August 3rd, 2015

Dear Editor,

I am submitting the revised version of the manuscript entitled

“Analysis of the Impact of Inhomogeneous Emissions in the Operational Street Pollution Model (OSPM)”

authored by T.-B. Ottosen, C. Johansson, O. Hertel, J. Brandt, H. Skov, R. Berkowicz, T. Ellermann, S.S. Jensen, M. Ketzel and myself based on the editor’s and referees’ comments and recommendations. Herein I include:

- The point by point responses to the editor and the referees
- A marked up version of the manuscript
- The abstract of the manuscript, and
- A full version of the manuscript including tables and figures

I hope everything is as requested.

Thanking you very much, I remain

Sincerely yours

Dr Konstantinos E Kakosimos
Dear Dan Lunt,

Thank you for bringing our attention to the editorial of GMD. Below is a point-to-point response to your comments (original comments in regular font, authors reply in bold font):

“– All papers must include a section at the end of the paper entitled "Code availability". In this section, instructions for obtaining the code (e.g. from a supplement, or from a website) should be included; alternatively, contact information should be given where the code can be obtained on request, or the reasons why the code is not available should be clearly stated.”

The revised version will contain the section below entitled “Code availability”.

Code availability
Name of the Software: WinOSPM (Windows version of the Operational Street Pollution Model, OSPM)
Developer: Department of Environmental Science (ENVS), Aarhus University, Denmark
Contact address: Aarhus University, Department of Environmental Science
Frederiksborgvej 399, 4000 Roskilde, Denmark.
e-mail: ospm@au.dk
Operational System: Microsoft Windows 7 or later
Software requirements: None
Hardware requirements: At least 100 Mb free hard drive space and 1 Gb RAM
Program language: Visual Basic 6 combined with linked libraries written in Fortran 77
Availability and cost: WinOSPM is a commercial software requiring licensing. Information on the actual licensing conditions is given on www.au.dk/OSPM. A fully functioning 100 days evaluation version can freely be downloaded from this site.

“– All papers must include a model name and version number (or other unique identifier) in the title.”

The revised version of the article will be entitled: “Analysis of the Impact of Inhomogeneous Emissions in the Operational Street Pollution Model”.

Yours,
The Authors
Point-to-point response to comments by Stijn Janssen

We thank both the reviewers for their positive and constructive comments, and finding the article interesting and worthy of publication. We have carefully considered their suggestions and necessary changes have been made to the manuscript. Our detailed responses to their comments are provided below.

The authors have presented an interesting manuscript in which they describe the impact of an inhomogeneous emission scheme for the widely used street canyon model OSPM. After a brief theoretical description of the OSPM model and the way the inhomogeneous emissions are implemented, the updated model is tested with field data for two Scandinavian cases. Validation statistics are convincing and show that the improved model is able to better describe pollution dispersion from asymmetric emission sources in a canyon.

I can recommend publication once my comments below are properly addressed.

Specific comments

-P4, line 5-9: It is unclear why CO is mentioned here. CO is not discussed at all further on in the text. So clarify or remove the paragraph at all.

Upon a closer thought the section about CO should be removed. When validating air pollution models it can be a good idea to look at several species, but in this case it will only point to the validity of the emission model. Therefore it will be removed in the final version of the manuscript.

-P4, line 30: a multiplication factor of 4.2 is mentioned. This seems to be a very big factor to correct for a bias. Or this is a mistake, of the sever underestimation should be discussed in more detail.

The exact technical reason for the factor 4.2 is not known, but the important thing is that we know that we can correct for this bias. Firstly we have the manual checks of the number of vehicles in each lane, and then we have compared the counts reported by the Marksman counter with automatic camera recordings in a campaign during the fall of 2009. The automatic camera recordings are described in the manuscript, but we will add that we also compared the camera recordings and the Marksman counter and found excellent agreement using the factor 4.2.

-P5, line 13: Would be interesting to mention here already the differences in emission for uphill/downhill driving to have an idea about the size of the effect.

Since this article is not about emission modelling, the emissions are not presented. However, Gidhagen et. al. quotes other similar studies where the uphill emissions are 3-4 times larger than the downhill emissions. These studies will also be quoted here in the revised manuscript.

-P6, line 16: the mean value of 2.27 seems to be higher than the values in Fig. 2. Please check or clarify.

The number given in the text is the median value whereas the numbers in the figure are the mean weekly and diurnal variation in the mean value. This will be clarified in the final version of the article.
-P8, line 22: the statement “... from inside the recirculation zone...” seems to be incorrect when the recirculation zone covers the whole canyon? Please clarify.

When the recirculation zone covers the entire canyon both receptors are exposed to the emissions inside the recirculation zone, however, the windward receptor is only exposed to the recirculating contribution whereas the leeward receptor is exposed to both the direct and the recirculating contribution. This will be clarified in the text.

-P9, line 3: “h0, is the initial dispersion” seems to be a strange definition. It is at least a height. The height due to the initial dispersion?

The plume is assumed to disperse initially to the height h0 regardless of the spatial position in the canyon. The height of the emission plume will subsequently increase linearly above h0 downwind of the location of the source. H0 can thus be said to be the height of the plume in the wake of the cars. This will be clarified in the article.

-P9, line 27: it seems more logical to me to express the criteria “f_ext is greater than zero” as a function of “Theta_street”. Is this possible?

Yes. This means the definition rather than being “close to parallel” will be “Theta_street<45”

-P10, Eq 2: u_b is not defined.

U_street used to be called u_b in earlier versions of the model. This is a mistake in the manuscript and will be corrected in the final version.

-P10, Eq 9: it is unclear how the remaining parameters in the equation are defined. I believe they are completely fixed by the street geometry and the wind vector. Please mention this for the sake of clarity.

The remaining parameters will be defined in a table in the revised version.

-P10, end: after those two sections 3.1.1 and 3.1.2 it is still not fully clear from the equations why the leeward receptor in a canyon receives more than the windward site. A brief discussion summarizing the principle ideas of the OSPM formula would be very instructive. Not all readers are familiar with the Berkowicz et al paper.

This will also be added in the revised version.

-P11, Eq 10 -12: I’m confused here. The model user defines the W_i values based on street (lanes) geometry. But if the W_i bands do not match with the dynamic L_rec, x_esc,... values, the limits of the sum in Eq 10 -12 are not determined by the dynamics of the canyon flow (e.g. e_esc, x_end). This seems to be a fundamental issue in the new scheme. Or I still don’t fully understand the newly proposed scheme.

This is a good and valuable point. The limits created by the dynamics of the canyon flow (x_esc, L_rec etc.) are in the implementation treated like any other segment. In order to handle this, an “artificial segment limit” is inserted at these points. Subsequently the impact of the different “artificial” and user-defined segments can be calculated with the corresponding equation. This will be clarified in the revised version without going into too many calculation details.
-P11, line 26: Why does the integration length approaches zero for parallel wind? Can you make this visual in a figure?

It should say that this is only for a canyon with segments with zero emission at the sides. This will be illustrated with a figure.

-P14, line 15-17: It seems to me a poor argument that the bad performance is due to a previous calibration. Is this something that can be solved for this study?

In the present study the most up-to-date emission input for Jagtvej is used. This emission input is markedly different from the emissions used in previous validations of this model against this street. Previously some model parameters (e.g. fRoof) that had high degree of uncertainty were used to tune the model against the measurements. For this study, no further tuning of the model has been performed, since this would distract the focus from the inhomogeneous emissions. The poor model performance with the new emissions is an ongoing area of research and it was considered to be outside the scope of the present article to solve this issue as well.

-P14, line 22: Nothing is mentioned about the mismatch at 100. and 250-360. In general, this case Jagtvej is rather poorly discussed compared to the first one. Some more discussion about model performance would be welcome.

The mismatch at 100 is probably a result of a random error since this spike in the curve is not seen when comparing the wind direction for the full diurnal cycle. The mismatch at 250-300 has been reported in previous calculations and is caused by an opening in the street canyon at this wind direction. The cause of this deviation has not been examined before and was assessed to be outside the scope of the present study. These discussions will be added in the revised manuscript.

-P14, line 24: Please give a short introduction and motivation (1-2 lines) why the theoretical calculations are added to the analysis.

The theoretical calculations are added to illustrate the impact of inhomogeneous emissions alone without the confounding effects of the emission model, the aerodynamics of the street etc. This will be added to section 2.3

-Fig 5: An additional schematic figure comparable to Figure 5 but for another recirculation zone would be very useful to understand the general principles of OSPM. Not all readers will be familiar with the Berkowicz et al paper. Please also illustrate (if possible) the lengths x_start, x_end, x_esc, W. The definition of L_b in the caption is very unclear (it is the distance to the next corner, I suppose?).

This is a useful comment. We will improve Figure 5 and the description in Table 4 in the revised version.

-Fig 13: Complicated graph and difficult to analyse and understand. The authors could consider to only show 2 sets (e.g. 50/50 and 70/30) since the general trend for the other fractions is similar and does not add new information. Probably this will simplify the graph and result in a better interpretation.

The graph will be simplified in the revised version
- Fig 13, caption: the description of the setup of the theoretical exercise should be given in the text, not in the caption.

This will be corrected in the revised version.

- Fig 15 and Fig 15, caption: same comments as for Fig 13. Further, it is not fully clear what the difference is between solid and dashed line. I suppose leeward and windward, but this should be mentioned explicitly in the caption.

This will be corrected in the revised version.

- Table 4, caption: All definitions should be given in the text and not in the caption! Further, I notice that some of the symbols are mixed: eg. Theta and Theta_street although they refer to the same physical quantity, I suppose. Please make sure that only one consistent set of symbols is used throughout the text.

The definition of the lengths will be added to the table. There is a missing symbol for the street level wind direction (right now called theta). Moreover, there is a missing definition of theta_l. These will be corrected in the revised version.

- Table 4, x_start definition. As far as I understand x_start = 0 if h_r < h_0. If so, please include in the definition.

This will be corrected in the revised version.

Technical corrections

- P3, line 4: Clarify “this” in “… of this type of model...”. It is unclear to what model you refer.

This will be clarified in the revised version.

- P3, line 22: replace “Figure 1” by “Table 1”

In the word file and in the pdf on the webpage it says “table 1”

- P3, line 28-29: update reference to Sect. 0

In the word file and in the pdf on the webpage is says “section 3.2”

- P5, line 7: “classified” or “categorized” seems to be a more appropriate term than “harmonized”.

“scaled” is probably a better term. This will be used in the revised version

- P5, line 14-16: Sentence is difficult to understand. Please reformulate.

This sentence will be rephrased in the final version

- P5, line 21: update reference to Sect. 0
In the word file and in the pdf on the webpage is says “section 3.2”

-P9, line 1: should “receptor” not be replaced by “source” in this sentence?

No. What is meant is the distance from the receptor into the area source where a plume originating would reach the receptor height. This will be clarified in the revised version.

-P9, line 25: “parallel” should be replaced by “perpendicular”, I suppose?

No. The integration length is extended for parallel wind directions to account for the contribution to the lee side receptor from the segment outside the recirculation zone.

-Fig 1 & 2: add the location of the data set to the caption.

Both figures are data from Hornsgatan, Stockholm. This will be added to the captions in the revised version.
We thank both the reviewers for their positive and constructive comments, and finding the article interesting and worthy of publication. We have carefully considered their suggestions and necessary changes have been made to the manuscript. Our detailed responses to their comments are provided below.

The paper takes forward the well known OSPM model developed some 20 years go by allowing for some limited aspects of inhomogeneous emission geometry in a street canyon. Given the time lapse, it is surprising that the authors make little or no mention of studies of urban flows that have taken place during this period nor the improved understanding gained, nor, on the basis of this work what are the strengths and weaknesses of OSPM.

>> The paper is on implementing inhomogeneous emissions in OSPM, not a review of studies on urban flows and how these might be used to improve process descriptions/parameterizations in OSPM. This would make the paper too lengthy and distract the focus from the aim of the study on inhomogeneous emissions. To get an overview of studies on urban flow or strength and weaknesses of OSPM in particular, the reader is referred to the review paper mentioned in the introduction (Kakosimos et. al., 2010)

Overall the paper seems unambitious and quite limited in scope.
The correlations do not give confidence that there is much if any improvement over the original OSPM model.

>> Even it seems simple at first glance, introducing inhomogeneous emissions into OSPM requires substantial changes and re-thinking of the integration procedures in the model. We will not judge if this is ambitious or not, but just note that the result is a significant upgrade of the OSPM and for sure a highly requested upgrade by all the users of OSPM, which will lead to a much better scientific understanding of the concentration distribution in street canyons. We are aware that more complex descriptions of flow and dispersion in street canyons have been made but these are beyond the scope of this article. It should be noted that one of the main advantages of OSPM is that the model is fast and simple to operate and the aim is thus not to make an upgrade of the model to a version that would be more resource demanding.

Specific questions and comments:

- Under future work is stated: ‘At present the receptor is located at the wall of the street ....’ Obviously it would be much more useful if receptors could be located anywhere in the canyon. It needs to be clear earlier in the text where receptors can be located and why there are limitations in where they can be located.
The receptor point can be moved along the street canyon by adjusting the length to the respective end of the street canyon. The receptor height can likewise be adjusted. The receptor point cannot (at present) be moved in the crosswise direction, since this would require allowing a contribution from “the back” of the receptor. Such an option would require significant redesigning of the model and was therefore deemed outside the scope of the present work. Allowing the receptor to move away from the building walls will be a next step of the model development that also requires more experimental data that will first be available in the coming year.

At section 3.2 is stated ‘Introducing horizontal diffusion was deemed outside the scope of the present study’. Why?

Is it indeed possible to include horizontal diffusion neatly within the OSPM framework?

It is possible to implement a description of horizontal diffusion in the formulas of OSPM, however, it would require some significant reprogramming of the model plus development of a mathematical model for this. Implementing and validating this would therefore make the paper too long, and was therefore deemed outside the scope of the present study.

It’s also not clear why only two segments have been allowed for.

There is no limit on the number of segments the user can decide to split the street canyon into. The number two was chosen as a pragmatic limit, given the above limitations, in order to be able to validate the inhomogeneous emission scheme on its own. We will formulate this more clearly in the final version of the manuscript.
Analysis of the Impact of Inhomogeneous Emissions in a Semi-Parameterized Street Canyon Model the Operational Street Pollution Model (OSPM)

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Abstract

Semi-parameterized street canyon models, as e.g. the Operational Street Pollution Model (OSPM®), have been frequently applied for the last two decades to analyse levels and consequences of air pollution in streets. These models are popular due to their speed and low input requirements. One often used simplification is the assumption that emissions are homogeneously distributed in the entire length and width of the street canyon. It is thus the aim of the present study to analyse the impact of this assumption by implementing an inhomogeneous emission geometry scheme in OSPM. The homogeneous and the inhomogeneous emission geometry schemes are validated against two real-world cases: Hornsgatan, Stockholm, a sloping street canyon; and Jagtvej, Copenhagen; where the morning rush hour has more traffic on one lane compared to the other. The two cases are supplemented with a theoretical calculation of the impact of street aspect (height/width) ratio and emission
inhomogeneity on the concentrations resulting from inhomogeneous emissions. The results show an improved performance for the inhomogeneous emission geometry over the homogeneous emission geometry. Moreover, it is shown that the impact of inhomogeneous emissions is largest for near-parallel wind directions and for high aspect ratio canyons. The results from the real-world cases are however confounded by challenges estimating the emissions accurately.

1 Introduction

Semi-parameterized models as e.g. the Operational Street Pollution Model (OSPM®; Berkowicz et al. (1997)) have been frequently applied in cities around the globe over the last 20 years (Assael et al., 2008; Berkowicz et al., 1996; Berkowicz et al., 2006; Ghenu et al., 2008; Gokhale et al., 2005; Hertel et al., 2008; Kakosimos et al., 2010; Ketzel et al., 2012; Kukkonen et al., 2000; Vardoulakis et al., 2005). This type of model has the advantages of low input requirements and short execution times. This means that the model can cover many streets over long time periods due to its low computational demand.

In order to retain the low calculation time of these models, a number of simplifying assumptions have to be made. One assumption, present in e.g. OSPM, is that the emissions are distributed homogeneously over the street canyon in the full length and width of the canyon. However, real streets have traffic lanes with finite width and varying traffic loads, either permanently or as a function of time as e.g. rush hours. Moreover, they might have sidewalks or cycle lanes with no emissions or wide central reserves likewise without emissions. Modelling these situations as homogeneous emission will potentially overestimate one side of the street and underestimate the other side of the street. This has an influence on e.g. limit values, where one side of the street can exceed the limit value while the other doesn’t.

Sloping streets represent a natural case of inhomogeneous emissions in that vehicles driving uphill have a higher emission due to the increased engine load compared to vehicles driving downhill. Gidhagen et al. (2004) examined the measured NOx concentrations from a measurement campaign in Hornsgatan in Stockholm, Sweden; which has a slope of 2.3%, using a Computational Fluid Dynamics (CFD) model. It was shown that the model representation of the wind direction dependence of the concentrations compared to the wind direction dependence of the measurements improved by assuming an emission relationship of
between the uphill and downhill side of the road. This followed along a marginal improvement in the correlation between the model and the measurements. In Gidhagen et al. (2004), Kean et al. (2003) is also quoted for reporting markedly higher emissions for vehicles going uphill compared to vehicles going downhill, a feature also implemented in emission models like the Handbook Emissions Factors for Road Transport - HBEFA (www.hbefa.net).

Moreover, (Kakosimos et al., 2010) and Vardoulakis et al. (2007) suggested that an improvement in the applicability of this type of model semi-empirical street level air quality models could be achieved by implementation of an inhomogeneous emission geometry scheme.

The present study is therefore based on the following research question:

To what extend do the performance of street pollution models like OSPM improve as a result of moving from homogeneous emissions to inhomogeneous emissions, and how is this change influenced by the aspect ratio of the street and the inhomogeneity of the emissions?

The methods applied in the present study are explained in Sect. 2. This is followed by a description of how the concentrations are calculated based on respectively the homogeneous and the inhomogeneous emissions in Sect. 3. The results and discussion are placed in Sect. 4 and the conclusions are presented in Sect. 5.

2 Methods

To analyse the impact of inhomogeneous emissions in OSPM two real-world cases were selected as being representative for inhomogeneous emission geometry streets as found in urban areas. The two real-world cases were supplemented by a set of theoretical calculations to analyse the impact of inhomogeneity and aspect ratio on the results.

The two street canyons chosen to analyse the impact of inhomogeneous emissions were respectively Hornsgatan in Stockholm, Sweden and Jagtvej in Copenhagen, Denmark. The main characteristics of the two street canyons are summed up in Table 1.

Hornsgatan is an example of a sloping street canyon with the average slope being 2.3% (Gidhagen et al., 2004), and Jagtvej is diurnally inhomogeneous in that, depending on the time of day, there is more traffic in the northeast direction compared to the southwest direction. Both streets have two driving lanes in each direction (four lanes in total) plus non-
emitting areas at the sides. The non-emitting areas are however not modelled explicitly in the present analysis, since including this would require the implementation of horizontal diffusion in the model cf. the discussion in section 3.2.3.2. This task remains for future work.

In the analysis, the NO\textsubscript{x} concentrations were used since in OSPM the concentration of NO\textsubscript{2} is calculated based on the concentration of NO\textsubscript{x} and O\textsubscript{3}. Thus in order not to add the uncertainties from the chemistry in the analysis, the primary emitted tracer (NO\textsubscript{x}) is used. Moreover, previous studies (Ketzel et al. (2011); (Ketzel et al., 2012)) have shown that the emission and dispersion module implemented in OSPM have an acceptable performance for this species. The CO concentrations were not used since the accuracy of the COPERT-4 emission model, as implemented in OSPM, is not known for CO emissions in Denmark and the general levels are low, which means that the CO measurements are fraught with a large uncertainty (Ellermann et al., 2013).

The years 2007-2009 were chosen for Hornsgatan, since a ban on the use of studded tires was implemented in this street from 2010 and onwards, which probably effected the vehicle distribution. Modelling the influence of this was assessed to be complicated and outside the scope of the present study. For Jagtvej the two years 2003 and 2013 were chosen since traffic counts were performed next to the measurement station in these years. In order to assess the influence of inhomogeneous emissions, accurate traffic input is very important.

Both streets are part of routine air quality control monitoring programs and have been studied extensively in the past. One year of data from Hornsgatan were included in the Street Emission Ceiling Exercise (Larssen et al., 2007; Moussiopoulos et al., 2005; Moussiopoulos et al., 2004) and has thus been subject of a number of modelling studies (e.g. Denby et al. (2013a); Denby et al. (2013b); Johansson et al. (2009); Ketzel et al. (2007); Olivares et al. (2007)). The Jagtvej measurement station is part of the Danish air quality monitoring programme (Ellermann et al., 2013) and has likewise been the subject of extensive analysis (e.g. Ketzel et al. (2011); Ketzel et al. (2012); Silver et al. (2013)).

### 2.1 Emission modelling and measurements from Hornsgatan

The emission modelling for Hornsgatan uses the hourly automatic vehicle counts for the two driving directions on Hornsgatan. The vehicle counts were made using an inductive loop technology (Marksman 660 Traffic counter and Classifier, Golden River Traffic Ltd., UK). It
provides hourly mean total traffic counts, classification of vehicles based on the length of the vehicle, plus mean speed on a lane by lane basis. The automatic counts in the east inner lane were multiplied by 4.2 to compensate for a bias in the counting based on a manual counting check. The exact technical reason for this factor is not known. However, comparison between the Marksman counter and manual counts and between the Marksman counter and automatic camera recordings (Burman and Johansson, 2010) have confirmed the validity of this factor.

The vehicle distribution was modelled as the average weekly vehicle distribution based on vehicle classifications obtained by video number plate recognition in the fall of 2009 (Burman and Johansson, 2010). This ensured that the emission factors reflected the average weekly variation in vehicle distribution. All vehicle categories were modelled using HBEFA 3.2 (www.hbefa.net) except ethanol buses, which do not appear as vehicle category in HBEFA. These were instead modelled using the ARTEMIS emission model (Boulter and McCrae, 2007). The emission factors from ARTEMIS were scaled harmonized to a different set of velocities compared to HBEFA. In order to harmonize the two emission models, the emissions from ARTEMIS were linearly interpolated to match the travel speeds from HBEFA.

The emission factors from HBEFA version 3.2, were used for the emission modelling since this emission model includes the effect of slope on the emissions. The emissions were exported from this model for slopes of +/- 2% and +/- 4% and a linear interpolation to the slope of +/- 2.3%, as given by Gidhagen et al. (2004), was performed. In Gidhagen et al. (2004) “Tehran Emission Reduction Project” is cited for reporting uphill emissions being 3-4 times larger than downhill emissions. A significant emission difference between the North and South side of the street can therefore be expected.

The traffic flow situation (called ”level of service” in HBEFA) was modelled as a set of discrete categories. This was done by categorizing the individual hour based on the total number of vehicles in the hour—as measured by the automatic vehicle counts. The categorization was performed based on the scheme from the ARTEMIS model reprinted in Table 2.

In setting up OSPM, the street was divided into two emission segments of equal width, although the inhomogeneous emission scheme described in Sect. 3.2 allows for any number of segments, thus each segment covering two traffic lanes. The emissions were distributed over
both the lanes and the sidewalk since the modelling of sidewalks is not yet a feature of the model, cf. the discussion in Sect. section 3.23.2. The vehicle speed, used for the calculation of traffic-produced turbulence, was assumed equal to the mean speed between the two lanes comprising the segment.

The emission modelling for this streetHornsgatan was performed based on two approaches:

- An approach based on the hypothesis that the traffic on the individual lane can be modelled as half the total traffic, subsequently referred to as the “proportional” approach. The inhomogeneity thus only arises from the slope of the street. This approach is useful if directional- or lane divided traffic counts don’t exist for the street in question.

- An approach based on the modelling of inhomogeneous emissions based on traffic counts from the individual lane as described above. This approach is subsequently referred to as the “exact” approach.

The two approaches to emission modelling were subsequently compared.

NO\textsubscript{x} was simultaneously monitored on the northern and southern sides of the road with a commercial NO\textsubscript{x} chemiluminescence analyser (model 31 M LCD, Environment SA, France). Urban background concentrations were taken from an identical instrument at a monitoring station located on the roof of a building approx. 500 m east of the Hornsgatan street station. The roof level station is representative of the urban background and is not influenced by the emissions in any nearby street canyon.

To analyse if the emission distribution between the north side and the south side of the street can be modelled as a constant ratio, an analysis of measurements for near-parallel (± 30°) wind directions for the conditions of a minimum wind speed of 2 m/s was performed. It was hypothesized that the ratio between the measured concentrations corresponds to the proportions between the emissions. This assumption is of course violated as a result of horizontal dispersion in the street canyon, but this effect was disregarded.

As seen from Fig. 1, the distribution of concentration ratios between the northern and southern side of the street is skewed with the mode being around 1.2 and the mean value being 3.22.27. This result is not too far from the result presented by Gidhagen et al. (2004), that the emissions at the north side were three times as large as on the south side. Moreover,
the distribution is unimodal and has a relatively low standard deviation, which supports the assumption of an even traffic distribution between the north- and the south side of the street.

The hypothesis of a constant ratio distribution will be fortified if the ratio is not changing systematically with time.

The diurnal and weekly variation of the ratio is shown in Figure 2. As can be seen the values show no clear diurnal or weekly variation and thus the assumption of an even distribution of traffic, but inhomogeneous emissions due to the slope in the two directions, between the two segments seems valid.

2.2 Emission modelling and measurements from Jagtvej

Manual traffic counts next to the measurement station at Jagtvej were performed respectively in 2003 and in 2013. The traffic was counted in two directions on a weekday for 24 hours in 2003 and between 7am-7pm in 2013. The number of vehicles was split into a number of vehicle classes to provide the vehicle distribution. The emissions were modelled using the COPERT 4 model (EEA, 2009).

The diurnal vehicle speed profile for Jagtvej was based on a national study aiming to establish typical diurnal speed profiles for different types of urban streets (TetraPlan A/S, 2001) where the most representative for Jagtvej was chosen. Furthermore, average travel speed data were obtained from a recent national data set (http://speedmap.dk/portal) managed by the Danish Road Directorate. SpeedMap is based on GPS readings from vehicle fleets and provides travel speeds on all major roads in Denmark in a high spatial and temporal resolution. The average vehicle speed from 2011 was used to scale the diurnal profiles from the original study, and the velocity profile was assumed valid for both 2003 and 2013, since no information on the temporal development in vehicle speeds were available within the limits of the present study.

The emissions were subsequently distributed in two segments each covering half of the street width thus both covering the traffic lanes and the sidewalks. The choice of two segments was made since the traffic counts were only distributed into driving directions and not on the individual lane.

The NOx measurements at the east side of Jagtvej were performed continuously by chemiluminescence using NOx Aerodyne API instruments. The urban background
measurements were measured from a roof level measurement station approximately 500m from the street using similar instrumentation as the street level measurements.

2.3 Theoretical calculations

The resulting concentrations of inhomogeneous emissions as a function of street aspect ratio and emission inhomogeneity were calculated, using an Excel version of OSPM, for 360 wind directions with wind speed and total emission approximately similar to the average conditions for Hornsgatan in order to generate comparable results. The calculations were performed on a hypothetical street canyon with two emission segments each covering half the width of the street. Subsequently the aspect ratio and the emission inhomogeneity were varied over a reasonable interval.

3 Model description

In the following sections the currently applied homogeneous and the tested inhomogeneous emission dispersion schemes will be described. This section does not contain a complete description of the OSPM model, for this the reader is referred to e.g. Berkowicz et al. (1997). However, sufficient details will be provided to understand the modifications in the model regarding handling the emission geometry.

3.1 The homogeneous emission dispersion scheme

To illustrate the modelling principles of OSPM, a typical street canyon situation is illustrated in Fig. 3. OSPM calculates the concentrations \( C \) at the wall side of the street canyon as a contribution from the street canyon \( C_{\text{street}} \) plus a contribution from urban background concentrations \( C_{\text{bg}} \). The contribution from the street canyon is subsequently a sum of a direct contribution \( C_{\text{dir}} \) plus a recirculating contribution \( C_{\text{rec}} \) (Berkowicz et al., 1997):

\[
C = C_{\text{street}} + C_{\text{bg}}
\]

\[
C_{\text{street}} = C_{\text{dir}} + C_{\text{rec}}
\]

It is a fundamental assumption of the model that when the wind blows over a rooftop in a street canyon an hourly averaged recirculation vortex is always formed inside the canyon as illustrated in Fig. 3.
It is assumed that the ground level wind direction inside the recirculation zone is mirrored compared with the roof level wind direction, whereas outside the recirculation zone the wind direction follows the roof level wind direction as illustrated in Fig. 4.

The receptor at the leeward (1) side of the canyon is thus only exposed to a direct contribution from emissions inside the recirculation zone (unless the wind direction is close to parallel as described in Sect. 3.1.1) plus a recirculating contribution, and the windward receptor (2) is only exposed to a direct contribution from emissions outside the recirculation zone (Berkowicz et al., 1997) and to a from-diluted recirculating emissions from inside the recirculation zone (Ketzel et al., 2014). In the case where the recirculation zone occupies the whole street canyon, the leeward (marked with “1” in Fig. 5) side of the canyon will be exposed to both a direct and a recirculating contribution, whereas the windward receptor (marked with “2” in Fig. 5) will only be influenced by the recirculating contribution.

3.1.1 The direct contribution:

The direct contribution can be written on integral form as (Hertel and Berkowicz, 1989):

\[ \int_{x_{\text{start}}}^{x_{\text{end}}} \frac{dC_{\text{dir}}}{dx} \, dx = \frac{2}{\pi W \sigma_w} \int_{x_{\text{start}}}^{x_{\text{end}}} \frac{1}{u_{\text{street}} h_0} \, dx \] (3)

Where \( C_{\text{dir}} \) is the direct contribution, \( x_{\text{start}} \) is the distance from the receptor where the plume has the same height as the receptor, which can also be zero in case \( h_r \leq h_0 \), and \( x_{\text{end}} \) is the upper integration limit as defined in Table 3, \( h_0 \) is the height of the plume in the wake of a car (usually termed the “initial dispersion”), \( h_r \) is the height of the receptor (the height of the calculated concentration), \( Q \) is the emission flux (in g m\(^{-1}\) s\(^{-1}\)), \( W \) is the width of the street, \( u_{\text{street}} \) is the street level wind speed, and \( \sigma_w \) is the vertical turbulence flux calculated as a function of the street level wind speed and the traffic produced turbulence.

The integration is performed along a straight line path against the wind direction as illustrated in Fig. 5. Equation (3) is used for calculating the direct contribution on both the leeward side and the windward side; however, the length of the integration paths can differ likewise as illustrated in Fig. 5.

In Fig. 5, it is assumed that \( x_{\text{end}} = L_{\text{rec}}, \) the length of the recirculation zone, however, as shown in Table 3, this need not be the case.
\( L_{\text{rec}} \) as a function of the upwind building height \((H_u)\) and the shortening function \((f_{\text{red}})\) is defined in Table 4.

For very long street canyons the plume will start dispersing out of the canyon at the top. In OSPM, this is assumed to happen when the plume height \( \sigma_z \) equals the general building height \((H_g)\) (Ketzel et al., 2014) of the canyon. This point is called \( x_{\text{esc}} \) and is defined as

\[
x_{\text{esc}} = \frac{u_{\text{street}}(H_g - h_0)}{\sigma_w}
\]

Where \( H_g \) is the general building height of the canyon.

Beyond the point \( x_{\text{esc}} \) the contribution to the concentration at the receptor is assumed to decay exponentially with distance according to (Hertel and Berkowicz, 1989):

\[
\int_{x_{\text{esc}}}^{x_{\text{end}}'} \frac{dx}{dx} = \sqrt{\frac{2}{\pi}} \int_{x_{\text{esc}}}^{x_{\text{end}}'} \frac{Q}{u_{\text{street}} W H_g} e^{-\frac{\sigma_{wt}}{H_g u_{\text{street}}}(x - x_{\text{esc}})} \, dx
\]

Where \( \sigma_{wt} \) is the roof level turbulence, and \( x_{\text{end}}' \) is the upper limit of the integral as defined in Table 3. The calculations and definitions of the critical lengths \( x_{\text{start}} \), \( x_{\text{esc}} \), \( L_{\text{rec}} \), and \( L_{\text{max}} \) are summed up in Table 4.

For close to parallel wind directions the integration length \( (x_{\text{end}}) \) for the leeward side receptor (marked with “1” in Figure 5) is extended from \( L_{\text{rec}} \) to \( L_{\text{max}} \) to account for concentration resulting from emissions outside the recirculation zone. The calculation of \( L_{\text{max}} \) as a function of the street width \((W)\), the wind direction with respect to the street axis \((\theta_{\text{street}})\), and the length to the end of the canyon is defined in Table 4. The integration This is done extended when the factor \( f_{\text{ext}} = \theta_{\text{street}} \) is greater than \( \text{zero} \). and the contribution to the concentrations from the path outside the recirculation zone is then multiplied by \( f_{\text{ext}} \)

(Hertel and Berkowicz, 1989):\(^1\)

\[
f_{\text{ext}} = \cos(2f_{\text{red}}\theta_{\text{street}}) \quad f_{\text{red}} = \begin{cases} 1 & u_{\text{street}} > 2 \frac{m}{s} \\ \sqrt{0.5u_{\text{street}}} & u_{\text{street}} < 2 \frac{m}{s} \end{cases}
\]

\(^1\) In Hertel, O. and Berkowicz, R.: Modelling Pollution from Traffic in a Street Canyon. Evaluation of Data and Model Development., National Environmental Research Institute, 1989. \( f_{\text{red}} \) is defined as \( f_{\text{red}} = 0.5u_{\text{street}} \) for \( u_{\text{street}} < 2 \frac{m}{s} \). This has subsequently been changed to \( f_{\text{red}} = \sqrt{0.5u_{\text{street}}} \) for \( u_{\text{street}} < 2 \frac{m}{s} \).
(6) Where $\theta_{\text{street}}$ is the angle between the street and the street level wind direction.

### 3.1.2 The recirculating contribution

The recirculating contribution is parameterized as a box model, where it is assumed that the inflow of pollutants equals the outflow of pollutants as illustrated in Figure 6.

The inflow of pollutants is the emission density in the street multiplied by the integration length $L_{\text{base}}$ (Berkowicz et al., 1997):

$$Q_{\text{in}} = \frac{Q}{W} L_{\text{base}}$$  \hspace{1cm} (7)

Where $L_{\text{base}} = \min(L_{\text{rec}}, L_{\text{max}})$. The recirculation zone is modelled as a trapezium with the upper length being half of the baseline length. The outflow from the box model is thus the ventilation at the top of the recirculation trapezium ($\sigma_{\text{wt}} L_{\text{top}}$) plus the ventilation at the hypotenuse of the trapezium ($\sigma_{\text{hyp}} L_{\text{hyp}}$) as illustrated in Figure 6 (Berkowicz et al., 1997):

$$Q_{\text{out}} = C_{\text{rec}} (\sigma_{\text{wt}} L_{\text{top}} + \sigma_{\text{hyp}} L_{\text{hyp}})$$  \hspace{1cm} (8)

Where $C_{\text{rec}}$ is the recirculating concentration contribution and $\sigma_{\text{hyp}}$ is the average turbulence at the hypotenuse. Equations 7–(7) and 8–(8) can now be solved for the recirculating concentration by setting the inflow equal to the outflow:

$$C_{\text{rec}} = \frac{Q}{\sigma_{\text{wt}} L_{\text{top}} + \sigma_{\text{hyp}} L_{\text{hyp}}}$$  \hspace{1cm} (9)

### 3.1.3 Summarizing the dispersion module in OSPM

For regular street canyons (height to width ratio close to one) the recirculation zone will occupy the majority of the canyon. This means that, for a large wind direction interval, the integration length for the leeward receptor will be significantly longer than the integration length for the windward receptor. Furthermore the leeward receptor will be exposed to the full recirculating contribution, which will only to a minor extent influence the windward receptor only receives a further diluted recirculating contribution. These two effects mean that the leeward receptor will experience significantly higher concentrations than the windward receptor for a large wind direction interval.
3.2 The inhomogeneous emission dispersion scheme

In order to facilitate the modelling of streets with inhomogeneous emission distributions, the street was divided into a number of parallel segments as illustrated in Fig. 7. The model user will define the width and the emission strength of each segment. At run-time the model calculates a variable number of several distances generated by the flow \( L_{\text{rec}}, x_{\text{esc}} \) etc. that depend on wind flow conditions. The user-defined emission segments are subsequently split into one or more segments with constant emission at these points distances. This means that the above presented integrals become divided into a number of integrals and subsequently summed to yield the final concentration. The direct contribution thus becomes:

\[
\int_{x_{\text{start}}}^{x_{\text{end}}} \frac{d c_{\text{dir}}}{dx} dx = \frac{2}{\sqrt{\pi} \sigma_w} \sum_{i=n_{\text{start}}}^{n_{\text{end}}} \frac{Q_i}{W_i - W_{i-1}} \int_{W_i - W_{i-1}}^{W_i'} \frac{1}{\sigma_w} dx
\]  

(10)

Where \( n_{\text{end}} \) is the segment number of the last segment influencing the receptor, \( n_{\text{start}} \) is the first segment to influence the concentration at the receptor, \( W_i \) is the accumulated width of the segment calculated from the receptor, and \( W_i' \) is the accumulated width of the segment calculated along the integration path from the receptor. The segments defined by \( W_i \) and \( W_i' \) can be either user-defined or dynamically generated.

The exponentially decaying concentration contribution from segments further away than \( x_{\text{esc}} \) from the receptor becomes:

\[
\int_{x_{\text{esc}}}^{x_{\text{end}}} \frac{d c_{\text{dir}}}{dx} dx = \frac{2}{\sqrt{\pi} \sigma_w} \sum_{i=n_{\text{start}}}^{n_{\text{end}}} \frac{Q_i}{u_\text{street}(W_i - W_{i-1})H} \int_{W_i - W_{i-1}}^{W_i'} e^{-\frac{\sigma_{\text{wt}}}{H_\text{street}}(x-x_{\text{esc}})} dx
\]  

(11)

The recirculating contribution becomes:

\[
C_{\text{rec}} = \frac{1}{\sigma_{\text{wt}}L_{\text{top}} + \sigma_{\text{hyp}}L_{\text{hyp}}} \sum_{i=n_{\text{start}}}^{n_{\text{end}}} \frac{Q_i}{W_i - W_{i-1}} (W_i' - W_{i-1})
\]  

(12)

In the homogeneous emission scheme the limits of the integrals are determined by the street geometry and the recirculation zone geometry. In the inhomogeneous scheme the limits of the integrals are always \( W_i - W_{i-1} \) and \( W_i' \). Instead the limits of the sum determine which segments contribute to the concentration at the receptor.

As seen from the lack of \( y \)-dependence in Eq. (33) and (10), the model does not contain expressions for horizontal dispersion. In the original model this was unnecessary since
the emissions were homogeneous in the entire canyon. In order to model sidewalks or similar segments with zero emission, horizontal dispersion has to be implemented in the model. This is the case due to the geometry of the canyon with zero emission segments on the sides, meaning that as the wind direction approaches parallel, the integration length quickly approaches zero thus leading to zero concentration as illustrated in Fig. 7. Introducing horizontal dispersion in OSPM was however deemed outside the scope of the present study. In the following cases the streets are therefore divided into segments covering both the traffic lanes and the sidewalks. It would be possible to divide the street into more segments to model the individual traffic lanes. However, either the emission of the inner lane had to be distributed over the sidewalk as well, leading to a too low emission density, or the two lanes would have to be of equal width meaning that the segment division would not correspond to the traffic lane division. To avoid these methodological difficulties, it was decided to model the streets as two segments.

4 Results and discussion

4.1 Hornsgatan

The correlation coefficient ($R^2$), the Fractional Bias (FB), and the Normalized Mean Square Error (NMSE) for the homogeneous and the exact- and proportional inhomogeneous schemes at Hornsgatan for the years 2007-2009 are shown for the North side receptor in Table 5 and for the South side receptor in Table 6.

As can be seen from Table 5 and Table 6, there is a noticeable change in the performance of the model when moving from homogeneous emissions to inhomogeneous emissions, but only very little between the two approaches for modelling inhomogeneous emissions. This confirms the assumption made in Sect. 2.1 that the emission distribution at Hornsgatan is not, to any significant extend, influenced by diurnal variations. It is also noticeable that the increase in performance is especially pronounced for the North side receptor where the FB is markedly improved and the NMSE is improved as well. For the South side receptor a smaller improvement is seen in FB. Conversely, moving from homogeneous emissions to inhomogeneous emissions has almost zero impact on the correlation coefficient on both sides and only a smaller effect on the NMSE on the north side.
The results are, however, confounded by the modelled street level contributions to the concentrations decline whereas the measured concentrations are almost stable. This effect is especially seen on the North side receptor and to a smaller extend on the South side receptor. This effect can most likely be ascribed to the emission model performance, since the effect is time dependent, and no interannual change in wind speed or direction is found (data not shown). Most likely the emission model is predicting too optimistic reductions for the modern EURO 5/6 vehicles that are not abstained under real-world driving conditions as reported in literature (Carslaw et al., 2011) This is also underlined by the fact that the traffic counts from the inductive loop technology matches fairly well with the camera recordings from 2009. The camera recordings were done over three months where individual cars were identified and compared with register data (Burman and Johansson, 2010). This means that the total traffic counts must be considered reasonably accurate. Since the vehicle distribution for the year 2009 is known very accurately from the camera recordings, this is probably not the explanation either. This leaves a change in traffic flow situation (levels of service) or a difference between the actual and modelled vehicle fleet; in terms of age composition, emissions as a function of slope, or other factors; over time as possible explanations for this discrepancy.

The wind direction dependency of the concentrations is shown in Fig. 8. As can be seen, the impact of moving from homogeneous emissions to inhomogeneous emissions is largest for parallel wind directions, where each receptor is only exposed to one emission segment. For perpendicular wind directions there is a small difference when the uphill emissions are close to the North side receptor and no difference when it is further away. A similar pattern is seen for the South side receptor with 180° displacement. The wind direction plot shows a noticeable discrepancy between the model and the measurements around 200° for both receptors. Gidhagen et al. (2004) states that horizontal dispersion is underestimated in the applied κ-ε CFD model, and that this is the cause of this discrepancy. If this is the case the underestimation will also appear in the present wind direction plots due to the lack of horizontal dispersion in OSPM.

The weekly variation in concentrations is shown in Fig. 9. The general diurnal variation plus the difference between weekdays and weekends are reproduced well by the model. As can be seen, the two approaches to inhomogeneous emission modelling are almost indistinguishable. It can also be seen from the figure that the impact of inhomogeneous
emissions is largest during day time where the concentrations are largest. Figure 9 shows as well that the diurnal variation is not reproduced in detail. On the north side, the morning rush hours and the evening hours are still underestimated, whereas the nighttime concentrations are underestimated. Moreover, the figure indicates a faster diurnal change in the modelled concentrations as compared to the measured concentrations. This probably has to do with the way the traffic flow situation is modelled as four discrete categories, whereas real traffic will behave like a continuum. This is a potential area of improvement for a future study.

Certain times of the week are also clearly wrong most noticeably Saturday afternoon on the north side receptor and Saturday morning on the south side receptor. This is likewise a potential area of improvement in a future study.

### 4.2 Jagtvej

The diurnal variation in personal cars and emissions for the two driving directions is shown in Fig. 10. As can be seen the emissions follow the variation in personal cars fairly close. The deviations between the variations in emissions and number of cars can be explained by the diurnal variation in heavy duty vehicles. As can be seen, the largest inhomogeneity arises between North and South direction in the morning rush hour. Moreover, it can be seen the plots show that the traffic and the corresponding emissions have declined substantially from 2003 to 2013.

The diurnal variations in measured and modelled concentrations for weekdays for the two years are shown in Fig. 11. As can be seen, expected, the change from homogeneous to inhomogeneous emissions only has a small influence on the concentrations around rush hour from 8-9 am, where also traffic is inhomogeneous. Here the difference between the homogeneous and the inhomogeneous emissions is relatively small, approximately 6 ppb. As also seen from the graph, the model tends to overestimate the emissions in 2003, whereas the 2013 emissions seem fairly correct. The poor model performance for 2003 has to do with the way the model has previously been calibrated to match the measurements. This means that the emissions used in the present study are markedly different from the emissions used when the model was designed. Adapting the model to the new emissions was deemed outside the scope of the present study and an area of improvement for a future study.
The average concentration as a function of wind direction for the morning rush hour for the two years is shown in Fig. 12. As can be seen, the difference between the homogeneous and the inhomogeneous emission is approximately homogeneously distributed among the different wind directions with difference up to 7 ppb. When averaging over the two years, the emission biases equilibrate each other, and gives a clearer picture of the wind direction dependency. When looking carefully at the graph it can be seen that the difference in concentration between homogeneous and inhomogeneous emissions is slightly larger for parallel compared to perpendicular directions. The spike in the measurements around 100 degrees is likely a result of a random error, since this spike is not seen in the data for the full diurnal cycle (data not shown). Both the homogeneous and the inhomogeneous emission model have difficulties capturing the measurements from approximately 260° degrees to 360° degrees. From 290 to 345 there is an opening in the street canyon and the difficulties of the model to capture this phenomenon was reported in an earlier study (Ottosen et al., 2015). It was thus deemed outside the scope of the present study to develop a solution to this issue as well.

4.3 Theoretical calculations

A set of theoretical calculations were performed to clearer illuminate the impact of inhomogeneous emissions without the confounding variables influencing the results of the real street canyons. The calculations are performed with a wind speed of 3.5 m/s, total emissions of 250 μg/m, and no urban background concentration. These conditions are corresponding approximately to the average conditions at Hornsgatan. The results of the theoretical analysis of the concentration dependency of the emission inhomogeneity are shown in Fig. 14. As can be seen, the larger emission difference between the two segments also results in a larger difference in concentration. As earlier shown for Hornsgatan, the largest difference is seen for near-parallel wind directions. However, bearing in mind the scale of the y-axis, the differences are small. The inhomogeneity at Jagtvej corresponds to approximately 10 ppb and for Hornsgatan to approximately 20 ppb, orders of magnitude also confirmed by Fig. 8 and Fig. 12. The comparison with measurement will however give a smaller difference, since the real world data are averages of many different wind speeds and emissions.
The impact of the street canyon aspect ratio on the concentrations resulting from inhomogeneous emissions is shown in Fig. 14. As seen, the impact is largest for high aspect ratio (building heights larger than street width) canyons. This is natural - expected, since “the street canyon effect”, where the impact of the recirculation zone means larger concentrations for the leeward side compared to the windward side, is larger for high aspect ratio canyons. As such, the impact of inhomogeneous emissions will also be larger for high aspect ratio canyons.

5 Conclusions

The present study presented an approach to, and analysed the impact of, implementation of inhomogeneous emissions in a semi-parameterized street canyon model (OSPM). The results were validated against two real world data-sets: One being inhomogeneous as a result of the slope of the street and the other being inhomogeneous as a result of inhomogeneous directional traffic during rush hours. Moreover, the impact of emission inhomogeneity and street aspect ratio was analysed theoretically.

The results showed that the model including inhomogeneous emissions were better able to reproduce the measured values on the two real-world streets. The impact of the inhomogeneous emissions was largest for the sloping street and the largest effect was seen for near-parallel wind directions. The results for both streets were however influenced by other factors as well, most likely uncertainties in the emissions, which led to less clarity in the results. Overall the adoption of inhomogeneous emissions leads to a performance increase of up to 15% in fractional bias at the north side receptor of Hornsgatan and a difference in street level contribution of up to 8 ppb. For Jagtvej the difference was shown to be up to 7 ppb in the morning rush hour.

6 Future work

The present study showed a potential for obtaining an improvement in model performance by introducing inhomogeneous emissions in models like OSPM. Two model elements are of immediate interest in relation to the present work:

- At present the receptor is located at the wall of the street. In reality measurement stations are often located several meters from the wall leading to a shorter dilution of the emissions and thereby a higher concentration. Being able to move the receptor
freely in the cross-canyon direction could potentially lead to a model performance
improvement.

- At present the model does not facilitate the inclusion of zero emission segments such
  as pedestrian areas. As described in section Sect. 3.2, this means that an accurate
description of a road like Hornsgatan, where traffic counts exist for all four lanes, is
not yet possible. Introducing horizontal dispersion in the model will thus potentially
make it possible to describe streets like Hornsgatan more accurately.

**Author contribution**

T.-B. O., M.K, K. K., C. J., R.B., O. H., and J. B. participated in setting up the study concept
and the study design was done by T.-B. O., M.K, K. K., C. J., and R.B. T. -B. O. did the
implementation of inhomogeneous emissions in OSPM with input from M. K. and K. K. T.-B.
O conducted the data analysis with contributions to analysis and interpretation from M. K., K.
K., and C. J. C. J. furthermore provided access to data from Hornsgatan and T. E. provided
access to data for Jagtvej. S. S. J. provided input on the traffic profile for Jagtvej. H. S. and K.
K. obtained funding for the study. T.-B. O. wrote the article manuscript. All the co-authors
participated in the interpretation of the results, provided critical comments to the manuscript,
and read and approved the final manuscript.

**Code availability**

Name of the Software: WinOSPM (Windows version of the Operational Street Pollution
Model, OSPM)

Developer: Department of Environmental Science (ENVS), Aarhus University, Denmark

Contact address: Aarhus University, Department of Environmental Science
Frederiksborgvej 399, 4000 Roskilde, Denmark.

e-mail: ospm@au.dk

Operational System: Microsoft Windows 7 or later

Software requirements: None

Hardware requirements: At least 100 Mb free hard drive space and 1 Gb RAM

Programming language: Visual Basic 6 combined with linked libraries written in Fortran 77

Availability and cost: WinOSPM is a commercial software requiring licensing. Information
on the actual licensing conditions is given on www.au.dk/OSPM. A fully functioning 100 days
evaluation version can freely be downloaded from this site.
References


Carslaw, D. C., Beevers, S. D., Tate, J. E., Westmoreland, E. J., and Williams, M. L.: Recent evidence concerning higher NOx emissions from passenger cars and light duty vehicles, Atmospheric Environment, 45, 7053-7063, 2011.


Ketzel, M., Hertel, O., Ottosen, T.-B., Kakosimos, K., and Berkowicz, R.: Validation of New Parameterisations for the Operational Street Pollution Model (OSPM). In: Proceedings of Abstracts 9th International Conference on Air Quality - Science and Application, University of Hertfordshire, Hatfield, United Kingdom, 2014.


Vägverket and SMHI: Dokumentation ARTEMIS i SIMAIR, Vägverket och SMHI, 2007.
Histogram of ratio between concentrations
Figure 14: Histogram of ratio between North- and South side receptor for near-parallel wind directions for Hornsgatan, Stockholm.
Figure 222 Diurnal and weekly variation in the mean ratio between the concentrations for the north- and south side receptor for near-parallel wind directions with wind speeds above 2 m/s for Hornsgatan, Stockholm.
Figure 3 Cross-section of a street canyon. The figure illustrates the governing flow patterns as modelled in OSPM. The two receptors are marked with red diamonds. In the figure the recirculation zone occupies the whole canyon although this need not be the case as e.g. shown in the following figures. Figure modified from Silver et al. (2013).
Figure 4: Schematic view of a street canyon seen from the top. The arrows represent the wind directions as modelled in OSPM. The length of the arrows are not proportional to the wind speed. The blue arrows are rooftop wind directions and the red arrows are street level wind directions. The receptors are marked with red diamonds.
Figure 5.55 Illustration of the integration paths (red dotted lines) for an arbitrary wind direction for the two receptors in the canyon. The upper blue dotted line marks a critical wind direction ($\theta_1$) which affects the calculation of the integration path length, and $L_b$ is the length to the end of the canyon used to calculate the maximum integration length ($L_{\text{max}}$). $L_{\text{rec}}$ is the length of the recirculation zone. A second recirculation zone is illustrated in blue with the new integration lengths likewise plotted with dotted blue lines.
Figure 6. Cross-section of a street canyon with the dimensions of the recirculation zone illustrated. The red blue arrows represent the street level wind direction. Based on (Hertel and Berkowicz, 1989) p. 69.
Figure 7.7 Illustration of the division of the street canyon into a number of segments with accumulated widths $W_1, W_2, W_3, \ldots$ and emission strengths $Q_1, Q_2, Q_3, \ldots$. The red dotted lines represent the integration path for receptor 1 for different wind directions. The blue dotted lines represent the contribution from segment $Q_2$. 
Figure 8. Mean NOx concentrations as a function of wind direction for the period 2007-2009 for the North side receptor (left side) and the South side receptor (right side). Where the black curve is hardly visible it is identical to the cyan curve.
Figure 9 Weekly variation in NO$_x$ concentrations for the period 2007-2009 for the North side receptor (left) and the South side receptor (right). Where the black curve is not visible it is below the cyan curve.
Figure 10: Diurnal variation for weekdays in personal cars per hour and total NO\textsubscript{x} emissions for all vehicles for 2003 (left) and 2013 (right). The red and orange graphs are for the northeast direction and the blue graphs are for the southeast direction. The curves marked with dots are the emissions and the curves marked with crosses are the number of personal cars per hour.
Figure 11.11 Diurnal variation in NO$_x$ concentrations on weekdays for 2003 (left) and 2013 (right).
Figure 12 Average NOx concentrations as a function of wind direction for the morning rush hour 7am-9am for both 2003 and 2013.
Figure 13. Theoretical calculation of the concentration for the two receptors for a street canyon with two emission segments each covering half the street width and an aspect ratio of one as a function of the emission inhomogeneity and wind direction. Receptor 1 is marked with green colour and receptor 2 is marked with blue colour. The inhomogeneity is given as percentages of the total emission for the two segments and the inhomogeneous case is marked with dotted lines. The street orientation is $0^\circ$ so the street runs North-South. The calculation is performed with a wind speed of $3.5 \frac{m}{s}$, a total emissions of $250 \frac{mg}{m^2}$, and no urban background concentration. Conditions are corresponding approximately to the average condition at Hornsgatan.
Figure 14. Theoretical calculation of the concentration for the two receptors for a street canyon with an emission inhomogeneity of 70% (north going) / 30% (south going) as a function of aspect ratio (AR) and wind direction. Receptor 1 is marked with green colour and receptor 2 is marked with blue colour. The case with high aspect ratio is marked with dotted lines. The calculation is performed with a wind speed of $3.5 \text{ m s}^{-1}$, total emissions of $250 \text{ g m}^{-2}$, and no urban background concentration. Conditions are corresponding approximately to the average conditions at Hornsgatan.
Table 1 Overview of the properties of the two street canyons used for validation of the dispersion schemes in the study. There is a measurement station (receptor) at each side of the street in Hornsgatan, but only one measurement station on the East side of Jagtvej.

<table>
<thead>
<tr>
<th>Name:</th>
<th>Hornsgatan</th>
<th>Jagtvej</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>Stockholm</td>
<td>Copenhagen</td>
</tr>
<tr>
<td>Country</td>
<td>Sweden</td>
<td>Denmark</td>
</tr>
<tr>
<td>Latitude</td>
<td>55° N</td>
<td>59° N</td>
</tr>
<tr>
<td>Width</td>
<td>24m</td>
<td>25m</td>
</tr>
<tr>
<td>Height</td>
<td>24m</td>
<td>22m</td>
</tr>
<tr>
<td>Years in analysis</td>
<td>07, 08, 09</td>
<td>03, 13</td>
</tr>
<tr>
<td>Street orientation</td>
<td>76°</td>
<td>30°</td>
</tr>
<tr>
<td>Average daily traffic</td>
<td>35.500</td>
<td>20.000</td>
</tr>
<tr>
<td>Mean vehicle speed (km/h)</td>
<td>45</td>
<td>29</td>
</tr>
<tr>
<td>Heavy duty share</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>Receptor height</td>
<td>3.0m(North)</td>
<td>3.3m(South)</td>
</tr>
</tbody>
</table>
Table 2 Level of service as a function of total number of vehicles per hour based on (Vägverket and SMHI, 2007)

<table>
<thead>
<tr>
<th>Level of service</th>
<th>Total number of vehicles per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeflow</td>
<td>&lt;601</td>
</tr>
<tr>
<td>Heavy</td>
<td>601 – 899</td>
</tr>
<tr>
<td>Saturated</td>
<td>900 – 1399</td>
</tr>
<tr>
<td>Stop + Go</td>
<td>&gt;1400</td>
</tr>
</tbody>
</table>
Table 3 Table of upper integration limits for respectively equation Eq. 3-3 (\(x_{\text{end}}\)) and equation Eq. 5-5 (\(x'_{\text{end}}\)). The definition and calculation of the lengths can be found in Table 4.

Magnitude: \(x_{\text{end}} \quad x'_{\text{end}}\)

<table>
<thead>
<tr>
<th>Condition</th>
<th>(x_{\text{end}})</th>
<th>(x'_{\text{end}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{\text{rec}} &gt; x_{\text{esc}} &gt; L_{\text{max}})</td>
<td>(L_{\text{max}})</td>
<td>-</td>
</tr>
<tr>
<td>(L_{\text{rec}} &gt; L_{\text{max}} &gt; x_{\text{esc}})</td>
<td>(x_{\text{esc}})</td>
<td>(L_{\text{max}})</td>
</tr>
<tr>
<td>(x_{\text{esc}} &gt; L_{\text{rec}} &gt; L_{\text{max}})</td>
<td>(L_{\text{max}})</td>
<td>-</td>
</tr>
<tr>
<td>(x_{\text{esc}} &gt; L_{\text{max}} &gt; L_{\text{rec}})</td>
<td>(L_{\text{rec}})</td>
<td>-</td>
</tr>
<tr>
<td>(L_{\text{max}} &gt; x_{\text{esc}} &gt; L_{\text{rec}})</td>
<td>(L_{\text{rec}})</td>
<td>-</td>
</tr>
<tr>
<td>(L_{\text{max}} &gt; L_{\text{rec}} &gt; x_{\text{esc}})</td>
<td>(x_{\text{esc}})</td>
<td>(L_{\text{rec}})</td>
</tr>
</tbody>
</table>
Table 4 Table of the critical lengths along the integration path. These lengths determine the upper and lower limit of the integrals in the homogeneous emission dispersion scheme and of the sums in the inhomogeneous emission dispersion scheme. Moreover, they determine if the dispersion should be calculated according to Eq. 3-33 or Eq. 5-55 plus whether the concentration should be multiplied with $f_{ext}$ as defined in Eq. 6. $f_{red}$ is the shortening function as defined in Eq. 6. $H_u$ is the upwind building height, $\theta_{street}$ is the wind direction compared to the street direction, $\theta_l$ is the critical wind direction as illustrated in Figure 5, $W$ is the street width, $L_b$ is the length from the receptor to the end of the street as illustrated in Figure 5, and $h_r$ is the height of the inlet of the receptor above street level.

<table>
<thead>
<tr>
<th>Name:</th>
<th>Expression:</th>
<th>Description:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{rec}$</td>
<td>$2 \cdot f_{red} \cdot H_u$</td>
<td>Length of the recirculation zone</td>
</tr>
<tr>
<td>$x_{esc}$</td>
<td>$\frac{u_{street}(H_g - h_0)}{\sigma_w}$</td>
<td>Length where the plume starts to disperse vertically out of the canyon.</td>
</tr>
<tr>
<td>$x_{start}$</td>
<td>$\frac{u_{street}(h_r - h_u)u_{street}(h_r - h_0)}{\sigma_w}$</td>
<td>$h_r \geq h_0$</td>
</tr>
<tr>
<td>$L_{max}$</td>
<td>$\frac{W}{\sin(\theta_{street})}$; $\frac{L_b}{\cos(\theta_{street})}$</td>
<td>$\theta_{street} &gt; \theta_l$</td>
</tr>
</tbody>
</table>
Table 5 Correlation coefficient, Fractional Bias, and Normalised Mean Square Error for the years 2007-2009 for the North side receptor. “Exact” and “Proportional” refer to the emission modelling approaches described in section 2.1. Moreover, the measured and modelled annual mean NO\textsubscript{x} concentrations for the individual years are also shown. These are calculated as local street contribution only i.e. the background concentration subtracted from the measured/modelled street concentration to reflect the street contribution.

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Homogeneous emissions</th>
<th>Inhomogeneous emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Exact</td>
<td>Proportional</td>
</tr>
<tr>
<td>Correlation coefficient ($R^2$)</td>
<td></td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Fractional Bias (FB)</td>
<td></td>
<td>-0.30</td>
<td>-0.16</td>
</tr>
<tr>
<td>Normalised Mean Square Error (NMSE)</td>
<td></td>
<td>0.36</td>
<td>0.26</td>
</tr>
<tr>
<td>Annual mean 2007 (ppb) ($\Delta C$)</td>
<td></td>
<td>56.8</td>
<td>44.3</td>
</tr>
<tr>
<td>Annual mean 2008 (ppb) ($\Delta C$)</td>
<td></td>
<td>53.9</td>
<td>37.7</td>
</tr>
<tr>
<td>Annual mean 2009 (ppb) ($\Delta C$)</td>
<td></td>
<td>53.9</td>
<td>35.0</td>
</tr>
</tbody>
</table>
Table 6 Statistical quantities for the South side receptor. Same definitions as in Table 5.

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Homogeneous emissions</th>
<th>Inhomogeneous emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Exact</td>
<td>Proportional</td>
</tr>
<tr>
<td>Correlation coefficient ($R^2$)</td>
<td>0.83</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>Fractional Bias (FB)</td>
<td>0.08</td>
<td>-0.08</td>
<td>-0.07</td>
</tr>
<tr>
<td>Normalised Mean Square Error (NMSE)</td>
<td>0.27</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Annual mean 2007 (ppb) ($\Delta C$)</td>
<td>32.7</td>
<td>41.2</td>
<td>33.1</td>
</tr>
<tr>
<td>Annual mean 2008 (ppb) ($\Delta C$)</td>
<td>34.5</td>
<td>37.2</td>
<td>34.0</td>
</tr>
<tr>
<td>Annual mean 2009 (ppb) ($\Delta C$)</td>
<td>34.6</td>
<td>34.5</td>
<td>20.1</td>
</tr>
<tr>
<td></td>
<td>Measured</td>
<td>Homogeneous emissions</td>
<td>Inhomogeneous emissions</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------</td>
<td>-----------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exact</td>
<td>Proportional</td>
</tr>
<tr>
<td>Correlation coefficient ($R^2$)</td>
<td>0.83</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>Fractional Bias (FB)</td>
<td>0.08</td>
<td>-0.08</td>
<td>-0.07</td>
</tr>
<tr>
<td>Normalised Mean Square Error (NMSE)</td>
<td>0.27</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Annual mean 2007 (ppb) (ΔC)</td>
<td>32.7</td>
<td>41.2</td>
<td>33.1</td>
</tr>
<tr>
<td>Annual mean 2008 (ppb) (ΔC)</td>
<td>34.5</td>
<td>37.2</td>
<td>31.0</td>
</tr>
<tr>
<td>Annual mean 2009 (ppb) (ΔC)</td>
<td>34.6</td>
<td>34.5</td>
<td>29.1</td>
</tr>
</tbody>
</table>