetin, 1994*).

Another approach is based on the stochastic Lagrangian trajectory model (*Lamb et al., 1985*). Concentrations of pollutants are calculated tracing the movement of particles representing air parcels. The trajectories are calculated using the mean flow fields on which a random fluctuation component is superimposed. The statistics of the fluctuating component depend on the turbulence characteristics of the flow field and can be supplied by the flow model. The stochastic Lagrangian approach permits one to avoid using the diffusivity "closure" (3.2) for modelling dispersion. The eddy diffusivity approach is known to be applicable only when the scale of the turbulent motions is much smaller than the scale of pollution distribution (*Pasquill and Smith, 1983*). This might not be the case in street canyons where both scales are of a comparable size and limited by the canyon dimensions. Some examples of stochastic modelling of traffic pollution can be found in *Lamb et al. (1979)*, *Geomet (1985)*, *Schorling (1994)* and *Lanzani and Tamponi (1995)*.

Numerical models based on solution of the diffusivity equation (3.1) or stochastic models with the corresponding wind flow models are still too complex for practical applications, e.g. in support of air pollution management. As research tools they can, however, provide significant insight into the essential processes and results used for constructing more simple models. The models in question here are basically parameterized semi-empirical models making use of a priori assumptions about the flow and dispersion conditions and limitations of such an approach must certainly be recognised. Anyhow, it is this kind of modelling that until now has found the broadest application. Some of the more commonly

used models will be discussed in the following. The Danish model OSPM, which will be presented in more detail, belongs to this category of parameterized models.

3.1 Some applied street pollution models

3.1.1 The STREET model

One of the earliest street pollution models is the STREET model by *Johnson et al. (1973)*, (see also *Ludwig and Dabberdt, 1972; Dabberdt et al., 1973)*. The model is empirically derived based on pollution measurements in streets of San Jose and St. Louis. The model assumes that emissions from the local street traffic (street contribution c_s) are added to the pollution present in the air that enters from roof level (background contribution c_b).

$$c = c_b + c_s \tag{3.3}$$

The street contribution is proportional to the local street emissions Q ($gm^{-1}s^{-1}$) and inversely proportional to the roof-level wind speed u. For winds blowing at an angle of more than 30° to the street direction, two formulas are derived:

for the leeward side,

$$c_s = \frac{K}{u + u_s} \sum_i \frac{Q_i}{[(x_i^2 + z^2)^{1/2} + h_o]} \tag{3.4}$$

for the windward side,

$$c_s = \frac{K}{(u + u_s)} \frac{H - z}{H} \sum_i \frac{Q_i}{W} \tag{3.5}$$

where

    K is an empirically determined constant ($K \approx 7$),
    u_s accounts for the mechanically induced air movement caused by traffic ($u_s \approx 0.5$ ms^{-1}),
    h_o accounts for initial mixing of pollutants ($h_o \approx 2$ m)
    x_i and z are the horizontal and the vertical distances from the i-th traffic lane to the receptor point,
    Q_i is the emission strength of the i-th traffic lane,
    H and W are the height and the width of the canyon, respectively.

For wind directions at angles less than 30° to the street direction, the average of (3.4) and (3.5) is recommended but actually, the model is not designed for this condition.

The formulas (3.4) and (3.5) are based on the observations that when the roof-level wind blows within about $\pm 60^o$ of the cross-street direction, a helical circulation develops in the street. This causes the pollutants emitted from traffic in the street to be primarily transported towards the upwind building (lee-side) while the downwind side is primarily exposed to background pollution and pollution that has recirculated in the street. The model predicts thus that the concentrations on the leeward side of the street are higher than on the windward side. These are the most essential features of pollutant dispersion in street canyons and therefore the STREET model, with some minor modifications (*Benesh, 1978; Sobottka and Leisen, 1980a,b*), is still widely used, especially for engineering

applications. The more detailed features of pollution dispersion in street canyons can, however, not be described by such a simplified model as STREET. An essential drawback of the model is the very crude parameterization of wind direction dependence. Furthermore, at reduced ambient wind speeds (calm conditions), a uniform concentration distribution is expected across the street-canyon. The STREET-model does not describe this feature and actually it is not recommended for ambient wind speeds less than 1 ms^{-1} (although it is frequently used for evaluation of "worst-case" pollution levels which usually are associated with low wind speed conditions). In spite of these limitations, the model is a useful tool for a "first-order" evaluation of air quality in street-canyons.

3.1.2 Hotchkiss and Harlow model

Another analytical model was proposed by *Hotchkiss and Harlow (1973)*. This model is based on an approximate solution of the two-dimensional steady state advection-diffusion equation

$$-u \frac{\partial c}{\partial x} - w \frac{\partial c}{\partial z} + \nu_t \left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial z^2} \right) = 0 \qquad (3.6)$$

and the previously mentioned wind field model (Eqs. (2.11) and (2.12)).

The expression for the concentration field in a two dimensional street canyon, which they derive keeping only terms up to a first order in expansion in series of cos(kx), reads:

$$c_s = S \left[\frac{1}{u_w} - \frac{y}{\nu_t} \right] - \frac{S \cdot u_n \cdot y}{4 k \nu_t^2 (1 - \beta)} \left[e^{ky} (1 - ky) - \beta e^{-ky} (1 + ky) \right] \cos(kx) \qquad (3.7)$$

where $S = Q/W$ is the emission density, which is assumed to be uniform across the street. u_n is the component of the wind speed at canyon top normal to the canyon axis, while all the other terms have the same meaning as explained in connection with Eqs. (2.11) and (2.12).

Hotchkiss and Harlow (1973) proposed to model the eddy diffusivity, ν_t, using expression (2.4), where the turbulence velocity scale is related to the wind speed at the top of the canyon, u_t, and the stirring speed, u_s, due to vehicle motion (traffic induced turbulence),

$$\nu_t = L \sqrt{(\alpha_1 u_t)^2 + u_s^2} \qquad (3.8)$$

where L is an appropriate length scale, and which they suggest to set equal to the canyon width, W.

For the canyon ventilation velocity, u_w, which determines the concentrations at the top of the canyon, *Hotchkiss and Harlow (1973)* propose,

$$u_w = \left(\frac{\nu_t u_t}{W} \right)^{1/2} \qquad (3.9)$$

One could, however, reason that a more consistent formulation should be based on the previously defined turbulence velocity scales, u_t and u_s,

$$u_w = \sqrt{(\alpha_2 u_t)^2 + (\alpha_3 u_s)^2} \qquad (3.10)$$

where the proportionality constants, α_2 and α_3, as well as α_1, require empirical determination.

The Hotchkiss and Harlow's model was originally derived for wind flow perpendicular to the street canyon only, but it is easy to reformulate the model to be valid for any wind direction making the substitution,

$$u_n = u_t \cdot \sin(\Phi) \qquad (3.11)$$

where Φ is the angle between wind direction above roof level and the street axis.

The Hotchkiss and Harlow's analytical model has some qualitative properties that were missing in the STREET model. The difference between the leeward and windward side concentrations is determined by the term with $\cos(kx)$ in Eq. (3.7). For vanishing wind speeds ($u_n=0$) this term vanishes too, resulting thus in an uniform concentration distribution across the canyon. This behaviour is expected from physical reasoning. The quantitative behaviour of the model is examined in Figures 3.1 and 3.2. The empirical constants, α_1 and α_2, are given values 0.1 and 0.3, respectively, and the W/H ratio is set to 1. Comparison is made with the even notch configuration wind tunnel data of *Hoydysh and Dabberdt (1988)*. For this purpose the calculations with the Hotchkiss and Harlow model are made with the steering velocity, u_s, set to zero and the concentrations are normalised with respect to the wind speed and emission density. Corresponding results are also shown for the STREET model, where both u_s and h_o are set to zero. The dependence on wind direction of street level concentrations is shown in Figure 3.1. The wind direction is with respect to the street axis, i.e. 0° and 180° correspond to wind parallel to the street axis. Presenting the wind tunnel data, symmetry of the concentration distribution with respect to wind direction normal to the street (90° and 270°) was anticipated.

Due to the rather arbitrary choice of the values of the empirical constants and somewhat unclear definition of the source strength in *Hoydysh and Dabberdt (1988)*, not much attention should be given to the absolute concentration values, but it is noticeable that neither the analytical model, nor the STREET model can reproduce the large difference between the leeward and windward concentrations shown by the wind tunnel data. As noted by *Hotchkiss and Harlow (1973)*, the analytical expression derived by them, due to the anticipated approximations, is not valid if the cross-canyon concentration difference is larger than about a factor of two. The STREET model produces leeward concentrations, which are exactly twice the windward concentrations.

The vertical concentration profiles for wind direction normal to the street are shown in Figure 3.2. Here it is again obvious that both models predict much stronger vertical gradients than observed from the wind tunnel measurements.

One important difference is worth to notice when comparing the empirical STREET model and the analytical model by Hotchkiss and Harlow. The STREET model is based on the assumption that the dilution of pollutants emitted form the vehicles is proportional to the distance from the source to the receptor, while in the Hotchkiss and Harlow model, the dispersion is described using the eddy diffusivity formulation, which results in a square root dependence of dilution as function of distance from the source. For the short

source-receptor distances, relevant for street canyons, the linear dilution concept is known to be more appropriate than the square root dependence resulting from the eddy diffusivity formulation. This means that the simple empirical STREET model is conceptually more correct than the analytical model based on the diffusivity equation, but the simplifications anticipated in both models preclude any decisive statement.
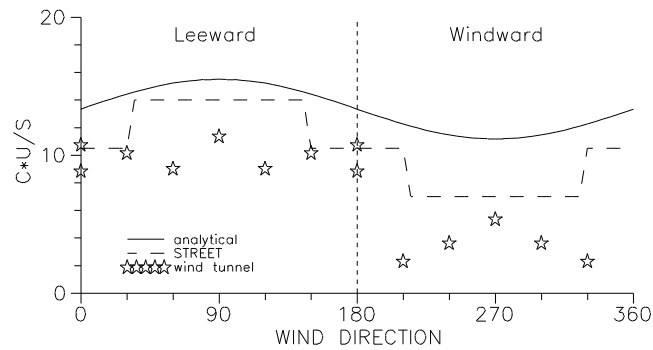

Figure 3.1 Street level concentrations versus wind direction. 0° and 180° - wind parallel to the street axis. Wind tunnel measurements from Hoydysh and Dabberdt (1988).
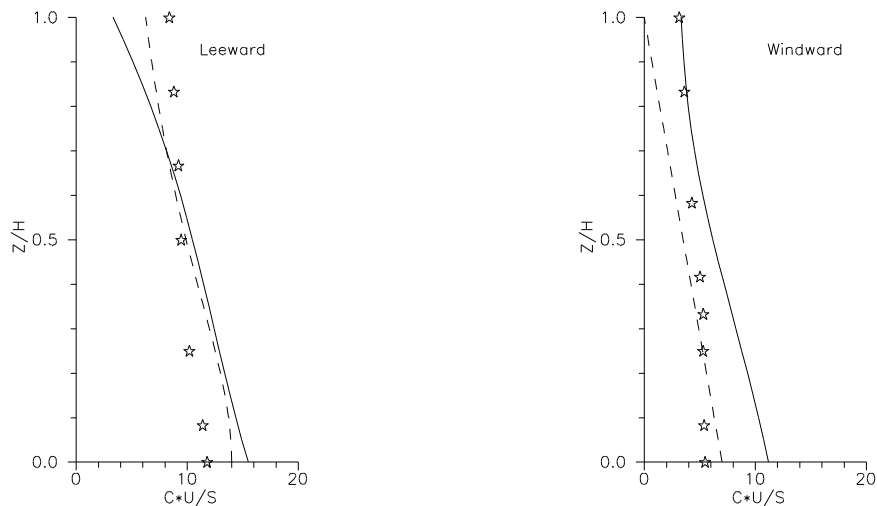
Figure 3.2 Vertical concentration profiles. Wind direction perpendicular to the street. Symbols as in Figure 3.1.

3.1.3   The CPBM model

An innovative approach was introduced by *Yamartino and Wiegand (1986)* in their Canyon Plume-Box Model (CPBM). The concentrations are calculated combining a plume model for the direct impact of vehicle emitted pollutants with a box model that enables computation of the additional impact due to pollutants recirculated within the street by the vortex flow. The wind flow in the canyon is defined using the aforementioned model by *Hotchkiss and Harlow (1973)* for the transverse components, u and w, while a simple logarithmic profile is anticipated for the longitudinal component, v. An empirical turbulence model is used for the turbulence parameters σ_u, σ_v and σ_w, repre-

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senting the standard deviations of flow velocities about the mean flow. Variables used to estimate the turbulence include the mechanical component driven by the roof top wind and the thermal component, dependent on the global solar radiation and the number of vehicles. The last accounts for the heat released by the vehicles in the street.
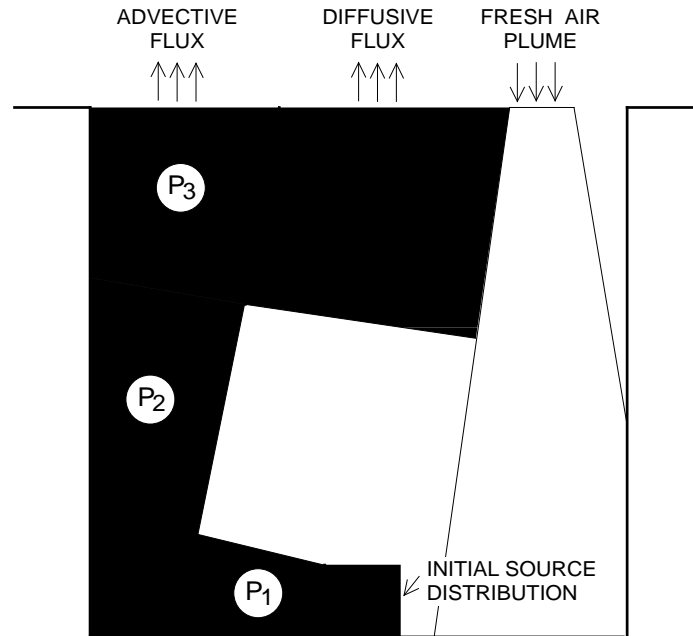

Figure 3.3 Schematic diagram of the principal mechanisms of the vortex sub-model in the Canyon Plume-Box Model (after *Yamartino and Wiegand (1986)*).

The main features of the plume model are illustrated in Figure 3.3. The plume is divided into three segments (P_1, P_2 and P_3) which are assumed to follow straight line trajectories and disperse according to Gaussian plume formulas. The largest impact occur on the lee side, due to contribution from the plume P_1. The vertical dispersion parameter, σ_z, is given by,

$$\sigma_z(t) = H_1 / \sqrt{2\pi} + \sigma_w \cdot t \qquad (3.12)$$

where H_l is the initial plume dispersion, dependent on the size and the speed of vehicles. σ_w is calculated at the effective source height, being equal to the half of the vehicle height. The transport time, t, is equal to x/u_b, where x is the distance from the source (a vehicle line) to the receptor point and u_b is the cross canyon velocity calculated from the Hotchkiss and Harlow model. Across canyon average values, calculated at the effective source height, are used for u_b. Similar formulations are used for the plume segments P_2 and P_3, but with appropriate turbulence parameters and the transport winds calculated from the Hotchkiss and Harlow model as average values along the plume trajectories.

The contribution to concentrations resulting from the recirculation component is calculated from the considerations of the mass budget within the canyon. The following expression is derived,

$$C_R = \frac{Q}{u_b(W/2)} \frac{F}{(1-F)} \qquad (3.13)$$

where Q is the emission rate per street length, W is the width of the canyon and F is the fraction of material that is recirculated, given by,

$$F = \exp(-t_s / \tau) \tag{3.14}$$

where t_s is a time scale related to the vortex recirculation time, given by

$$t_s = 2H / u_b \tag{3.15}$$

The life time, τ, determining the canyon ventilation speed, is expressed in terms of advective and diffusive components τ_A and τ_D, respectively as

$$\tau^{-1} = \tau_A^{-1} + \tau_D^{-1} \tag{3.16}$$

where

$$\tau_A^{-1} = \sqrt{2\pi}\, \sigma_j\, w_j / (H \cdot W) \tag{3.17}$$

$$\tau_D^{-1} = (W - 2\sqrt{2\pi}\, \sigma_j)\, \sigma_{wt} / (\sqrt{2\pi}\, H \cdot W) \tag{3.18}$$

σ_j is the size of the fresh air plume at the top of the canyon and w_j is the speed of the plume. σ_{wt} is the turbulent velocity at the top of the canyon. w_j is calculated from the Hotchkiss and Harlow model, while σ_j was empirically determined to be 0.25 m. *Yamartino and Wiegand (1986)* claim, however, that the advective process contributes only marginally to canyon ventilation and setting $\sigma_j = 0$ provides only slightly worse model performance.

For all receptors on the lee side of the canyon, the recirculation concentration C_R is added to concentrations calculated by the direct plume model. For the wind side, where the only contribution arises from the recirculating air, the dilution of the concentrations due to entrainment of the clean air is calculated assuming a linear growth of the size of the jet, with the growth rate proportional to σ_u, the standard deviation of the cross canyon velocity.

The plume-recirculation model is used only for the case when the vortex advection dominates over diffusion, i.e.

$$u_b \geq \frac{1}{2} \sigma_{ub} \tag{3.19}$$

where σ_{ub} is the average cross-canyon turbulence calculated at the effective source height.

When the condition (3.19) is not satisfied, what usually will occur when the wind direction is close to the street axis or in the case of very light winds, a simpler, non-vortex dispersion model is used. Concentrations are then computed by assuming a plume diluted with velocity v (along-street component) and travelling parallel to the canyon axis. The Gaussian plume dispersion parameters are again calculated assuming a linear growth proportional to the turbulence parameters and initial plume size depending on the size and speed of vehicles.

The CPB model was tested on data from the Bonner Strasse experiment in Cologne, Germany (*Yamartino and Wiegand, 1986*). A subset of the data was used for optimisation

of the model. The performance of CPBM was shown to be significantly better than of the empirical STREET model, especially considering the broad range of the meteorological conditions for which the STREET model was not specifically designed.

3.1.4 The CAR model

An empirical approach was used in development of the Dutch traffic pollution model CAR (Calculation of Air pollution from Road traffic) (*Eerens et al., 1993*). Based mainly on wind tunnel experiments (*van den Hout and Baars, 1988; van den Hout and Duijm, 1988; van den Hout et al., 1989*) a set of empirical relationships was established between wind direction and concentrations for various street configurations. The wind tunnel experiments covered 49 configuration sets which differed with respect to dimensions, distances and shapes of streets and its buildings. Also the influence of trees along streets was investigated. The results were incorporated in a plume type model, called TNO traffic model (*van den Hout and Baars, 1988*) which was the basis for finally development of the more operational CAR model in which few most distinguish street configurations with respect to dispersion conditions were categorised. For each street category a source-receptor relationship is specified as a function of the distance between the receptor point and street axis. Only annual average concentrations are calculated and other statistical means are estimated based on empirical relationships are derived from measurements in the national pollution network. Those relationships are updated every year. The model is now applied as a regulatory model in Dutch cities, and an international version, CAR International (*Boeft et al., 1995*) is also available.

4   The Operational Street Pollution Model (OSPM)

With the purpose of providing a simple method for estimation of pollution from traffic in Nordic cities the Nordic Council of Ministers promoted development of the Nordic Computational Method for Car Exhausts (NBB). The method is described in *Larssen (1984)*. The NBB method is based on two submodels: an emission model and a dispersion model. The emission model was developed using the current experience with emission factors, traffic flow modelling, traffic composition etc. The dispersion model was based on the STREET- model, but only the worse-case conditions were considered. NBB was used for prediction of NO_2 and CO pollution. Shortcomings of the dispersion part of NBB lead to the need of better description of the dispersion phenomena in streets. This work was initiated in 1987 at the National Environmental Research Institute (NERI), Denmark, in co-operation with the Norwegian Institute for Air Research (NILU) and The Swedish Meteorological and Hydrological Institute (SMHI). As a result of this work a new dispersion model was developed - the Operational Street Pollution Model (OSPM) *(Hertel and Berkowicz, 1989a)*. In 1993 the revised version of the Nordic Computational Method was issued, where the dispersion part was based on the OSPM model, but still only for prediction of the highest concentrations, disregarding the actual meteorological conditions *(Hertel and Berkowicz, 1990)*.

OSPM is based on similar principles as the CPB-model by *Yamartino and Wiegand (1986)*. Concentrations of exhaust gases are calculated using a combination of a plume model for the direct contribution and a box model for the recirculating part of the pollutants in the street (Figure 4.1). OSPM makes use of a very simplified parameterization of flow and dispersion conditions in a street canyon. This parameterization was deduced from extensive analysis of experimental data and model tests *(Berkowicz et al., 1995a,b)*. Results of these tests were used to improve the model performance, especially with regard to different street configurations and a variety of meteorological conditions.
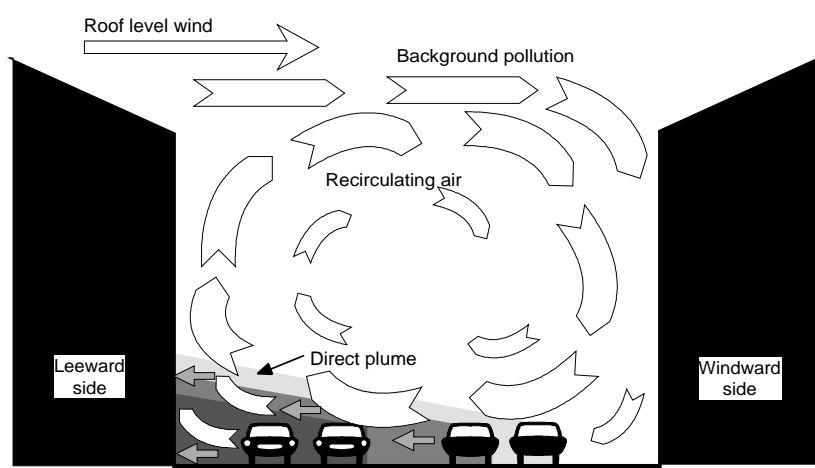

Figure 4.1 Schematic illustration of the basic model principles in OSPM. Concentrations are calculated as a sum of the direct plume contribution and the recirculating pollution

4.1 The direct contribution

The direct contribution is calculated using a simple plume model. It is assumed in OSPM that both the traffic and traffic emissions are uniformly distributed across the canyon. The emission field is treated as a number of infinitesimal line sources aligned perpendicular to the wind direction at the street level and with thickness dx. We disregard the cross wind diffusion and the line sources are treated as infinite line sources. The emission density for such a line source is

$$dQ = \frac{Q}{W} dx \tag{4.1}$$

where Q is the emission in the street (g m^{-1} s^{-1}) and W is the width of the street canyon.

The contribution to the concentration at a point located at a distance x from the line source is given by,

$$dC_d = \sqrt{\frac{2}{\pi}} \frac{dQ}{u_b \, \sigma_z(x)} \tag{4.2}$$

where u_b is the wind speed at the street level and $\sigma_z(x)$ is the vertical dispersion parameter at a downwind distance x.

Equation (4.2) is integrated along the wind path at the street level. The integration path depends on wind direction, extension of the recirculation zone and the street length. The main principles for estimation of the integration path for Equation (4.2) are illustrated in Figure 4.2. If the roof level wind direction is at angle Φ with respect to the street axis, then the street level wind in the recirculation zone forms also an angle Φ with the street axis, but the transverse component is mirror reflected. Outside the recirculation zone the wind direction is the same as at roof level.
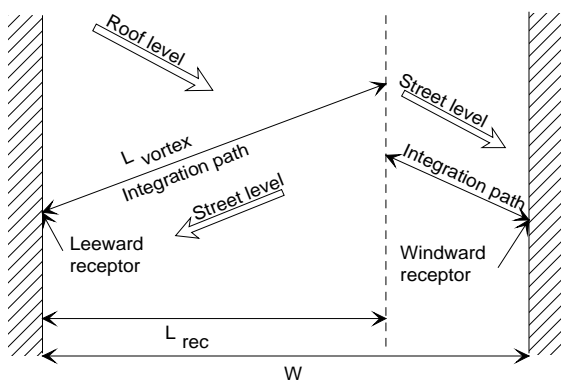

Figure 4.2 Illustration of the wind flow and formation of the recirculation zone in a street canyon.
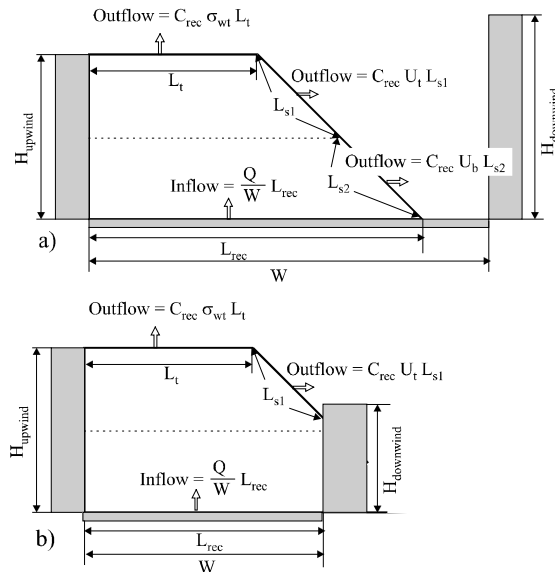
Figure 4.3 Geometry of the recirculation zone. a) the recirculation zone totally inside the canyon; b) the downwind building intercepts the recirculation zone.

The length of the vortex, L_{vortex}, is assumed to be twice the height of the upwind building, H_{upwind}. For wind speeds (roof level) less than 2 m/s, a linear decrease of L_{vortex} with wind speed is assumed. This is consistent with the observations of e.g. *DePaul and Sheih (1986)* indicating disappearance of vortex circulation at low wind speeds.

H_{upwind} depends on canyon geometry and wind direction at roof level. Openings between buildings will result in $H_{upwind} = 0$, depressing thereby formation of the recirculating vortex.

The maximum extension of the recirculation zone is given by the width of the street - W, or by the length of the vortex L_{vortex}, whichever is smaller. For an oblique wind direction and when $L_{vortex} > W$, the extension of the recirculation zone is given by

$$L_{rec} = \min(W, \ L_{vortex} \cdot \sin(\Phi)) \qquad (4.3)$$

There exists thus an angle Φ for which the extension of the recirculation zone is smaller than the width of the canyon. For street canyons with height to width ratio 1:1, this angle is 30°.

The vertical dispersion parameter, σ_z, is modelled assuming that the dispersion of the plume is solely governed by the mechanical turbulence. We disregard the turbulence due to thermal stratification, as it usually is small at street level. The mechanical turbulence is taken to be generated by two mechanisms: by the wind and by the traffic in the street.

$$\sigma_w = \left((\alpha u_b)^2 + \sigma_{wo}^2 \right)^{1/2} \qquad (4.4)$$

where σ_w is the vertical turbulent velocity fluctuation, α is a constant and σ_{wo} is the traffic created turbulence. Parameterization of σ_{wo} will be discussed later. The proportionality constant, α, is given a value of 0.1, what corresponds to typical levels of mechanically induced turbulence.

The dispersion parameter of the plume travelling a distance x is given by

$$\sigma_z(x) = \sigma_w \frac{x}{u_b} + h_o \qquad (4.5)$$

Here h_o is the initial (immediate) dispersion in the wakes of the vehicles and we assume that $h_o = 2m$.

For a receptor on the leeward side, the direct contribution is calculated considering the emissions from traffic in the recirculation zone only. For a receptor on the windward side, only contributions from the emissions outside the recirculation zone are taken into account. If the recirculation zone extends through the whole canyon, no direct contribution is given for the receptor on the windward side.

When the angle between wind direction and the street axis is small (near parallel flow) the recirculation zone may occupy only a small portion of the canyon. As the flow patterns inside and outside the recirculation zone do not differ much in this case (according to the concept used in OSPM, the angle between the respective wind vectors is 2Φ), emissions from outside the recirculation zone may contribute to the concentrations at the leeward receptor. This is accounted for in OSPM by extending the integration path for leeward

receptor to the whole canyon, but the contribution from outside the recirculation zone is weighted by an angle and wind speed dependent factor R, which is given by,

$$R = \max(0, \cos(2\,r \cdot \Phi)) \tag{4.6}$$

where r is a function of wind speed; r=1 for roof top wind speed greater than 2 m/s and decreases linearly to zero for wind speed less than 2 m/s. When Φ tends to zero, or the wind speed is very low, the weighting factor is 1. For wind speeds larger than 2 m/s the contribution from outside of the recirculation zone is zero for $\Phi > 45^{o}$. The procedure outlined here is solely based on intuitive reasoning, but the main purpose of this approach is to get a smooth transition from a recirculation regime to a parallel flow.

When the integration path is long (as usually is the case for a near parallel flow) the pollutants may be dispersed so much in the vertical direction that they escape from the canyon. In OSPM it is assumed that this takes place when $\sigma_z > H$ and contributions from sources further upwind are computed assuming an exponential decay with the rate given by,

$$\kappa = \frac{\sigma_{wt}}{H} \tag{4.7}$$

where σ_{wt} is the canyon ventilation velocity determined by the turbulence at the top of the canyon,

$$\sigma_{wt} = \left((\lambda u_t)^2 + 0.4\sigma_{wo}^2 \right)^{1/2} \tag{4.8}$$

where u_t is the wind speed at the top of the canyon and the term with σ_{wo} is added in order to account for the traffic created turbulence. The proportionality constant, λ, is given the same value as α, i.e. 0.1. This is the presently used approach, but contrary to the street level turbulence, some dependence on ambient air stability conditions can not be excluded and further research on this subject is needed.

The analytical expressions for the dependence of the direct contribution on wind direction are given by *Hertel and Berkowicz (1989a)*. These expressions were derived for infinite street canyons, while in the present version of OSPM, some modifications were introduced, so the integration path can be limited by a finite street length if e.g. a broad intersection exists at a shorter distance from the receptor or the street becomes broader or open.

For the special case of wind direction perpendicular to the street axis the expression for the direct contribution will read:

$$C_d = \sqrt{\frac{2}{\pi}} \frac{Q}{W \sigma_w} \ln \frac{h_o + (\sigma_w / u_b) W}{h_o} \tag{4.9}$$

This expression can be compared with the formula (3.4) for the leeward concentration in the STREET model, but only considering ground level concentrations, i.e. for z=0. However, in order to make this comparison more straight forward we have to replace the homogeneous emission distribution, assumed in OSPM, by a discrete distribution, as assumed in STREET;

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$$C_d \;=\; \sqrt{\frac{2}{\pi}}\,\frac{1}{u_b}\sum_i \frac{Q_i}{[h_o + (\sigma_w / u_b)x_i]} \tag{4.10}$$

Here, like in (3.4), Q_i is the emission strength of the i-th traffic lane and x_i is the corresponding horizontal distance. Similarity between the formulas (3.4) and (4.10) is obvious, especially regarding the dependency on wind speed and the distance to the source but the proportionality coefficients are different. The formula (3.4), used in the STREET model, is purely empirical and is supposed to match the leeward concentrations in a street canyon. Expression (4.10), and the continuous emission distribution formula (4.9), represent the direct contribution from a plume travelling with a speed u_b and which at a distance x from the source has the vertical dispersion $\sigma_z = h_o + (\sigma_w/u_b)x$. The total concentration is made up of the direct and the recirculation contributions.

4.2   Recirculation contribution

The contribution from the recirculation part is calculated assuming a simple box model. The box model is illustrated in Figure 4.3. It is assumed that the canyon vortex has the shape of a trapeze, with the maximum length of the upper edge being half of the vortex length L_{vortex}. The ventilation of the recirculation zone takes place through the edges of the trapeze but the ventilation can be limited by the presence of a downwind building if the building intercepts one of the edges.

The inflow rate per unit length is given by,

$$\text{INFLOW} \;=\; \frac{Q}{W}L_{rec} \tag{4.11}$$

where L_{rec} is the width of the recirculation zone. For narrow streets L_{rec} can be determined by the distance between buildings, W, (Figure 4.3b).

The outflow rate through the top and side edges is calculated with flux velocities given by: σ_{wt} - the top edge, u_t - the upper half of the side edge and u_b - the lower half of the side edge.

$$\text{OUTFLOW} \;=\; C_{rec}\left(\sigma_{wt}L_t \;+\; u_tL_{s1} \;+\; u_bL_{s2}\right) \tag{4.12}$$

L_t, L_{s1} and L_{s2} are calculated taking into account the canyon geometry and the extension of the recirculating zone (see Figure 4.3).

The concentration in the recirculation zone is calculated assuming that the inflow rate of the pollutants into the recirculation zone is equal to the outflow rate and that the pollutants are well mixed inside the zone.

When the wind vortex extends through the whole canyon, the direct contribution at the windward side is zero and the only contribution is from the recirculation component. The concentration at the leeward side is always computed as a sum of the direct contribution and the recirculation component. The direct contribution is usually much larger than the recirculation component.

Considering the simple case when the vortex is totally immersed inside the canyon (according to assumptions made in the OSPM, this is the case when $W/H \leq 1$), the recirculation contribution reads,

$$C_{rec} = \frac{Q}{\sigma_{wt} W}$$

(4.13)

Recalling that $\sigma_{wt} \approx 0.1 u_t$, the recirculation contribution given by (4.13) is practically identical with the formula (3.5) for the windward concentration in the STREET model (concerning ground level concentrations only).

4.3   Street level wind speed

The wind speed at street level, u_b, is calculated assuming a logarithmic reduction of the wind speed at roof top towards the bottom of the street. A simplified dependence on the angle between wind and the street axis is also introduced.

$$u_b = u_t \frac{\ln(h_o / z_o)}{\ln(H / z_o)} (1 - 0.2 \cdot p \cdot \sin(\Phi))$$

(4.14)

where H is the average depth of the canyon, while $p = H_{upwind}/H$ and this ratio is not allowed to exceed 1. h_o is the initial dispersion height, as defined in (4.5).

For a street with 15m high buildings, roughness length $z_o = 0.60$m and a parallel flow ($\Phi = 0$), we find that $u_b = 0.37 u_t$. For a perpendicular flow ($\Phi = 90^o$), the reduction is 20% larger. In the case of openings between buildings on the upwind side ($H_{upwind} = 0$) the wind speed will be the same as for a parallel flow.

4.4   Traffic induced turbulence

Generation of turbulence by moving cars has been the subject of several theoretical and experimental investigations *(Eskridge and Hunt, 1979; Thomson and Eskridge, 1987; Grønskei, 1988; Eskridge et al., 1991)*. The vehicle effects described in the mentioned papers are applicable for fast moving cars on open roads, as e.g. highways. In urban street canyons there is usually a dense flow of vehicles, and the turbulence field created by them cannot be considered as a simple superposition of non-interacting vehicle wakes, as it is proposed by *Eskridge and Hunt (1979)*. A simpler approach, which we believe is more suitable for street canyons, was suggested by *Hertel and Berkowicz (1989c)*.

Vehicles in the street are considered as moving flow distortion elements creating additional turbulence in the air,

$$\sigma_{wo}^2 = b^2 V^2 D$$

(4.15)

where V is the average vehicle speed, D is the density of the moving elements (cars) and b is an empirical constant related to the aerodynamic drag coefficient.

The density of the traffic in the street is given by the relative area occupied by the moving vehicles with respect to the street area,

$$D = \frac{N_{veh} \cdot S^2}{V \cdot W} \tag{4.16}$$

where N_{veh} is the number of cars passing the street per time unit, S^2 is the horizontal area occupied by a single car and W is the width of the street. Substituting (4.16) into (4.15) we obtain:

$$\sigma_{wo} = b \left(\frac{N_{veh} \cdot V \cdot S^2}{W} \right)^{1/2} \tag{4.17}$$

Expression (4.17) tells thus that the traffic created turbulence increases with the square root of the traffic flow ($N_{veh} \cdot V$) and that this turbulence decreases with increasing canyon width. The empirical constant, $b = 0.3$, as used in the present version of OSPM.

The traffic induced turbulence plays a crucial role in determination of pollution levels in street canyons. During windless conditions the ambient turbulence vanishes and the only dispersion mechanism is due to the turbulence created by traffic. Thereby, the traffic created turbulence becomes the critical factor determining the highest pollution levels in a street canyon. Some experimental results concerning the contribution of the traffic to the street turbulence are presented in Section 6.

4.5 Wind direction averaging

The wind direction in urban areas is seldom constant over a time period of an hour or even less, in particular for low wind speeds. Large fluctuations occur and thereby, the dependence of concentrations in a street canyon, when averaged over an hour or so, is significantly smoothed. In order to account for this effect an averaging of the calculated concentrations with respect to wind direction was introduced *(Hertel and Berkowicz, 1989c)*. The averaging interval is given by,

$$\begin{aligned} \Delta\Phi &= \pm \frac{\sigma_{vc}}{u} \quad \text{for } u < 1\,\text{m/s} \\ \Delta\Phi &= \pm 0.5 \quad \text{for } u \geq 1\,\text{m/s} \end{aligned} \tag{4.18}$$

where $\sigma_{vc} = 0.5$ m/s. $\Delta\Phi$ is in radians.

5 Model results

Model results are summarised in Figures 5.1 and 5.2. Ground level wall-site concentrations are calculated for two artificial East-West oriented street-canyons with H=20m and W=20m. A constant traffic flow consisting of 900 light and 100 heavy vehicles travelling with a speed of 40 km/h is assumed. The emission density in the street is set to 1000 units $m^{-1} s^{-1}$.

In the first example, the buildings on both sides of the street are assumed to be of equal height and densely spaced. Calculations are performed for seven different values of roof level wind speed: u_t = 8, 6, 4, 2, 1, 0.5 and 0 ms^{-1}. Resulting concentrations as function of wind direction are shown in Figures 5.1a and 5.1b for a north and a south side receptor, respectively. Due to the symmetry of the considered street, the wind direction dependency of concentrations on the respective sides of the street are just shifted by 180° with respect to each other. Dependence on wind direction shown in these figures is very pronounced. The leeward concentrations (southerly winds for the south side and northerly winds for the north side) are much higher than the windward concentrations. Maximum concentrations are calculated for wind directions close to parallel with the street (90° and 270°). This result is valid for long street canyons - the case anticipated in this example. Increasing concentrations for winds approaching the parallel direction were also observed in wind tunnel experiments by *Hoydysh and Dabberdt (1988)* (Figure 3.1). For perpendicular winds, a local maximum on the leeward side is seen too, but only for wind speeds larger than $2ms^{-1}$. For wind speeds smaller than $2ms^{-1}$ the extension of the vortex starts to decrease. According to assumptions made in OSPM and for the canyon geometry considered here, i.e. for H/W = 1, this will permit additional ventilation of the recirculation zone through the side edges (see Figure 4.3). This results in a small decrease of concentrations on the windward side where the only contribution is the recirculating component. For the windward side the direct contribution starts to become important for wind speeds less than $1ms^{-1}$. At still lower wind speeds, when the street vortex disappears, the wind direction dependence disappears too. We recall that at vanishing ambient winds the concentration levels are solely determined by the traffic created turbulence.

The second model example, shown in Figure 5.2, is for a street with 20m high buildings, but only on the south side of the street. Considering higher wind speeds, the concentrations calculated for the North side receptor (Figure 5.2a) are in general very low, except when the winds are close to parallel. The reason for this is the absence of the recirculation vortex for Northerly winds (H_{upwind} = 0) and for the southerly winds, when the vortex is created, the recirculation component (*the only contribution to the windward receptor*) is strongly diluted due to increased ventilation of the recirculation zone (see Figure 4.3). For vanishing wind speeds the concentrations become similar to that considered in the first example, shown in Figure 5.1a.

The most striking feature of the wind direction dependency of the concentrations on the south side of the street (Figure 5.2b) is that the strong minimum observed for the symmetrical canyon (Figure 5.1b) is much less pronounced. The difference between the modelled concentrations for southerly and westerly winds is small. The maximum observed for parallel winds is due to the assumption about an infinite street length. Southerly winds, for which the receptor point is leeward, result in concentrations only

slightly smaller than in the corresponding situation in the case of the symmetrical canyon. The only difference is here the strength of the recirculation contribution. The receptor point on the southern side receives direct contributions from the traffic in the street regardless of the wind direction. This is the consequence of the absence of recirculation vortex in the case of northerly winds.
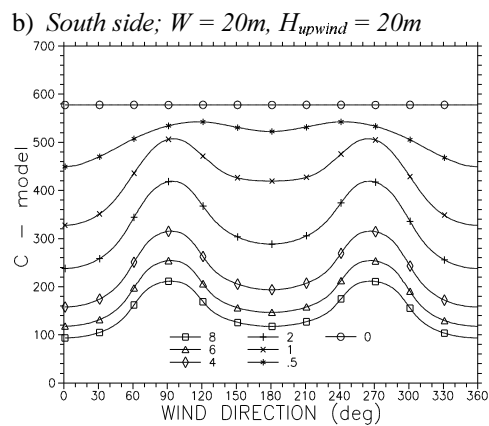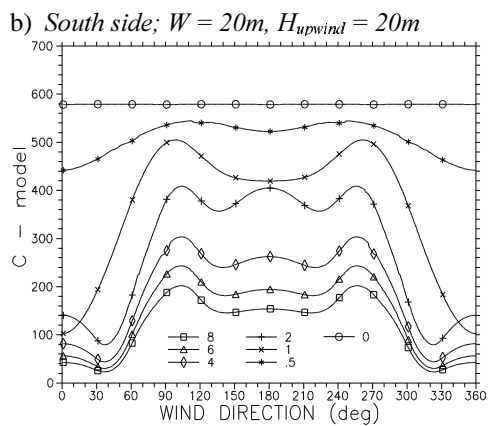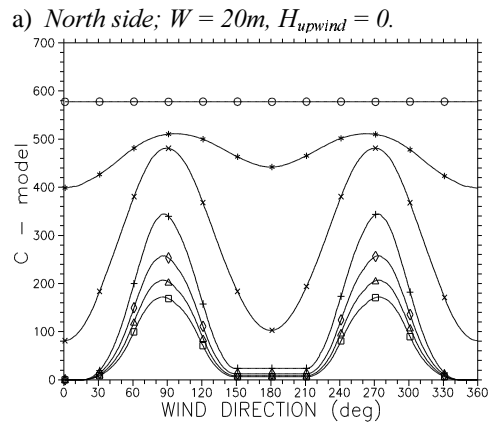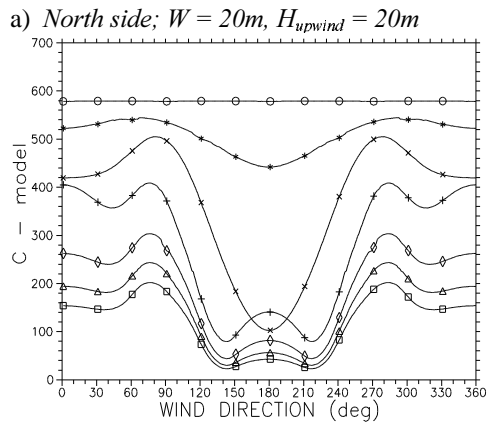
a) *North side; W = 20m, H_{upwind} = 20m*

a) *North side; W = 20m, H_{upwind} = 0.*

b) *South side; W = 20m, H_{upwind} = 20m*

b) *South side; W = 20m, H_{upwind} = 20m*

Figure 5.1 Modelled concentrations as function of wind direction and wind speed for an East-West oriented street canyon with 20m high buildings on both sides. Wind speed is given in the legend.

Figure 5.2 Modelled concentrations as function of wind direction and wind speed for an East-West oriented street canyon with 20m high buildings on the south side only.

The two examples considered here serve as an illustration of the model behaviour only. OSPM is based on many simplified assumptions about flow structure and dispersion conditions in street canyons and in order to verify the model performance, comparison with field measurements is necessary.

6 Comparison with measurements

OSPM has been extensively tested on data from several measuring campaigns (*Hertel and Berkowicz, 1989a,b,c; Berkowicz et al., 1995a,b*). Results from the model tests have contributed in order to improve the parameterization of the model.

Reliability and quality of a model test depend to a large extend on the quality of the input data. For traffic pollution models the most essential input parameters are emission and meteorological data. Traffic data and vehicle emission factors are required for estimation of emission. For streets in an urban environment the background contribution is important too. The background contribution is especially important considering formation of secondary pollutants, such as e.g. NO_2. This subject is discussed in more details in Section 7.

In 1993 a new measuring and modelling project, aimed for study of urban air pollution, was established in Denmark. The project was a part of the National Environmental Research Programme covering different aspects of strategic importance for the Danish environment. The project on traffic pollution in urban areas was one of the largest projects in the Programme.

6.1 The experimental site

An intensive measuring site was established in connection with a permanent pollution monitoring station, operating in the frames of the National Monitoring Programme (LMP III), in the street Jagtvej, Copenhagen (*Kemp et al., 1996)*. Continuous traffic counts provided data on the traffic flow. Measurements of background air pollution were available from a nearby site where a measuring station was established on the roof of a 20m high building (University of Copenhagen, H.C.Ø. Institute). The meteorological data used for the model calculations with OSPM also originate from the roof station, where a 10m tall mast was established, providing measurements of wind speed, direction, temperature, humidity and global radiation.

The map with location of the measuring sites is shown in Figure 6.1, while a more detailed map of the Jagtvej-site is given in Figure 6.7.

Measurements from the monitoring station at Jagtvej are used here for comparison and analysis of model calculations with OSPM. Before using for model evaluation the data were undergone a careful quality control and examined for inconsistent behaviour.

Additionally to air pollution measurements, special meteorological measurements were also conducted at the Jagtvej site. Here, two 18m high meteorological masts were raised on both sides of the street, close to the permanent air pollution monitoring station. Measurements from these masts are used for examination of flow and turbulence conditions in the street but only few selected results are presented here.

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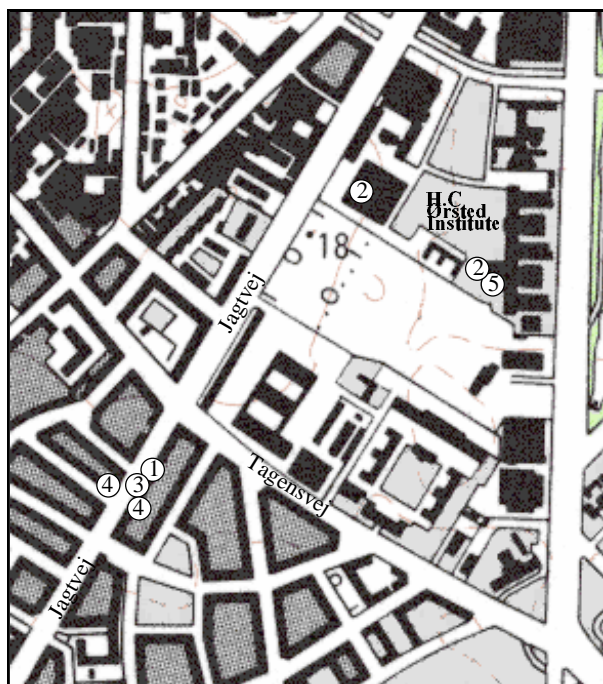
1 - LMP III monitoring station

2 - DOAS and conventional monitors (background monitoring station)

3 - Automatic traffic counts

4 - Special meteorological masts

5 - Standard meteorological mast

Figure 6.1 The map of the measuring site in Copenhagen. Locations of the measuring stations are indicated in the figure. A more detailed map of the Jagtvej site is shown in Figure 6.7.

6.2   Air pollution data

Comparisons of measured and modelled hourly concentrations of NO_x in Jagtvej are shown in Figures 6.2a and 6.2b for the measuring periods in 1993 (1230 hours) and 1994 (4275 hours), respectively.

Jagtvej is a busy street with about 22 000 vehicles/day. The street is 25m wide and is flanked on both sides with about 18m high buildings (4 -5 stories). Orientation of the street is 30° with respect to North. The pollution monitoring station is situated on the East side of the street where the building facades are closed. On the opposite side, narrow side-streets make openings between the building facades (Figure 6.7).

Hourly emissions of NO_x are estimated using the traffic counts in Jagtvej and average emission factors estimated in an earlier investigation (*Miljøstyrelsen, 1991*). An average diurnal traffic profile was constructed from the automatic countings in the street with differentiation between working days, Saturdays and Sundays. Data from working days only are used in calculations presented in Figure 6.2. The same average traffic profile is used both for 1993 and 1994 but assuming 17% catalyst cars in 1993 and 25% in 1994 (*Danish Environmental Protection Agency, personal communication*).

Very good correlation between the modelled and the measured concentrations is evident from the results presented in Figure 6.2. The correlation coefficient $R^2 = 0.85$ for the 1993 and $R^2 = 0.89$ for the 1994 data. Some larger scatter is, however, observed especially at the high end concentrations. Uncertainties in emission estimations have undoubtedly contributed to this scatter but the main contribution may be attributed to the uncertainties in the meteorological data and oversimplifications of the flow parameterization in OSPM.
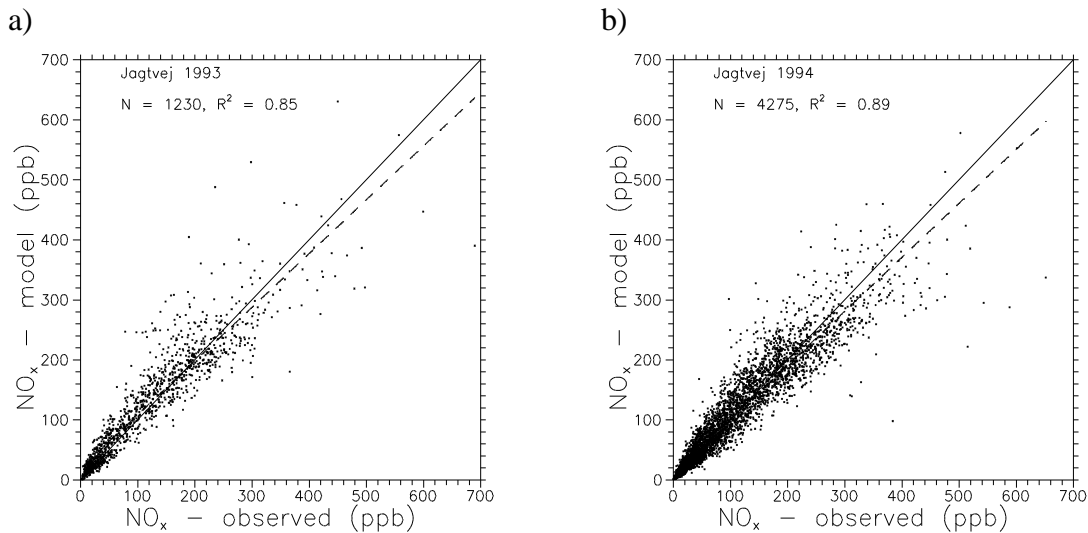
a)   b)

Figure 6.2 Comparison between measured and modelled concentrations of NO_x in Jagtvej. a) 1993 data; b) 1994 data.

A more detailed evaluation of a model performance requires an analysis of the behaviour of model results with respect to the meteorological conditions in comparison with experimental data. Such an analysis is presented in Figures 6.3 and 6.4 where the measured and modelled NO_x concentrations are shown as a function of wind direction (roof mast measurements). Only data from 1993 are used here but additionally to Jagtvej, comparison is also made for two other streets in Copenhagen: Bredgade and H.C. Andersens Boulevard where air pollution monitoring is conducted by the Environmental Protection Agency of Copenhagen (*HLU, 1996*).

Bredgade is a narrow street canyon (W = 15m and H = 15m) with closed building facades on both sides. The street is oriented 21° with respect to North and the monitoring station is on the West side of the street.

H.C. Andersens Boulevard is a broad avenue (W = 60m and H = 25m) oriented 130° with respect to North. The monitoring station is on the north-east side where the street is flanked by somewhat irregular, but on average 25m tall buildings. On the opposite side the street is practically open as it next to the Copenhagen Amusement Park Tivoli.

The traffic intensity in Bredgade is approximately the same as in Jagtvej (ca. 20 000 vehicles/day) while H.C. Andersens Boulevard is one of the most heavily trafficked streets in Copenhagen, with about 60 000 vehicles/day.

The measuring data presented in Figure 6.3 are from daytime hours only (from 8 to 18 hour) and additionally divided into two groups: wind speed between 1 m/s and 3 m/s and wind speed between 4 m/s and 6 m/s.
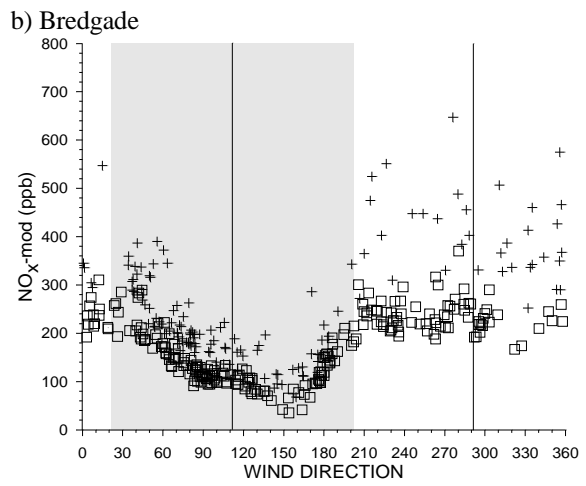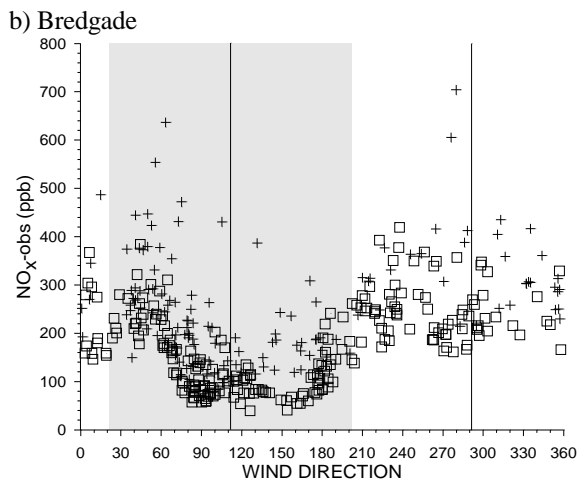
a) Jagtvej

a) Jagtvej

b) Bredgade

b) Bredgade

c) H.C. Andersens Boulevard

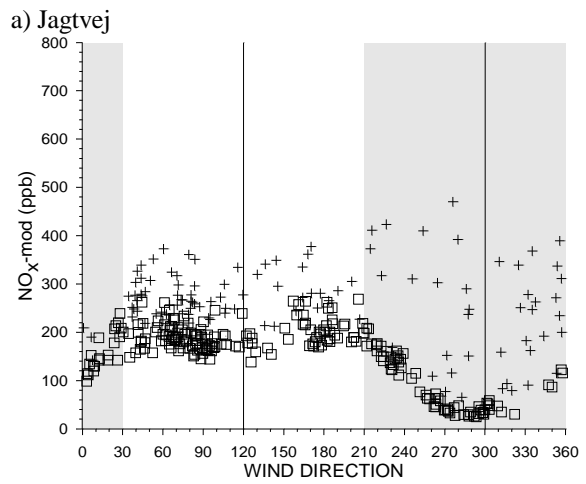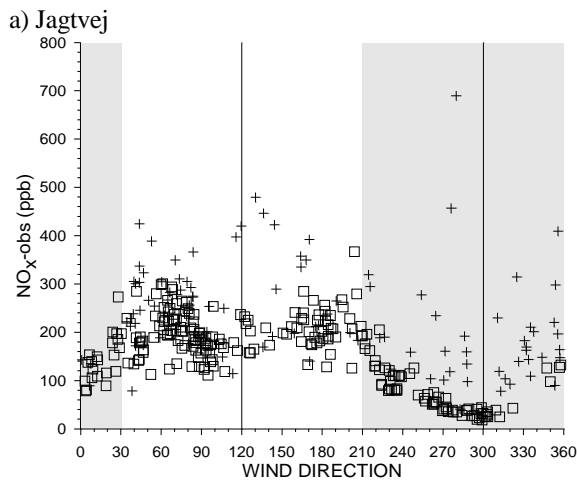c) H.C. Andersens Boulevard
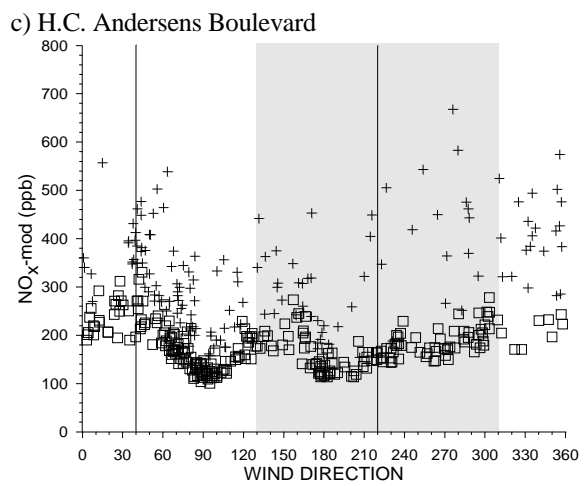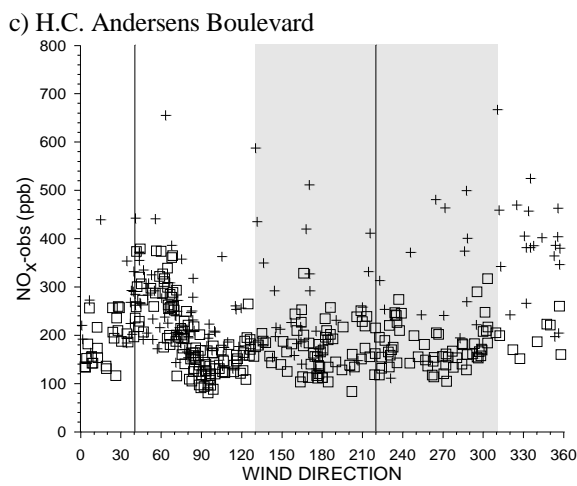
Figure 6.3 Wind direction dependence of measured NO$_x$ concentrations. The wind sector for which the monitoring station is windward is shadowed.

+ - 1 m/s < u < 3 m/s;
□ - 4 m/s < u < 6 m/s

Figure 6.4 Wind direction dependence of modelled NO$_x$ concentrations; symbols as in Figure 6.3.

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The well known street canyon effect is clearly evident from the results shown for Jagtvej and Bredgade. When the wind direction is such, that the measuring point is on the windward side (westerly winds for Jagtvej and easterly winds for Bredgade), the concentrations are much smaller than in the case of a leeward position. The windward wind sectors are shadowed in the figures. The difference is slightly larger for Jagtvej than for Bredgade, especially in the case of higher wind speeds (4 to 6 m/s). The dependence on wind direction is less pronounced in the case of low wind speeds.

The street Bredgade is narrower than Jagtvej and the dilution of pollution by the recirculating vortex is smaller. This is why the concentrations observed at the Bredgade monitoring station for the windward sector are slightly larger than the corresponding concentrations in the case of Jagtvej.

The dependence on wind direction observed in H.C. Andersens Boulevard is quite different from the two other streets. The south-westerly wind sector, for which the measuring point is on the windward side, is here relatively unobstructed. No concentration minimum is observed, due to absence of the recirculating vortex. On the contrary, there is a pronounced leeward maximum, which occurs for the north-easterly winds. This indicates formation of a vortex in the leeward wind sector.

Corresponding results from model calculations are shown in Figure 6.4. It is evident that the model reproduces the observed behaviour very well. Somewhat larger discrepancies observed especially for lower wind speeds are probably attributed to the models inability to adequately describe the flow conditions influenced by the complex street geometry.

Dependence of the measured concentrations of NO_x on wind speed is shown in Figure 6.5. Here, for each of the studied streets is selected a sector where the dependence on wind direction is not pronounced. The selected sectors are:

Jagtvej:	$60^o - 180^o$
Bredgade:	$230^o - 350^o$
H.C. Andersens Boulevard:	$90^o - 210^o$

The data are furthermore divided into two groups: one group for which the global radiation, is less than 400 W/m^2, and one for which the global radiation is greater than 400 W/m^2. Only daytime hours are considered. The separation with respect to global radiation is made in order to highlight the possible influence of the thermal stratification of the air on dispersion conditions in streets. The corresponding results from model calculations are shown in Figure 6.6.

The dependence on wind speed is obvious, and as expected, shows decreasing concentrations with increasing wind speed. Model calculations agree well with the measuring results.
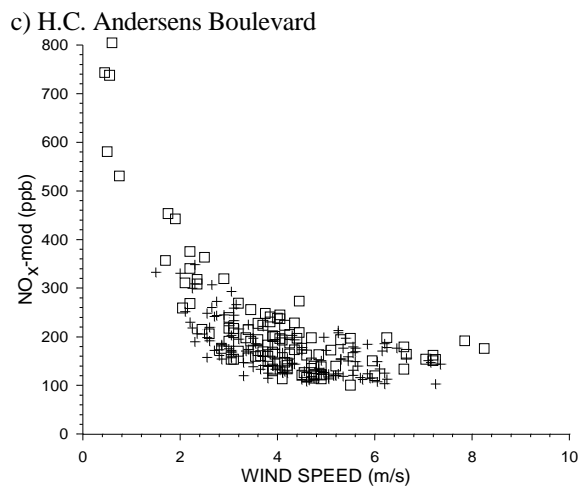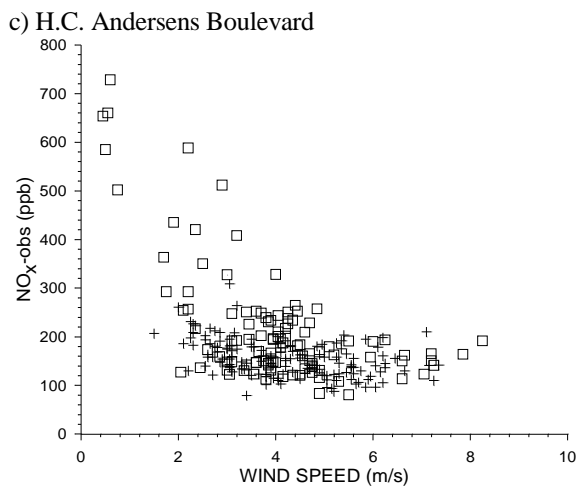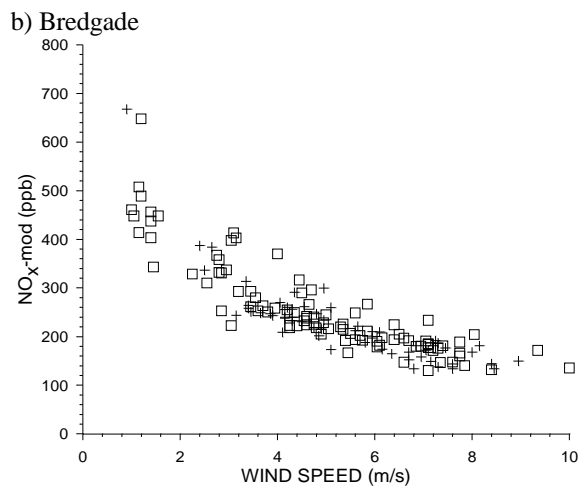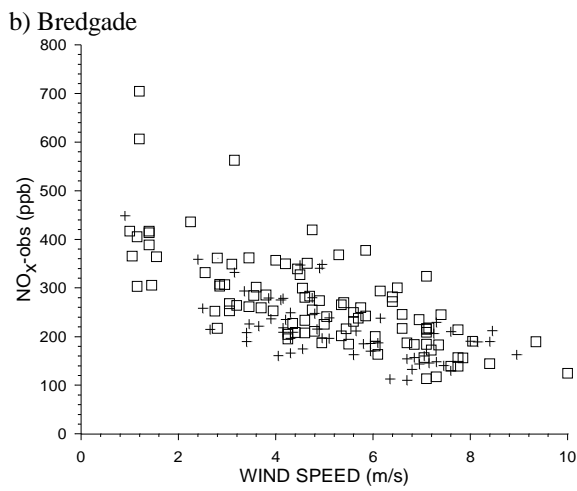
a) Jagtvej

a) Jagtvej

b) Bredgade

b) Bredgade

c) H.C. Andersens Boulevard

c) H.C. Andersens Boulevard
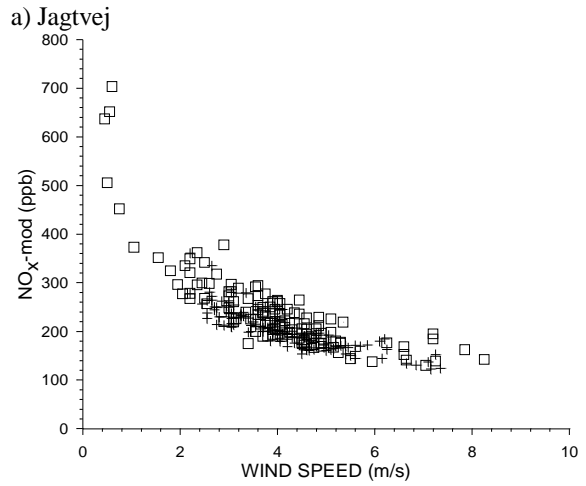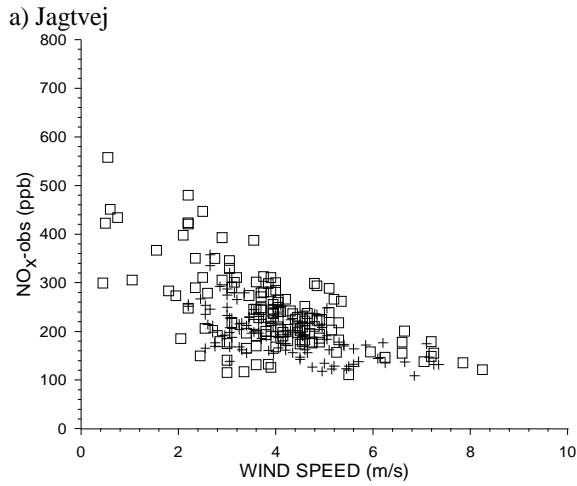
Figure 6.5 Wind speed dependence of measured NO_x concentrations,

+ - Global radiation > 400 W/m^2

☐ - Global radiation < 400 W/m^2

Figure 6.6 Wind speed dependence of modelled NO_x concentrations; symbols as in Figure 6.5.

No notable dependence is observed on global radiation. This indicates that the thermal stratification does not play any significant role in dispersion of pollutants in these streets. The main mechanism is mechanically created turbulence. In the case of low wind speeds, when the thermal stratification might be important, the traffic created turbulence appears to dominate. For H.C. Andersens Boulevard (Figures 6.5c and 6.6c) there is, however, some evidence of underprediction by OSPM of concentrations at low wind speeds when stable conditions may occur. The reason for this might be that the traffic created turbulence in this wide and open street is suppressed due to the stable stratification, so the street ventilation is less than predicted by the model. More experimental evidence is necessary to make decisive conclusions.

6.3   Wind and turbulence measurements in the street.

As a part of the project on Air Pollution from Traffic in Urban Areas, conducted with support from the National Environmental Research Programme, a meteorological measuring station was established in the street Jagtvej, close to the permanent pollution sampling station. The purpose of the meteorological station was to create a database that could be used to validate, calibrate or extend models in use to describe the flow and dispersion of pollutants in street canyons (*Nielsen et al., 1995*). Wind and turbulence parameters were measured on two masts placed on the opposite sides of the street. Location and design of the measuring station is depicted in Figure 6.7. The measurements were conducted for about a year and some selected data are presented here.

Measurements from the sonic anemometer, placed at a height of 6m on the east side mast (mast 1), are used in combination with the wind measurements from the roof mast on the nearby University building (HCØ) to visualise the flow and turbulence conditions in the street. In Figure 6.8 are shown measurements of the vertical velocity component as function of the above roof wind direction, but only for wind speeds larger than 5m/s. Wind directions parallel with the street are indicated by dashed lines in the figure. It is evident that in the case of easterly winds the vertical velocity is upward and is decreasing with wind approaching the parallel direction. This is a typical behaviour for a street vortex. In the case of westerly winds, the picture is less conclusive, perhaps due to the presence of small side streets on the west side of the street (see Figure 6.7b). The vertical velocity component is, however, predominantly downward when the wind direction is close to perpendicular to the street axis.

In Figure 6.9 the vertical velocity is shown as a function of the normal (perpendicular to the street) component of the free wind velocity, with the westerly winds corresponding here to positive values. Again it is seen that for the easterly winds the vertical wind velocity component in the street increases almost linearly with the normal component of the wind velocity but the behaviour is more obscure in the case of the westerly winds.
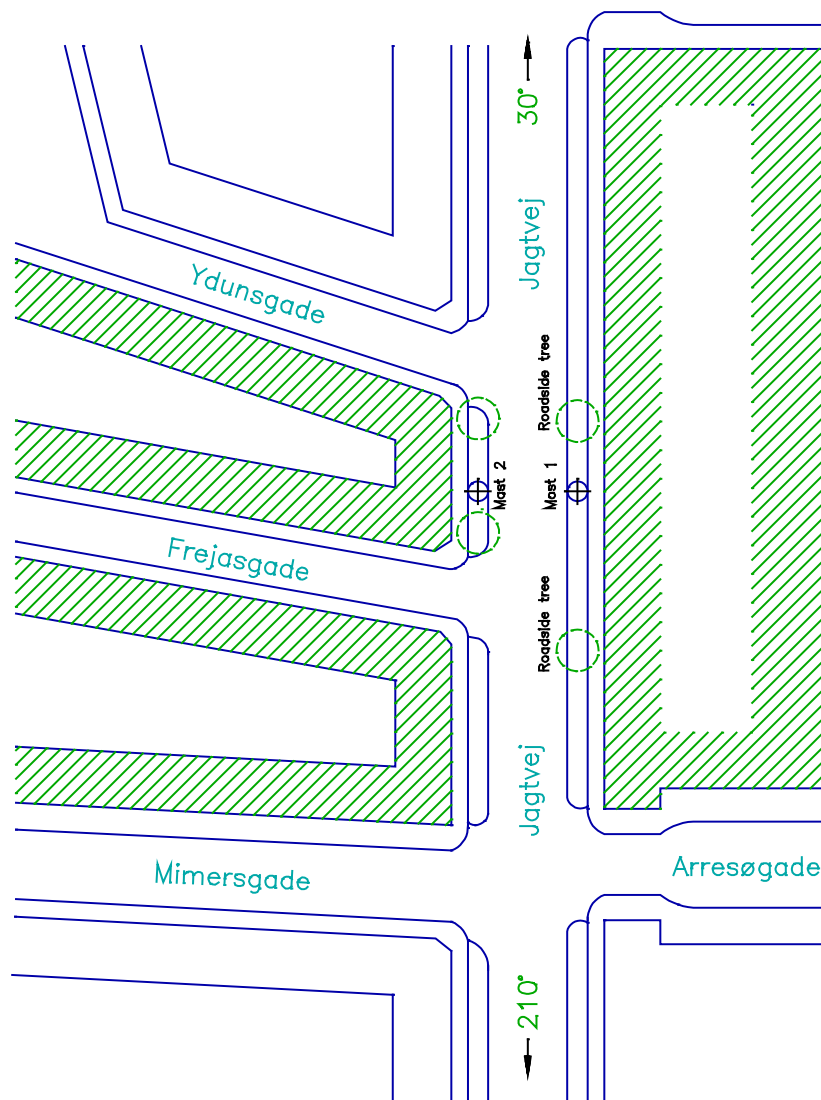
a)
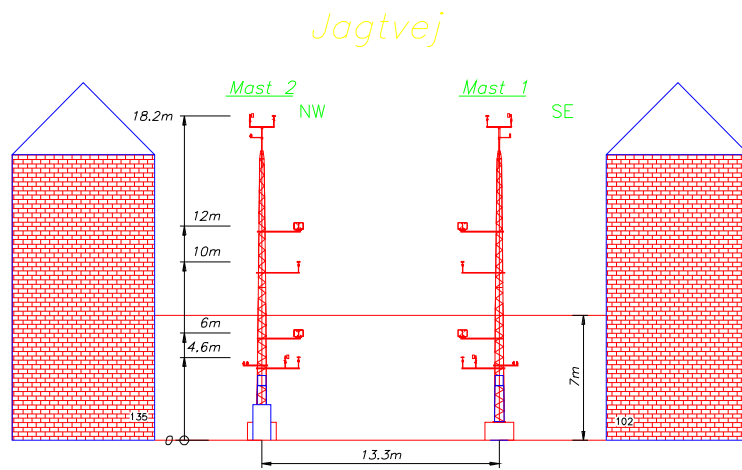
b)

Figure 6.7 Setup of the meteorological measuring station in Jagtvej. a) view from the South, b) map of the nearby surroundings.
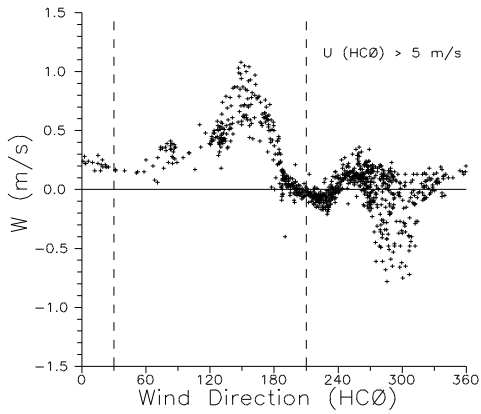
Figure 6.8 The vertical velocity component in the street as function of wind direction. Wind directions parallel with the street are indicated by dashed lines.
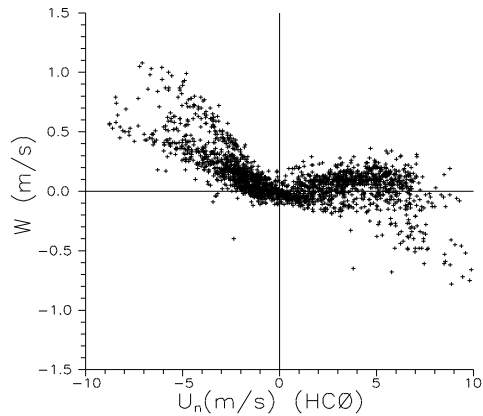
Figure 6.9 The vertical velocity component as function of the normal (perpendicular to street axis) component of the free wind velocity.
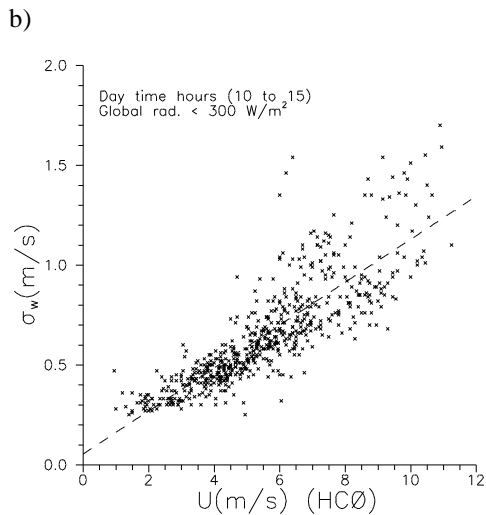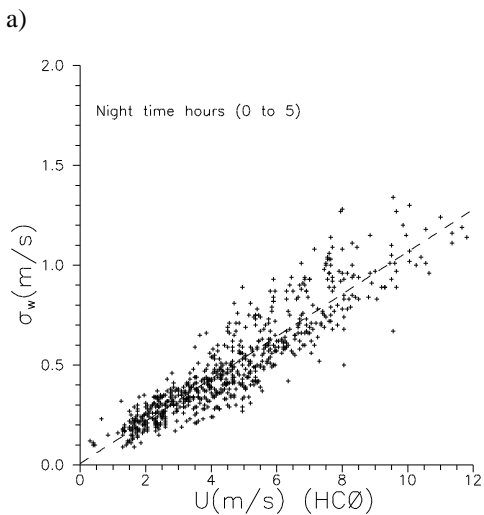
a)

b)

Figure 6.10 Relationship between the vertical velocity turbulence and the wind speed. Working days only. a) night time hours; b) day time hours. The dashed lines show the best linear fit.
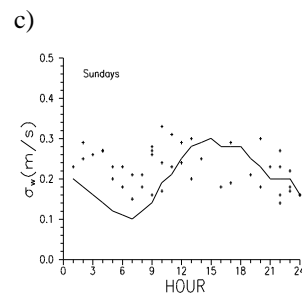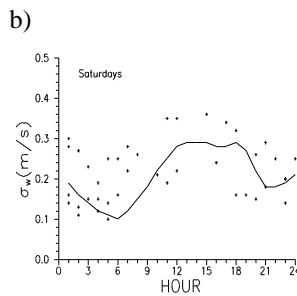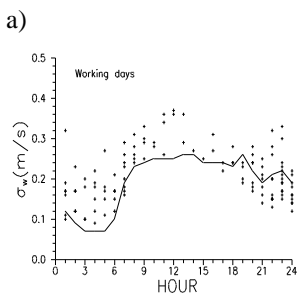
a)

b)

c)

Figure 6.11 Diurnal variation of σ_w for U < 1.5 m/s. The traffic created turbulence as calculated by OSPM is shown by continuous lines. a) working days; b) Saturdays; c) Sundays

The sonic-anemometer data are also used for examination of the turbulence properties of the street wind flow. In Figure 6.10 the standard deviation of the vertical velocity component is

shown as function of the free wind velocity. The data cover working days only but are divided into two groups: the night time observations (from midnight to 5 am; Figure 6.10a) and the day time observations (from 10 am to 15 pm; Figure 6.10b). A linear relationship between the turbulence parameter and the free wind speed is obvious. The slope of σ_w versus U is about 0.1 both for night and day time data. Contrary to the night time observations, the day time data have, however, a non-zero intercept and for U less then about 3m/s, σ_w approaches a more or less constant value of about 0.3-0.4 m/s. The difference between night and day time observations can probably be attributed to the traffic created turbulence. In order to rule out the influence of solar insolation on the day time turbulence, only observations with the global radiation less then 300 W/m^2 are selected here.

The influence of traffic on the turbulence in the street is illustrated in Figure 6.11. Here, only observations with the free wind speed U < 1.5m/s are selected and the diurnal variation of the vertical velocity turbulence is shown for working days, Saturdays and Sundays, separately. Additionally, the traffic created turbulence, as calculated by OSPM (see section 4.4) is shown by continuous lines in the figures. It is seen that the turbulence in the street has an evident diurnal variation which follows quite well the traffic pattern. Even the difference in the traffic pattern for working days and week-ends is more or less reproduced in the diurnal variation of the turbulence. The night time values of σ_w are, however, somewhat higher then one would expect from the traffic induced turbulence only. Some other mechanisms must be of importance here too, as e.g. wind circulation induced by across the street temperature differences (*Sini et al., 1996*) or other local wind effects.

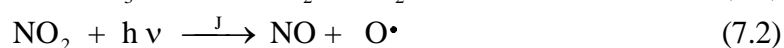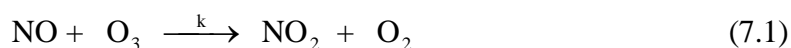The data analysis presented here concerns measurements at one point in the street only. Different relationships can be expected at other positions in the street canyon. Examination of measurements from both masts including sensors at different heights will put more light on the flow and turbulence conditions in the street. Some preliminary results were presented by *Nielsen et al. (1995)* and further work is in progress.

7　Modelling chemical processes in street canyons

Transport and dispersion processes are not the only factors determining relationships between emission sources and ambient concentrations. Chemistry plays a crucial role in transformation of pollutants resulting in degradation of some species and formation of others. Considering transport of pollution on a larger scale, when the transport times involved are of the order of hours or even days, hundreds of chemical reactions must often be considered in order to account for the chemical composition of the air. The situation is quite different when dealing with processes in street canyons. Due to the very short distances between the sources and receptors, only the fastest chemical reactions can have any significant influence on the transformation processes in the street canyon air. It means that most of the pollutants emitted from traffic can be considered as inert components for which chemical transformations inside the street canyon are unimportant. Such inert compounds on these time scales are CO and hydrocarbons which actually constitute the main composition of car exhaust gases. The situation is however different for nitrogen oxide gases which actually are the compounds most often considered in connection with impact of traffic pollution on human health.

The main nitrogen oxides are nitrogen monoxide (NO) and nitrogen dioxide (NO_2), the sum of which is denoted as NO_x. Regarding health effects, NO is considered to be harmless, at least at concentrations expected in urban air. On the contrary, NO_2 can have severe adverse health effects on humans.

Only a small portion of NO_x gases emitted by motor vehicles is in form of NO_2, the main part being NO. The presence of NO_2 in ambient air is mainly due to the subsequent chemical oxidation of NO. The chemistry of nitrogen oxides is quite complex but due to very short residence times of air pollutants in street canyons (of the order of seconds or minutes at highest) the only reactions of practical interest here are:

$$NO + O_3 \xrightarrow{\quad k \quad} NO_2 + O_2 \tag{7.1}$$

$$NO_2 + h\nu \xrightarrow{\quad J \quad} NO + O^\bullet \tag{7.2}$$

$$O^\bullet + O_2 \longrightarrow O_3 \tag{7.3}$$

The reaction between the oxygen radical ($O^\bullet$) and the molecular oxygen (O_2) (7.3) is very fast and for all practical purposes the reaction system (7.1 - 7.3) can be restricted to two reactions only:

- production of NO_2 due to reaction of NO with ozone (O_3); reaction coefficient k ($ppb^{-1} s^{-1}$),
- photodissociation of NO_2 leading to reproduction of NO and O_3; reaction coefficient J (s^{-1})

The time scales characterising these reactions are of the order of tens of seconds, thus comparable with residence time of pollutants in a street canyon. Consequently, the chemical transformations and exchange of street canyon air with the ambient air are of importance for processes leading to NO_2 formation. Taking this into account, the rate of change of the concentrations of NO, NO_2 and O_3 in the street can be approximated by the following equations:

$$\frac{d[NO]}{dt} = -k[NO][O_3] + J[NO_2] + \frac{[NO]_v}{\tau} + \frac{[NO]_b - [NO]}{\tau} \qquad (7.4)$$

$$\frac{d[NO_2]}{dt} = k[NO][O_3] - J[NO_2] + \frac{[NO_2]_v}{\tau} + \frac{[NO_2]_b - [NO_2]}{\tau} \qquad (7.5)$$

$$\frac{d[O_3]}{dt} = -k[NO][O_3] + J[NO_2] + \frac{[O_3]_b - [O_3]}{\tau} \qquad (7.6)$$

The first two terms on the right hand side of equations (7.4) - (7.6) account for the chemical reactions (7.1 - 7.3). Thereafter follow the contribution from the direct emission in the street ($[NO]_v$, $[NO_2]_v$; no direct emission of ozone) and the exchange rate between the street and the background air. The terms with index b are the background air concentrations. The exchange rate is governed by the time constant ϑ, the residence time.

Assuming that a steady state is achieved (time derivatives become zero), equations (7.4 - 7.6) can be solved analytically giving concentrations of NO_2 in the street canyon air;

$$[NO_2] = 0.5\left(B - \left(B^2 - 4([NO_x]\cdot[NO_2]_o + [NO_2]_n \cdot D)\right)^{1/2}\right) \qquad (7.7)$$

where

$$[NO_2]_n = [NO_2]_v + [NO_2]_b$$

$$[NO_2]_o = [NO_2]_n + [O_3]_b$$

$$B = [NO_x] + [NO_2]_o + R + D$$

The photochemical equilibrium coefficient is given by $R = J/k$ (ppb), while $D = (k\tau)^{-1}$ is the exchange rate coefficient (ppb).

Formula (7.7) is implemented in OSPM (*Hertel and Berkowicz 1989b*) and has successfully been used for estimation of NO_2 concentrations in Danish streets (*Palmgren et al., 1995a*).

In the model, the direct emission term, $[NO_2]_v$, is set to a constant fraction (=5%) of $[NO_x]_v$, which is calculated by the dispersion part of OSPM ($[NO_x]=[NO_x]_v+[NO_x]_b$). The residence time, τ, is approximated by H/σ_{wt}. The photodissociation coefficient, J, is calculated as function of global radiation using an empirical formula derived from measurements of NO, NO_2 and O_3 in rural areas (*Hertel and Berkowicz, 1989b*).

The NO_2/NO_x relationship computed according to formula (7.7) is shown in Figure 7.1. Here calculations are made for three values of background ozone concentrations: $[O_3]_b=5$, 40 and 80ppb. For simplicity, the background concentrations of NO_x are assumed to be zero. The photodissociation coefficient corresponds to a global radiation of 500Wm^{-2} and the canyon ventilation velocity is set to $\sigma_{wt}=0.5$ms^{-1} which results in the residence time of 40s for a 20m deep canyon. The direct emission of NO_2 is set to 5% of NO_x.
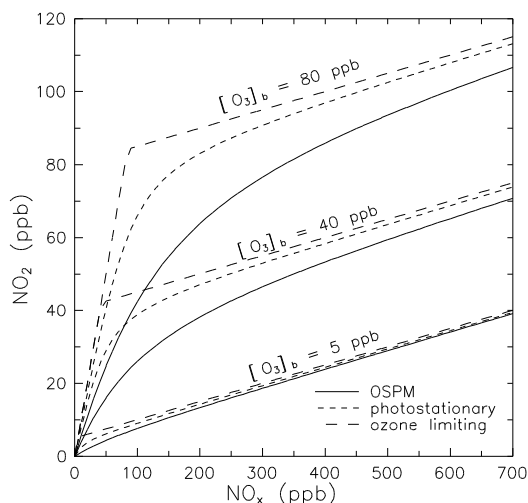
Figure 7.1 Relationship between NO_2 and NO_x for three values of background ozone. Results are shown using Equation (7.7) and two other models.
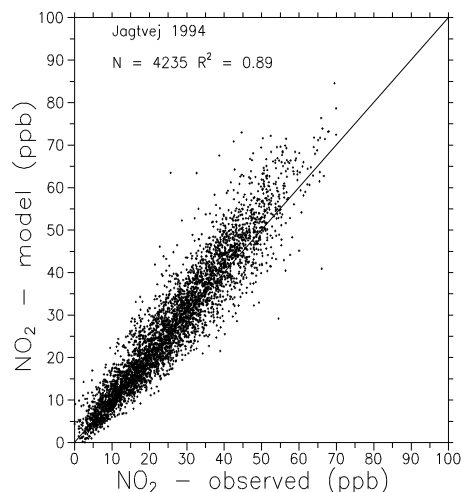
Figure 7.2 Comparison between measured and modelled concentrations of NO_2 for the street Jagtvej.

For comparison, predictions from two other simple models are also shown in Figure 7.1. The first implies that a photostationary state is achieved in the street. This is equivalent to the assumption that the residence time of pollutants in the street is infinite, or at least much larger than the chemical reaction time scale. This approach is used in the CPB model of *Yamartino and Wiegand (1986)*. The second model is based on the assumption that production of NO_2 in the street is equal to the amount of available ozone. This means that not only the residence time is large enough, but also that the photodissociation of NO_2 (reaction (7.2)) can be neglected. The latest approach is used in the Nordic Computational Method for Car Exhaust Gases *(Larssen, 1992)*. Both the photostationary assumption and the ozone limiting method clearly overpredict the NO_2 concentrations. The difference between the OSPM approach and the two other models decreases, however, with increasing NO_x concentrations. The deviations are also expected to decrease with decreasing street ventilation (increasing residence time). Because such conditions are also connected with the highest concentrations, the simple ozone limiting method used by *Larssen (1992)* for prediction of the highest NO_2 concentrations is not unreasonable.

In Figure 7.2 is shown a comparison between concentrations of NO_2 computed by OSPM and measurements from the monitoring station in Jagtvej. The agreement is very good, proving thus that the method based on the simplified chemistry given by reactions (7.1 - 7.3) and the formula (7.7) performs well. Other chemical mechanisms may however be important in some extreme cases.

One such extreme case was reported by *Bower et al. (1994)* and *Derwent et al. (1995)*. In their study, a pollution episode in London in December 1991 was reported where the concentrations of NO_2 reached levels which could not be explained by ozone controlled oxidation. They suggest that the probable reaction is oxidation of NO by molecular oxygen:

$$NO + NO + O_2 \longrightarrow 2NO_2 \tag{7.8}$$

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As this is a 3'rd order reaction, it requires very high concentrations of NO to be important. Such conditions appeared in December 1991 in London when due to stagnant weather conditions the concentrations remained significantly elevated for a period of a few days. However, because equally high concentrations of NO_2 were measured as well as at kerb sites and at urban background sites, this episode can not be explained by processes taking place in a street canyon alone

The contribution of the reaction (7.8) to winter time NO_2 concentrations in Oslo has also been considered by *Hov and Larssen (1984)*. Their conclusion was that the main effect is an increase of formation of NO_2 in an immediate vicinity of vehicles tail pipe exhaust where due to low dilution, the concentrations of NO are extremely high. The rate of formation of NO_2 by (7.8) increases with decreasing temperatures.

Other reactions can also be important in urban areas with strong photochemical activity and limited ventilation. Oxidation of NO by radicals, such as e.g. HO_2, can be the dominant path in this case. Again, this is an urban background phenomena and the additional formation of NO_2 in street canyons is expected to be less influenced by such mechanisms.

8   Outstanding problems and conclusions

Application of some few simple models for calculation of dispersion of traffic pollution in street canyons was discussed. It was demonstrated that even such simple and highly parameterized models, as e.g. OSPM, can handle a broad range of dispersion conditions and provide reliable results. The successful performance of OSPM is mainly due to parameterizations which were based on careful examination of available experimental data covering a broad range of conditions, but this is also the limitation of the model. Considering the "broad range of conditions" we have to emphasise that this never means - all conditions. Some of the problems that still lack a practical solution will be discussed in this section.

The most severe pollution episodes are usually associated with calm or very low wind speed conditions. Actually, differences in prevailing wind speed conditions seem to explain much of the differences in urban pollution levels (*Vignati et al., 1995*). Considering flow and dispersion regimes in street canyons at low wind speeds, we have already mentioned the important role of the traffic created turbulence (4.4 and 6.2) but some thermal effects can also be important as well. We have here in mind the modification of flow regimes due to differential heating of building walls. This effect is most pronounced for east-west oriented canyons where, due to solar insolation, the temperature of a north wall can be several degrees warmer than the temperature of a south wall (on the Northern Hemisphere). Field observations (*Nakamura and Oke, 1988*) and numerical simulations (*Mestayer et al., 1995; Sini et al., 1996)* have shown that such differential heating can substantially modify the wind flow in a canyon. If the heated wall is windward, this can even lead to reversing of the flow and thereby largely influence distribution of pollution in the street. Quantification of this effect in the form of relationships between solar radiation and wind flow is necessary in order to incorporate these phenomena into applied pollution models.

Traffic pollution models typically make use of wind flow data related to the roof level. Such data are rarely available and transformation of wind measurements undertaken at some few locations in the city or even outside the city are necessary. Taking into account that urban areas are strongly inhomogeneous, this task is far from trivial. Mesoscale meteorological models can be used in this case but very fine mesh resolution is required to resolve the building structures in the city. This is not possible with presently available models where urban areas are treated as bluff bodies and only the large topographical features are taken into account.

Rotach (1995) has shown that the relationship between the roof level wind speed and the speed aloft depends on the atmospheric stability conditions. This can be especially important in the case of stable conditions when the canyon ventilation velocity might be reduced due to attenuation of the roof level speed and perhaps turbulence.

Local modification of wind flow and turbulence might also be due to some pronounced building formations nearby the measuring site. Based on wind tunnel modelling, *Kennedy and Kent (1977)* have demonstrated that a twofold decrease of CO concentrations observed at a street site in Sydney, Australia, could be explained by construction of a

tower block that has largely influenced wind flow and thereby dispersion conditions at the measuring site.

Surroundings of the street canyon can in general have significant influence on flow and dispersion conditions in the canyon itself. Already the early experiments by *Hoydysh et al. (1974)* demonstrated that an upwind fetch of at least 8 to 10 street canyons is required before the wind flow can be considered stationary. Recent wind tunnel experiments by *Meroney et al. (1995)* have shown that ventilation of a canyon in an urban environment is less than ventilation of the same canyon but in an open country environment. The shape of roofs of surrounding buildings was also shown to influence the concentration distribution in street canyons (*Rafailidis and Schatzmann, 1995*).

The question may arise, whether is it possible at all to manage such a variety of different conditions and influencing parameters by mathematical models. Perhaps not, at least not by a single model. Do we need universal models? Are the simple models not adequate for most of the purposes? Perhaps yes, especially regarding routine applications.

More detailed models are however required when the problem is connected with interpretation of measurements. Measurements are, as rule, the basis for pollution surveillance programmes. Measurements provide the most direct information on pollution conditions (at least at the measuring sites) but as stand alone, they can not be used to explain the relationships between sources and ambient pollution. Such relationships are necessary if conclusions based on the surveillance programmes have to be used to any thing else than just reporting the present conditions. Interpretation of measurements in terms of source-receptor relationships, meteorological conditions, the local street conditions e.t.c. can only be done using well performing dispersion models.

One example of using dispersion models in connection with measurements is the application of OSPM for estimation of emissions of benzene from traffic in Jagtvej. As it was demonstrated that OSPM is able to properly describe the relationships between the meteorological conditions and air concentrations, it was possible to estimate the emission term by fitting model calculations to the observed concentrations. Using a multiple linear regression analysis method, the emission term was distributed among light and heavy vehicles providing thereby the respective vehicle emission factors. Preliminary results are presented by *Palmgren et al. (1995b)*. After refinement of the method, it will be applied for surveillance of development of traffic pollution in Danish cities.

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