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Research Article

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Evaluation of the Street Pollution Model OSPM for Measurements at 12 Streets Stations Using a Newly Developed and Freely Available Evaluation Tool

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Abstract

In the present work, the Operational Street Pollution Model (OSPM) has been evaluated in comparison with continuous half-hourly measurements over a multi-year period for five permanent street monitor stations that constitute part of the Danish Air Quality Monitoring Programme as well as with passive measurements with long averaging times at nine locations in Copenhagen as part of a specific project. Results are discussed in relation to the quality objective within the EU Air Quality Directive and general uncertainties in model parameters and model input data. It is demonstrated that OSPM reproduces the observed basic dependencies of concentrations on meteorological parameters–most notably wind direction and wind speed. However, in some cases the modelled annual trends in NO_x and NO_2 are slightly different from what is found in the measured concentrations. For NO_x the OSPM reproduces the observations well, especially for the most recent years, while for NO_2 the model over-predicts in two cases. The explanation for this over-prediction is believed to be uncertainties in the traffic or emission input data, but also in model parameters, and the representativeness of the urban background data may play an important role. The newly developed evaluation tool is used for exploratory data analysis of the large amount of data, and is free available for the research community. The evaluation tool is complementary to the 'Delta Tool' that has been developed in the framework of FAIRMODE by JRC Ispra.

OSPM calculations for nine streets with passive sampler measurements were conducted as 'blind test' i.e. without knowing the measured values. OSPM calculations were in good agreement with the measurements for seven out of nine street sections. Refinements of the input data lead to a significant improvement of the agreement between model results and measurements at the two remaining locations. Recommendations could be derived for an improved quality assurance of the input data and for minor adjustments in the OSPM.

Keywords: OSPM; Model evaluation; Street canyon; Urban air quality, Air quality directive, Traffic-related; Air pollution

Introduction

Model evaluation is crucial, since the European Air Quality Directive (EC, 2008) opens for the use of models in assessment of air quality also in relation to evaluating compliance with limit values. In this context, the directive defines model quality objectives that are now interpreted and discussed within the Forum for Air Quality Modeling in Europe (FAIRMODE, http://fairmode.ew.eea.europa.eu/). There are some ambiguities in the interpretation of these objectives, and their usefulness is limited. The present paper aims at contributing, to the discussion.

For more than two decades the Operational Street Pollution Model (OSPM) has been evaluated and applied by a wide range of users worldwide [1] for modelling urban air pollution at street level [2], in the framework of integrated air quality monitoring [3] and in assessment of human exposure to air pollution at address level [4-7]. However, the OSPM development is on-going in order to make the model more widely applicable for non-standard street canyons e.g. only buildings at one side of the street as often encountered in exposure analysis [8]. Moreover, OSPM input parameters as e.g. emission factors including emission ratios (e.g. share of directly emitted NO_2) need to be updated frequently, and new pollutants (e.g. particle number concentration) have to be included in the model. Therefore model evaluation continues being an important task.

In order to identify shortcomings of the OSPM, model results have been re-calculated with updated emission and traffic data for long-term measured time series at five Danish monitoring street stations, including non-regular street canyons. Model results regarding statistical parameters as e.g. the maximum uncertainty of the annual average show that all deviations between observed and modelled values for compounds with limit values or target values (NO_2, PM_{10}, $PM_{2.5}$) are within the required ± 30% range. However, this statistical analysis might obscure deficiencies of the model, and the obtained results could be "right for the wrong reason", i.e. the model quality objective for the performed calculations might be fulfilled even if the model fails to reproduce some essential features in observations. The necessity of a qualitative model evaluation in addition to the pure statistical/quantitative evaluation has been pointed out in many model evaluation protocols and exercises before, e.g. by the "COST 732 Model Evaluation Guidance and Protocol Document", and terms as 'diagnostic evaluation', 'qualitative analysis' or 'exploratory data analysis' are used in this context [9-11]. Therefore results of the evaluation have been analysed with a newly developed validation tool [12] allowing for a so-called exploratory data analysis. The validation tool examines trends in observed and modelled annual averages, and produces time series plots, scatter plots for hourly, diurnal and monthly mean concentrations as well as plots displaying concentrations as function of wind direction. This presentation of results allows the user to easily evaluate whether

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the model results show the correct pattern and dependencies regarding independent parameters (e.g. time of day, season/month, wind speed and direction).

Long-term measurements with hourly time resolution require large efforts to establish, are costly to operate and are generally available only for few sites. Therefore in a second part of the paper we present an evaluation of OSPM results in comparison with measurements from 10 streets in Copenhagen using passive samplers that have been collecting NO_2 over a five week period. The OSPM calculations were performed in two stages. The model calculations at stage 1 ('blind test') were carried out without knowledge about the results from the measurements. Model version and input data correspond to those used for the most recent OSPM calculations presented in reports for the routine monitoring programme in 2011 and a surveillance project, respectively [13,14]. At stage 2 input data were updated and revised in order to analyze the differences between measured and model calculated concentrations at stage 1.

The discussion in the paper leads to a number of conclusions and recommendations for the application of OSPM in practical applications, for input data requirements and for future improvements.

Methodology

OSPM set-up

The street canyon model OSPM (http://OSPM.dmu.dk/) is used to calculate air pollution at 2 m height at the sidewalks of selected streets. OSPM follows a semi-empirical approach that is based on a parameterization of the most important dispersion processes close to the street, including the influence of the traffic-produced turbulence (TPT) created by the movements of the vehicles within the street, the influence of the buildings close to the street on the dispersion (street canyon effect), but also of chemical transformation between NO-O_3-NO_2. The OSPM has been successfully tested and applied in many studies worldwide [1], and recently been evaluated in connection with a GIS-based procedure allowing calculations for a large number of street sections [8].

Traffic emission data are crucial input for the calculations with OSPM. The applied routine for calculating Danish traffic emission data has been substantially updated with detailed information (average daily traffic, vehicle distribution) collected from four Danish municipalities within a project on evaluation of the effects of low emission zones [15]. Emission factors are based on the most recent version 9 of the COPERT IV model and are applied for 2010 conditions. In order to account for the effect of the low emission zones inside the cities the vehicle composition has been analysed in detail using video licensing plate recordings linked to the National Auto Registry at a street in Copenhagen [15]. The input data for the OSPM regarding the street and building configurations for the selected urban streets are generated based on digital maps of the Danish road network and a comprehensive building foot print database using the AirGIS system (http://AirGIS.dmu.dk) [16,17].

The use of the close to real-world emission factors is obviously crucial for obtaining good results. Moreover, when validating and calibrating an semi-empirical model like the OSPM, the emission factors and the implemented parameterisations of physical and chemical processes are in combination governing the final concentration output. Too high (or too low) emission factors may thus be compensated by over-or underestimating the dispersion process in the model.

It is far from trivial to determine the most correct emission factors to be applied, even for the well studied compound NO_x. The official emission models as e.g. COPERT and HbEFA may be inconsistent and deviate from results obtained in remote sensing measurements with up to 30% for some vehicle classes [19,20]. In many cases the predicted emission reductions with the introduction of newer EURO classes are not accomplished under real-world driving conditions, leading to an underestimation of emissions when using the official emission models. As an example, the SCR-catalytic converter in EURO 5 heavy duty vehicles has been shown to be inefficient under urban driving conditions (Graz University of Technology) [20] and this is not thoroughly described in the emission models.

OSPM has previously used its own simplified emission model due to this type of inconsistency in the emission models as shown in Berkowicz et al. [21]. However, in recent years with an increasing complex structure and composition of the vehicle fleet (more EURO classes introduced, various technologies in parallel, variable direct NO_2 fraction) we have switched to using the COPERT emission model within OSPM. The now lower emissions implied by COPERT have been compensated by a reduction of a dispersion parameter in the model. The user now has the option of adjusting a previously fixed parameter in the model. The parameter f_{Roof} represents the ratio u_{roof}/u_{mast}, where u_{roof} is the roof-level wind speed and u_{mast} is the above-building wind speed, which is either measured at a meteorological mast or calculated using a meteorological model (typically at 10 m altitude). In earlier applications that gave good agreements compared to measurements, using the OSPM-internal emission factors, f_{Roof} was set to 0.82 [21]. Using the new COPERT emission factors, f_{Roof} had to be adjusted to a value of 0.4, due to approximately 30% lower NO_x emissions. Thus, a recent data assimilation study performed with OSPM where the parameter f_{Roof} among other parameters was allowed to be variable and estimated by a statistical data assimilation method, has pointed towards a value of about 0.4 [22].

The new set-up in OSPM, using the new COPERT emission factors and the changed f_{Roof} is tested for several street measurements in this paper.

Long-term series of half-hourly measurements

Measurements of NO_x, NO_2, PM_{10} and $PM_{2.5}$ from five streets in the four largest Danish cities (Copenhagen, Aarhus, Odense and Aalborg) are exploited with up to 17 years of data. The location of the 5 stations with respect to the surrounding buildings is shown in figure 1. All stations are permanent and operated by Department of Environmental Science at Aarhus University as part of the Danish Air Quality Monitoring Programme [13]. They deliver data with half-hourly time resolution. The geometric details of the street sections near the stations (street width, building height, direction) are given in table 1 while traffic characteristics of the streets are listed in table 2. The streets represent a wide parameter range in terms of traffic flow and street geometry (width and height), however, mostly with buildings on both sides, while only one street (H.C. Andersens Boulevard) has buildings on only one side.

Short-term set of passive measurements

10 street sections in Copenhagen were selected out of the 138 street sections that are modelled within the annual reporting of the Danish Air Quality Monitoring Programme [13] in order to test the OSPM for an even larger variety of cases with short-term passive sampling. Therefore the selected street sections represent high, medium and low concentration levels according to earlier calculations and half of the street sections have buildings only on one side. The positions of the

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10 street sections are shown in figure 2. The two permanent kerbside monitoring stations in Copenhagen (Jagtvej and H.C. Andersens Boulevard) are among the 10 locations to allow for a comparison between short- and long-term observations.

The company Force Technology carried out the measurements of NO_2 during a five weeks period from October 24th to November 28th 2011 using passive samplers by IVL, Gothenburg, Sweden, [23]. Unfortunately one of the measurements (Nørre Søgade) was removed by someone and therefore lost for analysis.

Input data regarding building geometry (height and width of the canyon) were originally obtained with the automatic routine from AirGIS, and such data were used in the step 1 (blind test). Despite AirGIS being thoroughly tested and verified the automatically generated building geometry might be imprecise in some cases and a verification of the geometry data is recommended in case a higher precision is intended and the number of streets is manageable. Therefore in the second step geometry was verified from maps, aerial photos and photos taken at the location. Both original and verified input data are listed in table 1.

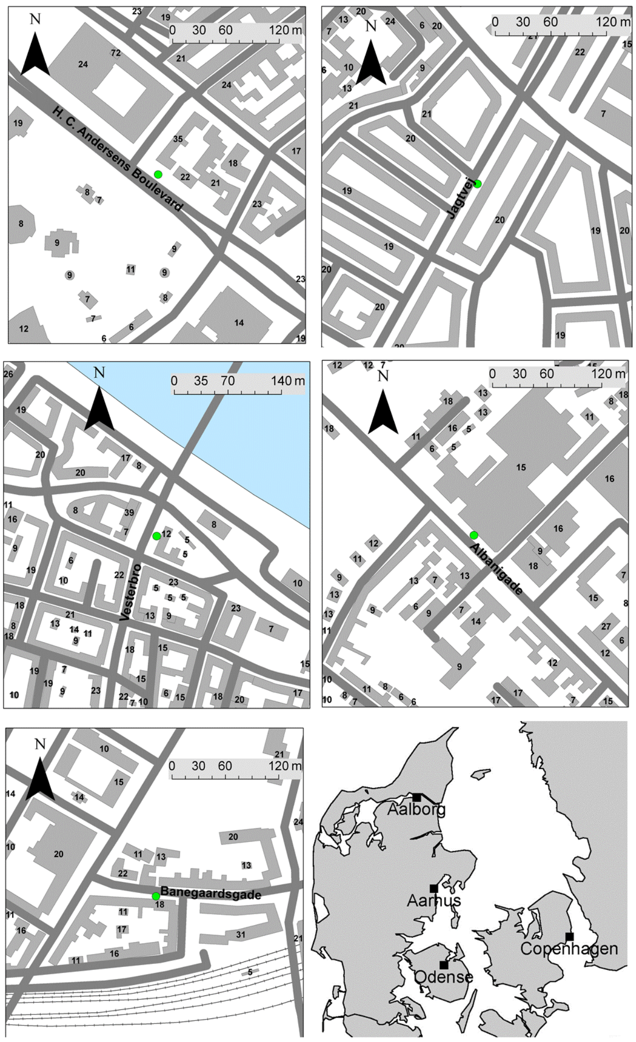

Figure 1: Locations of the five permanent monitoring stations, relative to surrounding buildings, roads,railways and water bodies. Building heights (in meters) are shown for each building. Water bodies are shown in blue. Clockwise from the bottom-left: Banegaardsgade (Aarhus), Vesterbro (Aalborg), H. C. Andersens Boulevard (Copenhagen), Jagtvej (Copenhagen) and Albanigade (Odense) [22].

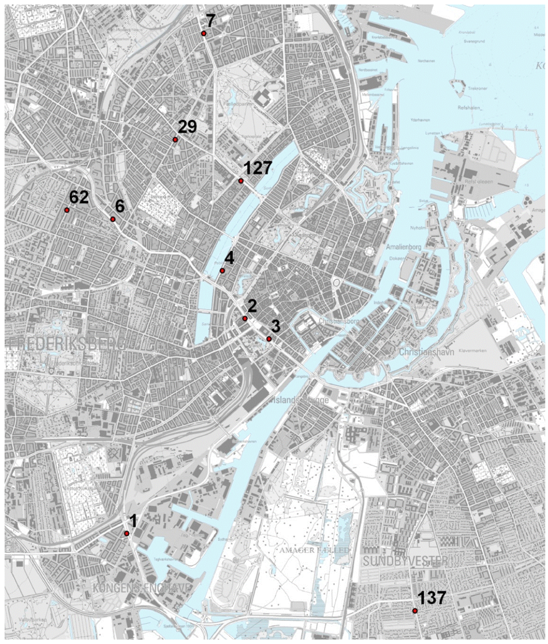

Figure 2: Location of the 10 measuring points in Copenhagen using passive samplers. The numbering of the street stations corresponds to the numbers in table 1 (“No. in 2010”).

Similarly, traffic data were originally obtained from a supposedly representative nearby traffic counting location, and later verified by closer analysis of all available traffic counts for several years and locations. Both original and verified traffic data are given in table 2.

The original model input data regarding geometry and traffic used in step 1 are identical with the data used in the annual reporting for the Danish Air Quality Monitoring Programme [13].

Meteorology and background concentrations

Meteorological and urban background data are required as input for OSPM and either measurements or model simulations are used in this work depending on the purpose of the evaluation as described below.

In each of the four cities where permanent street monitoring stations are located, urban background monitoring stations are operated, measuring as well urban background concentrations as meteorological parameters.

A part of this evaluation exercise aims at testing the performance of the OSPM as well as best available input data including emissions, measured urban background concentrations and measured meteorological variables. In Copenhagen the single urban background station is representative as background for one of the street stations (Jagtvej) while the second street station (H.C. Andersens Boulevard) experiences a slightly higher urban background concentration, which has been shown by model calculations. Therefore, for H.C. Andersens Boulevard 2 μg/m^3 for NO_2 and 3 μg/m^3 for NO_x are added to the measured urban background concentrations.

Since an urban background stations is only representative for certain parts of a city, model calculations at the regional scale and for the urban background are used in cases where street locations are distributed over a larger area. Moreover, these models are used in applications that aim at forecasting future pollution levels. In such cases OSPM uses input data from the meteorological model MM5v3 and air pollution concentrations from the Urban Background Model (UBM) [14]. This method is applied in parts of this evaluation and described briefly in the following.

OSPM calculations that are based on modelled background concentrations, use results from the THOR modelling system [24-27]. This is an integrated model system, capable of performing model calculations from regional scale (Hemispheric and European) to urban background scale and further down to individual street canyons in cities (http://thor.dmu.dk). The system includes the Danish Eulerian Hemispheric Model, DEHM (Christensen; Brandt et al.) [28,29] and the Urban Background Model, UBM [14] as well as the OSPM model. DEHM provides air pollution input data for UBM which again provides air pollution input data to OSPM. The emission inventories used in DEHM have a geographical resolution of 1 km×1 km for Denmark transformed into the 5.5 km×5.5 km resolution domain, covering Denmark, and 17 km×17 km the domain covering the northern parts of Europe. Further domains are included in DEHM, one covering Europe with a 50 km×50 km resolution and one covering the Northern hemisphere with a 150 km×150 km resolution. The emissions for

No. in 2010	City / Street name	Buildings on 1 or 2 sides	Street direction to north (º)	Street Width from AirGIS (m)	Street width from aerial photo/map (m)	Building height from Air GIS (m)	Building height from photo (m)
*	Aarhus / Banegaardsgade	2-sides	96º	14	14	17.7	18
*	Aalborg / Vesterbro	2-sides	24º	41	41	12	12
*	Odense / Albanigade	2-sides	135º	24	24	15	15
	Copenhagen /						
1	Sydhavnsgade	1-side		22	22	17.4	17
2	HC Andersens Boulevard(3)	2-sides		49	44	21.9	17
3*	HC Andersens Boulevard(1)	1-side	128º	68	50	21.8	30
4	Nørre Søgade	1-side		20	20	18.9	19
6	Ågade	1-side		32	32	15.1	15
7	Lyngbyvej(2)	2-sides		28	28	10.9	13
29*	Jagtvej(1)	2-sides	29º	25	25	21.9	22
62	Nordre Fasanvej(5)	2-sides		18	18	16	16
127	Fredensgade	1-side		65	30	0 (13.9)**	14
137	Englandsvej(2)	2-sides		38	38	5.7	10

Table 1: Street width and general building height, both for the original input data estimated with AirGIS and updated input data based on aerial photos, maps and photos. 'No. in 2010' gives the ranking of the street within the 138 street sections calculated for Copenhagen, with 1 being the highest.
* 5 street sections with long-term measuring stations
** The general building height was set to 0 and buildings were defined as exceptions.

No. in 2010	City / Street name	Speed (km/h)	ADT (veh/d) 2009	HD share (%) 2009	ADT (veh/d) 2011	HD share (%) 2011
*	Aarhus / Banegaardsgade	40	6 605	19.1	6 605	19.1
*	Aalborg / Vesterbro	32	28 710	4.1	28 710	4.1
*	Odense / Albanigade	45	20 800	4.9	20 800	4.9
	Copenhagen:					
1	Sydhavnsgade	41	48 700	4.7	25 000 (45 700)**	4.4
2	H C Andersens Boulevard(3)	41	52 600	3.9	48 200	3.5
3*	H C Andersens Boulevard(1)	45	58 050	3.9	51 500	4.7
4	Nørre Søgade	41	28 800	2.9	27 000	2.3
6	Ågade	51	57 000 (2007)	4.7	47 000	2.9
7	Lyngbyvej(2)	51	66 900 (2008)	2.5	65 600 (2010)	2.9
29*	Jagtvej(1)	42	23 500	3.1	23 500	3.1
62	Nordre Fasanvej(5)	40	15 600 (2007)	6.4	17 100 (2010)	5.1
127	Fredensgade	51	48 300	3.8	45 000	3.7
137	Englandsvej(2)	51	15 100 (2008)	6.4	13 200	2.5

Table 2: Average daily traffic (ADT), heavy-duty share in % and average travel speed. Values for 2009 are used in stage 1 and are based on information from the Municipality of Copenhagen in connection with a previous project [15]. Values for 2011 are based on latest traffic counts except for Jagtvej and HCAB, where detailed manual traffic counts from 2003 have been projected towards 2011. In cases with traffic data from earlier years the year is given in brackets. 'No. in 2010' gives the ranking of the street within the 138 street sections calculated for Copenhagen, with 1 being the highest.
*5 street sections with long-term measuring stations
**For Sydhavnsgade the traffic counts at Sjællandsbroen are not representative (45 700 vehicles per day), therefore a more realistic traffic volume has been estimated.

Denmark are based on Danish national emission inventories for the year 2010 compiled by Aarhus University (http://www.dmu.dk/luft/emissioner/emissioninventory) and international emission inventories for the year 2009 collected and distributed by EMEP (www.emep.int). Global emissions are used for the hemispheric domain (for further details) [29].

UBM calculates the urban background air pollution based on emission inventories with a spatial resolution of 1 km × 1 km and based on input data from DEHM concerning the regional background [14]. The emissions used in the UBM are based on the newly developed SPREAD model that spatially distributes national emissions from 2008 from all sectors on a 1 km x 1 km grid for Denmark based on different geographic variables [30]. More details about the model set-up can be found in Ellermann et al.[13].

Results and Discussion

Results for long-term measurements

This section presents validation results for a single year, 2010, as an example of an evaluation with a set of annual averages for several pollutants and for a larger number of years (1993-2010) for NO_x and NO_2 only. Finally, some examples of exploratory data analysis are presented using a newly developed tool.

According to the model quality objectives described in the Air Quality Directive (EC, 2008) [31] the maximum accepted annual average modelling uncertainty is ± 30% for NO_2 and ± 50% for PM_{10}. In table 3 we present annual averages of measured and modelled NO_x, NO_2, PM_{10} and $PM_{2.5}$ for 5 streets in 2010. All deviations between observed and modelled values for compounds with limit values or target values (NO_2, PM_{10}, $PM_{2.5}$) are within the required ±30% range. The largest deviation is observed in Aalborg where the model under predicts by 22% and 24% for NO_2 and $PM_{2.5}$, respectively. However, if we focus on NO_x (without air quality limits), the under prediction by the model appears to be more pronounced with deviations of 16% to 49%. The ratio between NO_x and NO_2 is obviously not the same in the model results and the measurements. The reason for this difference might be uncertainties in emission data, and especially in the fraction of direct NO_2 emissions (frac NO_2). This shows that just focussing on the annual statistics for the regulated compounds does not provide the full picture regarding the model performance. Model evaluation should be performed for all compounds for which reliable data are available and should furthermore include qualitative data analysis as described in the following section.

Results for several years of model runs at the different stations are given as annual averages in figure 3. For each station trends for both NO_x and NO_2 are given for modelled and observed street level concentrations, as well as the measured urban background concentrations that are used as input for the OSPM calculations. For NO_x a significant decrease in concentration levels can be observed at all stations. This trend is generally well reproduced by the model. At H.C. Andersens Boulevard in Copenhagen a significant increase in NO_x and NO_2 is observed from 2009 to 2010, probably due to emissions related to large on-going construction work close to the monitoring station and associated traffic changes unaccounted in the emission inventory. This additional source is not easy to quantify and has not been included in the model calculations. This has thus been concluded to be the explanation why model could not reproduce the observations in 2010.

For NO_2 the observed concentrations have been more or less constant over the past one to two decades, with a slight tendency for a reduction. Also this trend is in general well reproduced by the OSPM calculations. However, the model has a tendency to over-predict the observed NO_2 concentrations. Especially for the streets in Odense and Aarhus the OSPM results appear to be shifted by 5-10 µg NO_2/m^3 towards higher values. Possible explanations for this over-prediction are uncertainties in the traffic or emission input data, uncertainties in model parameters, (e.g. the NO=>NO_2 reactions rate) or possibly in the representativeness of the applied urban background data as representing urban background at the modelled street locations.

Regarding traffic and emissions, the most reliable data are available for the present situation, while historic traffic and emission data are much more uncertain. For the calculations presented here the historic traffic was assumed to be equal to current traffic (year 2010) on all stations. This assumption could be elaborated more and historic traffic counts should be incorporated in the model set-up when they are available. E.g. for the streets in Odense and Aarhus, the modelled NO_x is higher than measured in the first half of the calculation period while a good match is observed in the second half (Figure 3).

Another very efficient way to analyse the data and investigate the possible explanations for discrepancies between model results and measurements is the so-called exploratory data analysis using e.g. the previously mentioned newly developed tool (available from ospm.dmu.dk). The validation tool is based on MS Excel (version 2003) and is taking advantage of the plotting facilities, data analysis tools as well as macro language in Excel. It is a standard facility

Station name	Measurements		Model results		Relative difference	
	NO_x	**NO_2**	**NO_x**	**NO_2**	**NO_x**	**NO_2**
	µg/m³	µg/m³	µg/m³	µg/m³	(%)	(%)
Coph.-HCAB	133	56	88	51	-35%	-10%
Coph.-Jagtvej	86	39	63	39	-26%	-1%
Odense	75	32	63	35	-16%	12%
Aarhus	87	39	65	36	-25%	-8%
Aalborg	104	39	53	30	-49%	-22%
	PM_{10}	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**
	µg/m³	µg/m³	µg/m³	µg/m³	**(%)**	**(%)**
Coph.-HCAB	28,1	17,4	30,0	19,4	7%	11%
Coph.-Jagtvej	26,7	17,8	27,7	18,3	4%	3%
Odense	26,0	-	27,8	17,7	7%	-
Aarhus	24,8	15,3	23,8	15,5	-4%	1%
Aalborg	-	18,3	23,8	13,8	-	-24%

Table 3: Comparison of measurements and model results for five streets in four Danish cities adopted from Jensen et al. 2011 [15]. Annual averages for 2010 are given for NO_x, NO_2, $PM_{2.5}$, and PM_{10}. Calculations are carried out using the full Thor model calculation system including DEHM, UBM, and OSPM models. Coph.=Copenhagen; HCAB=H.C. Andersens Boulevard.

in OSPM that the output for several years and compounds may be directly saved in Excel file format (one sheet per year, separate files for each street), minimizing errors related to import, conversion and transfer of model data. After re-running the model, e.g. with a changed set of emission data, the plots and analysis of differences between the two model runs are available immediately.

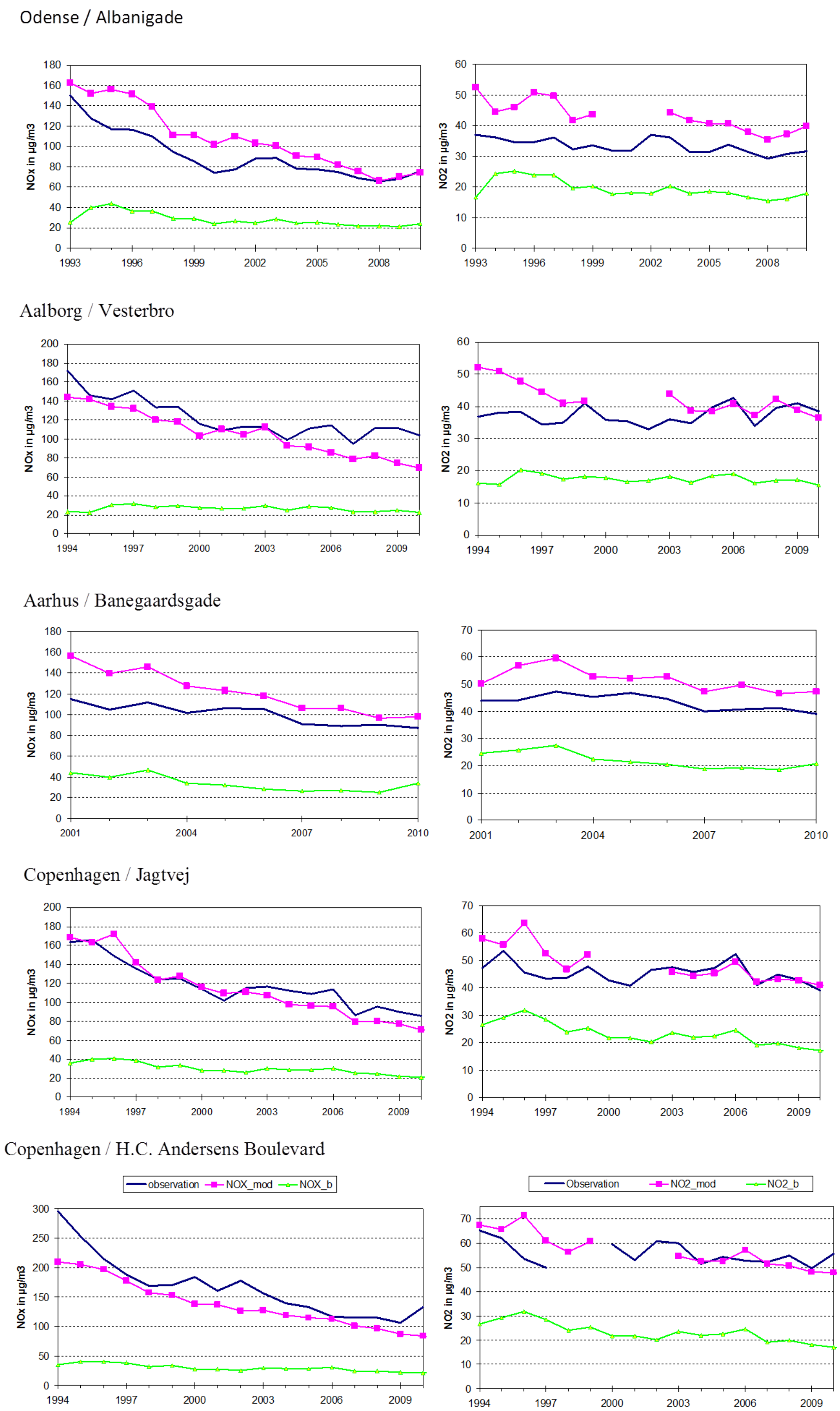

Figure 3: Trends in annual averages of NO_x (left column) and NO_2 (right column). Plotted are observed and modelled street concentrations as well as observed urban background concentrations between 1993 and 2010 for five street stations in Denmark.

The validation tool provides so far four types of plots for the parameters (NO_x, NO_2, frac NO_2, O_3, CO, PM_{10} and $PM_{2.5}$): (a) Time series plots of hourly values for background, measured and modelled concentrations. (b) Scatter plots of hourly values, point by point, measured versus modelled (for one year at the time). (c) Plots of aggregated data showing the measured and modelled concentrations as function of essential parameters like wind direction, hour of the day and month (for one year at the time). (d) Trend plots for annual averages for all calculated years.

The validation tool has its strength in the exploratory data analysis and is therefore complementary to the Delta Tool developed at the JRC Ispra (http://aqm.jrc.it/DELTA). The Delta tool has its strength in calculating several statistical parameters at the same time for large datasets but in its present version lacks some user-friendly import functions and is less flexible in the exploratory mode.

Figure 4 gives an example of exploratory data analysis and the use of the validation tool. Shown are the observed and modelled concentrations as function of wind direction using data for one selected year. For the four streets with buildings on both sides of the street a clear reduction of the concentrations is visible for wind directions that bring the monitoring station in windward position. This is due to the well-know vortex- like flow pattern in the street canyon that transports less polluted urban background air towards the street monitoring station. The relevant wind directions can be easily identified by comparing figure 1 and figure 4 as 225° for Odense; 290° for Aalborg; 360° for Aarhus and 300° for Jagtvej. For H.C. Andersens Boulevard, with buildings on one side only, high concentrations are observed for all wind directions.

For certain type of errors (e.g. wrong building geometry or a strong non-traffic source, which is not accounted for in the model calculations) figure 4 would reveal large discrepancies between model and observations. This seems not to be the case here, the dependency on wind direction is generally well reproduced. Only for Aalborg the model overestimates for north-western wind directions (270°-360°) and under-predicts for north-eastern directions where there is a large NO_x point source (a cement factory). Since the problem seems to persist for other years (not shown here) the geometry set-up for street and buildings should be checked again.

Results for short-term measurements

This section presents results from the two evaluation stages conducted for the short-term measurements at 10 locations in Copenhagen, stage 1 with original input data and stage 2 with verified and updated input data.

The model calculations in stage 1 with original input data were conducted as 'blind test' i.e. without knowing the measured values. The results of measurements and model calculations are shown in figure 5. The expected typical uncertainty for the model calculations of about 15% is indicated in the plot.

The comparison for the two permanent measurement stations at both H.C. Andersens Boulevard and Jagtvej shows good agreement between the measurements provided by Force Technology using passive sampling and measurements from Aarhus University using the EU reference method. The results from the 'blind test' of OSPM at stage 1 (Figure 5) show that the OSPM calculations are in good agreement with the measurements for seven out of nine street sections. The model results show good agreement for all street sections with two

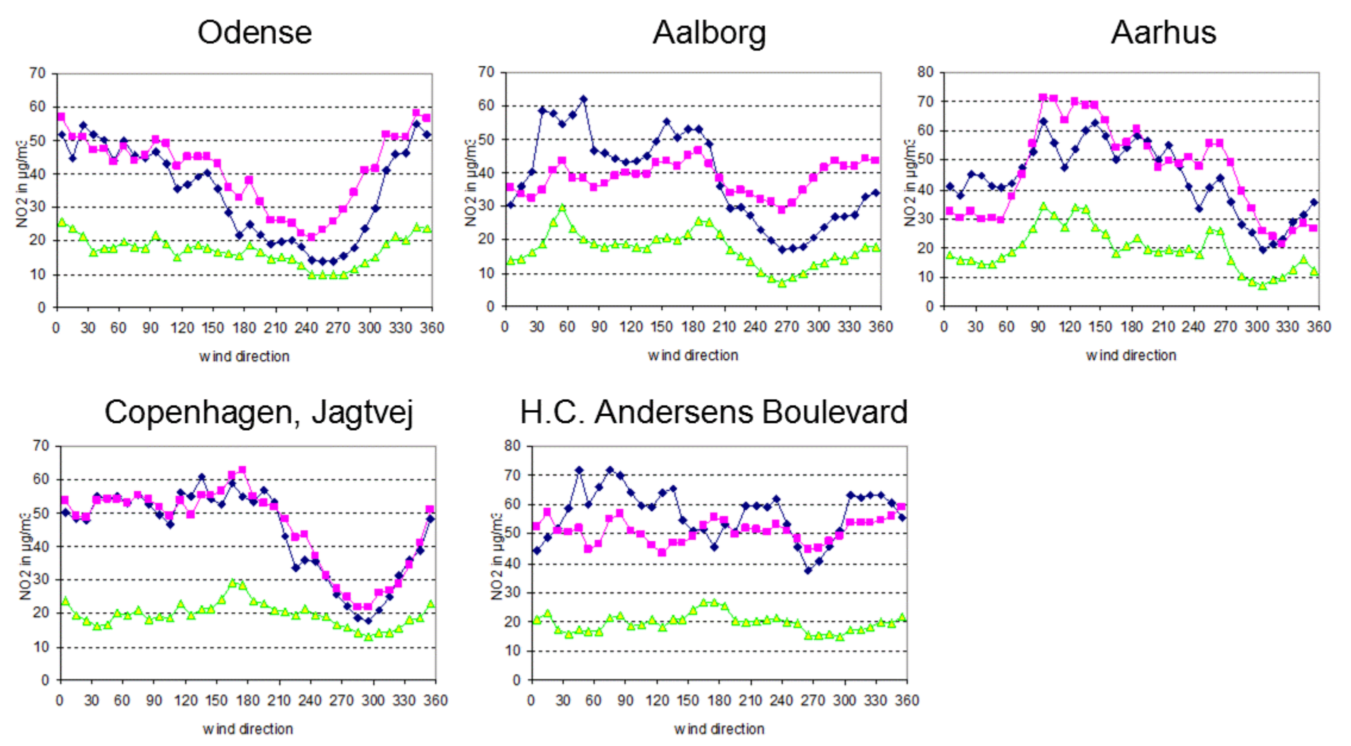

Figure 4: Observed (blue diamonds) and modelled (magenta squares) concentrations as function of wind direction. Plotted are aggregated data based on one full year of data (2007 or 2008, depending on which of them had the most data available). Urban background concentrations (green triangles) are shown as well for comparison.

No. In 2010	Street name	Measurements (5 weeks)	Model calculations Original Input	Model calcul. with updated Geometry	Model calcul. with updated Traffic+Geometry
1	Sydhavnsgade	38	59.7	59.7	48.8
2	H C Andersens Boulevard(3)	48	48.7	48.9	47.4
3	H C Andersens Boulevard(1)	52	47.1	52.7	52.0
4	Nørre Søgade		48.2	48.2	46.7
6	Ågade	48	46.5	46.5	42.7
7	Lyngbyvej(2)	45	43.8	42.4	42.4
29	Jagtvej(1)	47	41.1	41.2	41.2
62	Nordre Fasanvej(5)	35	33.1	32.8	33.1
127	Fredensgade	48	48	44.5	43.5

Table 4: NO_2 concentrations in µg/m^3 in the period October 24th to November 28th 2011. Results from measurements and model calculations with original input data (Stage 1) and with updated street geometry data and with updated geometry and traffic counts (Stage 2).

sided building facades. Large discrepancies between measurements and model results are found for two street sections (Sydhavnsgade and Fredensgade) both with one sided building facades. However, there are two other street sections with one sided building facades, where the model is in good agreement with the measurements. The discrepancies observed for Sydhavnsgade and Fredensgade are therefore not solely related to poor representation in the model of street sections with one sided building facades.

Moreover the quality of the model results essentially depends on the quality of the input data. The fact that a good agreement is achieved for seven out of nine streets indicates that the emission factors and dispersion parameters are in general reliable with respect to NO_2.

The reasons for the discrepancies between measured and modeled concentrations encountered at Sydhavnsgade and Fredensgade might potentially be found in the input data for street geometry, traffic volume and vehicle composition. Therefore we re-evaluated those input data in stage 2 in order to be able to analyze and determine the reasons for the discrepancies. In a first set of model calculations we modified the street geometry and later additionally the traffic data.

The original and updated street geometry are shown in table 1. For far most of the streets there are no or only small changes in the street geometry. The most significant changes in input data appear for HCAB (1) and Fredensgade, where the street width was too large in the original data. Both streets have buildings on only one side and here the AirGIS routine appears to be incorrect in estimating the street width, which is often not clearly defined in such cases. Furthermore there have been changes in building height at HCAB (1+3), Lyngbyvej, Englandsvej and Fredensgade.

The larges difference is seen for Fredensgade, where by mistake the general building height was set to 0 m, instead of the more correct 14 m. The general building height gives the average or typical height, while exceptions from this (gaps, lower or higher buildings) are defined separately.

Since OSPM used the general building height directly for estimation of several internal parameters, e.g. reaction or residence time of pollution inside the canyon, the conversion of wind speed at roof level to street level, it makes a significant difference whether the general building height is 0 m or 14 m.

The results with modified input data are shown in figure 6 and also given in table 4. The largest change due to update of street configuration (increase of 70%) is observed for Fredensgade, due to the changes in street width and general building height. For other street sections the changes are at maximum about 12%.

The original and updated traffic data are shown in table 2. There is a general trend for a reduction of the traffic volume from 2009 to 2011. For the heavy duty share there are 6 streets with a reduction and 2 streets with an increase of heavy duty share. The largest change is found for Sydhavnsgade where the original traffic data come from a not representative traffic counting location with significant more traffic (48700 veh/day) than expected at the measuring point (about 20-30000 veh/day) estimated based on traffic counts at other locations.

The available traffic counts are routinely performed during 12 hours (0700–1900) by Copenhagen municipality once a year at the defined fixed locations. This short counting period and the often encountered distance from the counting location to the actual measuring point leads to some uncertainty connected to the traffic input used for the OSPM calculations. Optimal would be to perform longer counts at the exact measuring location. However this was not possible in the frame of the project.

In 2003 detailed traffic counts were conducted close to the monitoring stations at HCAB (1) and Jagtvej over 24 hours on a working day and 12 hours during a weekend. This makes the data very reliable. Therefore this traffic variation has been adapted from 2003 to 2011 conditions based on the trends observed at other traffic counts nearby.

The traffic speed is an important parameter for emissions and should be carefully evaluated from measurements. However this was not possible in the frame of this work.

The results with modified traffic data are also shown in figure 6 and in table 4. The largest changes due to update of traffic data are observed at Sydhavnsgade (reduction in NO_2), and at Ågade (4 µg/m^3 reduction). For other street sections the changes are all smaller than 2 µg/m^3.

Conclusion

In this paper, the Operational Street Pollution Model (OSPM) has been evaluated with continuous measurements over a long period for five permanent street monitor stations and passive measurements with long averaging times at nine locations in Copenhagen. Results are discussed in relation to the quality objective within the EU Air Quality Directive and general uncertainties in model parameters and model input data.

An easily applicable evaluation tool to facilitate the qualitative analysis of large datasets has been applied for analysis of OSPM calculations at five permanent stations. The model is able to reproduce the basic dependencies of concentrations on meteorological parameters as wind direction and wind speed. However, in some cases the annual trends of NO_x and NO_2 are slightly different between

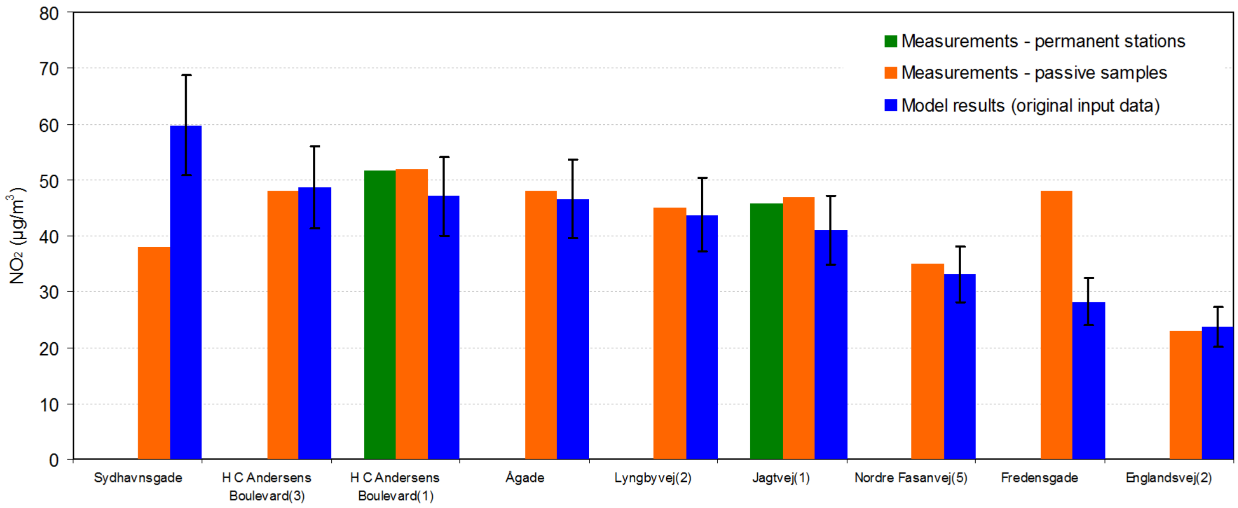

Figure 5: Results of measurements and model calculations (Stage 1 – original data). NO_2 concentrations at selected streets in the period October 24 to November 28 2011. The error bars indicate the estimated uncertainty of 15%. Since no measurements exist for Nørre Søgade, the street was skipped in the graph.Results from the permanent measurements at H.C. Andersens Boulevard (1) and Jagtvej (1) are plotted as well.

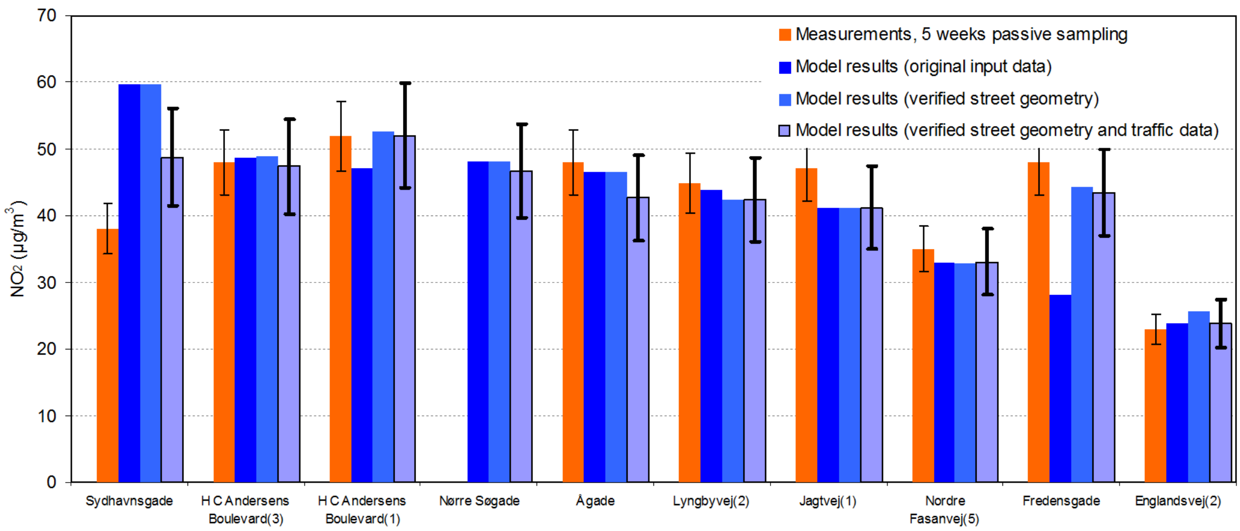

Figure 6: Results of measurements and model calculations (both with original data and with updated geometry and traffic counts). NO_2 concentrations at selected streets in the period October 24 to November 28 2011. The error bars indicate the estimated uncertainty of 15% and 10% for model results and measurements, respectively.

model and observed concentrations. For NO_x the model reproduces the observations well especially for the latest years, while for NO_2 the model over-predicts for two cases. The explanation for this over-prediction is believed to be uncertainties in the traffic or emission input data, but also in model parameters, and the representativeness of the urban background data may play an important role.

In this context the new Excel evaluation tool can help the model developer/user to identify and systematically investigate the nature of discrepancies between model calculations and measurements. Reasons for disagreement could be manifold, e.g. shortcomings in the model itself, errors in the model input data (emission factors, traffic information, meteorological data etc.) and also errors in the measurements. The tool is available to the modeling community from the OSPM web page (OSPM.dmu.dk).

OSPM calculations for nine streets in Copenhagen with passive sampler measurements were conducted as 'blind test' i.e. without knowing the measured values. OSPM calculations were in good agreement with the measurements for seven out of nine street sections.

A detailed analysis showed that input data in some cases are far from representing the "real" world. There is therefore a need for improving the quality assurance of the input data.

OSPM calculations using modified input data on traffic and street configuration lead to insignificant changes in the calculated NO_2 concentrations for the main part of the selected street sections. For H.C. Andersens Boulevard (near monitoring station) and Ågade the improved input data lead to a 10% higher and 6% lower concentration, respectively. For Sydhavnsgade and Fredensgade the improved input data lead to larger changes in the calculated concentrations. These are the streets with the largest difference between measurements and model calculations.

Using the modified input data, the model calculations lead to results that are in agreement with the observations for eight out of nine street sections, where measurements have been carried out. The main difference between model and measurements are at Sydhavnsgade where the model calculation leads to an about 20% higher concentration than measured. Overall, the performance of the model is therefore satisfactory.

The difference between measurements and model result at Fredensgade is a result of incorrect input data concerning street configuration.

For Sydhavnsgade, the difference between measurements and model result is mainly due to incorrect traffic data as the true traffic level for this street is unknown due to lack of traffic counts and the traffic level for this was estimated based on traffic counts from nearby streets.

At H.C. Andersens Boulevard there may be larger discrepancies due to the impacts of the on-going construction work, which is not accounted for in the model. Hence, an additional evaluation of the model performance was carried out for the period 2003 to 2011. This evaluation showed that a scaling of the model input was necessary in order to obtain agreement between model and measurements for this period. Moreover, the model showed lower results than the measurements for 2010 and 2011. This may be explained by the extra contribution to the emissions due to construction work and associated traffic changes in the area around the measurement station. A similar trend in measurements was not seen on the other street station (Jagtvej), which was not influenced by construction work during the same period.

Based on the results from the project it is concluded that it is necessary to make minor adjustments in the procedures used to determine the street configuration for the street sections with one sided building facades. The general building height must not be set to very small values or even zero, also for streets with very few buildings. This should be checked by OSPM and the user given a warning if this is the case. Moreover, it would be advisable to repeat the passive sampler measurements and perform model evaluation for additional street sections with one sided building facades including Nørre Søgade, where the measurements unfortunately were lost in the present campaign. Finally, it would be advisable to improve the input data for traffic in order to reduce the uncertainties related to these data.

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