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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

[Comments are in regular font and answers are in bold font.]

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 severe 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, line4: 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 it 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 it 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.

Point-to-point response to comments by Referee #2

[Comments are in regular font and answers are in bold font.]

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.

1 **Analysis of the Impact of Inhomogeneous Emissions in a ~~Semi-~~** 2 **~~Parameterized Street Canyon Model~~ the Operational Street** 3 **Pollution Model (OSPM)**

4
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17 **Abstract**

18 Semi-parameterized street canyon models, as e.g. the Operational Street Pollution Model
19 (OSPM®), have been frequently applied for the last two decades to analyse levels and
20 consequences of air pollution in streets. These models are popular due to their speed and low
21 input requirements. One often used simplification is the assumption that emissions are
22 homogeneously distributed in the entire length and width of the street canyon. It is thus the
23 aim of the present study to analyse the impact of this assumption by implementing an
24 inhomogeneous emission geometry scheme in OSPM. The homogeneous and the
25 inhomogeneous emission geometry schemes are validated against two real-world cases:
26 Hornsgatan, Stockholm, a sloping street canyon; and Jagtvej, Copenhagen; where the morning
27 rush hour has more traffic on one lane compared to the other. The two cases are supplemented
28 with a theoretical calculation of the impact of street aspect (height/width) ratio and emission

1 inhomogeneity on the concentrations resulting from inhomogeneous emissions. The results
2 show an improved performance for the inhomogeneous emission geometry over the
3 homogeneous emission geometry. Moreover, it is shown that the impact of inhomogeneous
4 emissions is largest for near-parallel wind directions and for high aspect ratio canyons. The
5 results from the real-world cases are however confounded by challenges estimating the
6 emissions accurately.

7 **1 Introduction**

8 Semi-parameterized models as e.g. the Operational Street Pollution Model (OSPM®;
9 Berkowicz et al. (1997)) have been frequently applied in cities around the globe over the last
10 20 years (Assael et al., 2008; Berkowicz et al., 1996; Berkowicz et al., 2006; Ghenu et al.,
11 2008; Gokhale et al., 2005; Hertel et al., 2008; Kakosimos et al., 2010; Ketzel et al., 2012;
12 Kukkonen et al., 2000; Vardoulakis et al., 2005). This type of model has the advantages of
13 low input requirements and short execution times. This means that the model can cover many
14 streets over long time periods due to its low computational demand.

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

25 Sloping streets represent a natural case of inhomogeneous emissions in that vehicles driving
26 uphill have a higher emission due to the increased engine load compared to vehicles driving
27 downhill. Gidhagen et al. (2004) examined the measured NO_x concentrations from a
28 measurement campaign in Hornsgatan in Stockholm, Sweden; which has a slope of 2.3%,
29 using a Computational Fluid Dynamics (CFD) model. It was shown that the model
30 representation of the wind direction dependence of the concentrations compared to the wind
31 direction dependence of the measurements improved by assuming an emission relationship of

1 3:1 between the uphill and downhill side of the road. This followed along a marginal
2 improvement in the correlation between the model and the measurements. In Gidhagen et al.
3 (2004), Kean et al. (2003) is also quoted for reporting markedly higher emissions for vehicles
4 going uphill compared to vehicles going downhill, a feature also implemented in emission
5 models like the Handbook Emissions Factors for Road Transport - HBEFA (www.hbefa.net).

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

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

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

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

19 **2 Methods**

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

24 The two street canyons chosen to analyse the impact of inhomogeneous emissions were
25 respectively Hornsgatan in Stockholm, Sweden and Jagtvej in Copenhagen, Denmark. The
26 main characteristics of the two street canyons are summed up in ~~Table 1~~Table 1~~Table 1~~.
27 Hornsgatan is an example of a sloping street canyon with the average slope being 2.3%
28 (Gidhagen et al., 2004), and Jagtvej is diurnally inhomogeneous in that, depending on the
29 time of day, there is more traffic in the northeast direction compared to the southwest
30 direction. Both streets have two driving lanes in each direction (four lanes in total) plus non-

1 emitting areas at the sides. The non-emitting areas are however not modelled explicitly in the
2 present analysis, since including this would require the implementation of horizontal diffusion
3 in the model cf. the discussion in ~~section 3.23.2~~. This task remains for future work.

4 In the analysis, the NO_x concentrations were used since in OSPM the concentration of NO₂ is
5 calculated based on the concentration of NO_x and O₃. Thus in order not to add the
6 uncertainties from the chemistry in the analysis, the primary emitted tracer (NO_x) is used.
7 Moreover, previous studies (Ketzel et al. (2011); (Ketzel et al., 2012)) have shown that the
8 emission and dispersion module implemented in OSPM have an acceptable performance for
9 this species. ~~The CO concentrations were not used since the accuracy of the COPERT 4
10 emission model, as implemented in OSPM, is not known for CO emissions in Denmark and
11 the general levels are low, which means that the CO measurements are fraught with a large
12 uncertainty (Ellermann et al., 2013).~~

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

19 Both streets are part of routine air quality control monitoring programs and have been studied
20 extensively in the past. One year of data from Hornsgatan were included in the Street
21 Emission Ceiling Exercise (Larssen et al., 2007; Moussiopoulos et al., 2005; Moussiopoulos
22 et al., 2004) and has thus been subject of a number of modelling studies (e.g. Denby et al.
23 (2013a); Denby et al. (2013b); Johansson et al. (2009); Ketzel et al. (2007); Olivares et al.
24 (2007)). The Jagtvej measurement station is part of the Danish air quality monitoring
25 programme (Ellermann et al., 2013) and has likewise been the subject of extensive analysis
26 (e.g. Ketzel et al. (2011); Ketzel et al. (2012); Silver et al. (2013)).

27 **2.1 Emission modelling and measurements from Hornsgatan**

28 The emission modelling for Hornsgatan uses the hourly automatic vehicle counts for the two
29 driving directions on Hornsgatan. The vehicle counts were made using an inductive loop
30 technology (Marksman 660 Traffic counter and Classifier, Golden River Traffic Ltd., UK). It

1 provides hourly mean total traffic counts, classification of vehicles based on the length of the
2 vehicle, plus mean speed on a lane by lane basis. The automatic counts in the east inner lane
3 were multiplied by 4.2 to compensate for a bias in the counting based on a manual counting
4 check. The exact technical reason for this factor is not known. However, comparison between
5 the Marksman counter and manual counts and between the Marksman counter and automatic
6 camera recordings (Burman and Johansson, 2010) have confirmed the validity of this factor.

7 The vehicle distribution was modelled as the average weekly vehicle distribution based on
8 vehicle classifications obtained by video number plate recognition in the fall of 2009 (Burman
9 and Johansson, 2010). This ensured that the emission factors reflected the average weekly
10 variation in vehicle distribution. All vehicle categories were modelled using HBEFA 3.2
11 (www.hbefa.net) except ethanol buses, which do not appear as vehicle category in HBEFA.
12 These were instead modelled using the ARTEMIS emission model (Boulter and McCrae,
13 2007). The emission factors from ARTEMIS were ~~scaled~~harmonized to a different set of
14 velocities compared to HBEFA. In order to harmonizescale the two emission models, the
15 emissions from ARTEMIS were linearly interpolated to match the travel speeds from
16 HBEFA.

17 The emission factors from HBEFA version 3.2, were used for the emission modelling since
18 this emission model includes the effect of slope on the emissions. The emissions were
19 exported from this model for slopes of +/- 2% and +/- 4% and a linear interpolation to the
20 slope of +/-2.3%, as given by Gidhagen et al. (2004), was performed. In Gidhagen et al.
21 (2004) “Tehran Emission Reduction Project” is cited for reporting uphill emissions being 3-4
22 times larger than downhill emissions. A significant emission difference between the North
23 and South side of the street can therefore be expected.

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

29 In setting up OSPM, the street was divided into two emission segments of equal width,
30 although the inhomogeneous emission scheme described in Sect. 3.2 allows for any number of
31 segments, thus each segment covering two traffic lanes. The emissions were distributed over

1 both the lanes and the sidewalk since the modelling of sidewalks is not yet a feature of the
2 model, cf. the discussion in [Sect. section 3.23.2](#). The vehicle speed, used for the calculation of
3 traffic-produced turbulence, was assumed equal to the mean speed between the two lanes
4 comprising the segment.

5 The emission modelling for ~~this street~~[Hornsgatan](#) was performed based on two approaches:

- 6 • An approach based on the hypothesis that the traffic on the individual lane can be
7 modelled as half the total traffic, subsequently referred to as the “proportional”
8 approach. The inhomogeneity thus only arises from the slope of the street. This
9 approach is useful if directional- or lane divided traffic counts don’t exist for the street
10 in question.
- 11 • An approach based on the modelling of inhomogeneous emissions based on traffic
12 counts from the individual lane as described above. This approach is subsequently
13 referred to as the “exact” approach.

14 The two approaches to emission modelling were subsequently compared.

15 NO_x was simultaneously monitored on the northern and southern sides of the road with a
16 commercial NO_x chemiluminescence analyser (model 31 M LCD, Environment SA, France).
17 Urban background concentrations were taken from an identical instrument at a monitoring
18 station located on the roof of a building approx. 500 m east of the Hornsgatan street station.
19 The roof level station is representative of the urban background and is not influenced by the
20 emissions in any nearby street canyon.

21 To analyse if the emission distribution between the north side and the south side of the street
22 can be modelled as a constant ratio, an analysis of measurements for near-parallel ($\pm 30^\circ$)
23 wind directions for the conditions of a minimum wind speed of $2\frac{m}{s}$ was performed. It was
24 hypothesized that the ratio between the measured concentrations corresponds to the
25 proportions between the emissions. This assumption is of course violated as a result of
26 horizontal dispersion in the street canyon, but this effect was disregarded.

27 As seen from [Fig. 14](#)~~Figure 4~~, the distribution of concentration ratios between the northern
28 and southern side of the street is skewed with the mode being around 1.2 and the mean value
29 being [3.22-27](#). This result is not too far from the result presented by Gidhagen et al. (2004),
30 that the emissions at the north side were three times as large as on the south side. Moreover,

1 the distribution is unimodal and has a relatively low standard deviation, which supports the
2 assumption of an even traffic distribution between the north- and the south side of the street.

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

5 The diurnal and weekly variation of the ratio is shown in Fig. -22Figure 2. As can be seen the
6 values show no clear diurnal or weekly variation and thus the assumption of an even
7 distribution of traffic, but inhomogeneous emissions due to the slope in the two directions,
8 between the two segments seems valid.

9 **2.2 Emission modelling and measurements from Jagtvej**

10 ~~One m~~ Manual traffic counts next to the measurement station at Jagtvej ~~was~~ were performed
11 respectively in 2003 and in 2013. The traffic was counted in two directions on a weekday for
12 24 hours in 2003 and between ~~7am~~0700-7pm ~~1900~~ in 2013. The number of vehicles was split
13 into a number of vehicle classes to provide the vehicle distribution. The emissions were
14 modelled using the COPERT 4 model (EEA, 2009).

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

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

29 The NO_x measurements at the east side of Jagtvej were performed continuously by
30 chemiluminescence using NO_x Aerodyne API instruments. The urban background

1 measurements were measured from a roof level measurement station approximately 500m
2 from the street using similar instrumentation as the street level measurements.

3 **2.3 Theoretical calculations**

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

11 **3 Model description**

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

17 **3.1 The homogeneous emission dispersion scheme**

18 To illustrate the modelling principles of OSPM, a typical street canyon situation is illustrated
19 in [Fig. 33Figure 3](#). OSPM calculates the concentrations (C) at the wall side of the street
20 canyon as a contribution from the street canyon (C_{street}) plus a contribution from urban
21 background concentrations (C_{bg}). The contribution from the street canyon is subsequently a
22 sum of a direct contribution (C_{dir}) plus a recirculating contribution (C_{rec}) (Berkowicz et al.,
23 1997):

$$24 \quad C = C_{\text{street}} + C_{\text{bg}} \quad (1)$$

$$25 \quad C_{\text{street}} = C_{\text{dir}} + C_{\text{rec}} \quad (2)$$

26 It is a fundamental assumption of the model that when the wind blows over a rooftop in a
27 street canyon an hourly averaged recirculation vortex is always formed inside the canyon as
28 illustrated in [Fig. 33Figure 3](#).

1 It is assumed that the ground level wind direction inside the recirculation zone is mirrored
2 compared with the roof level wind direction, whereas outside the recirculation zone the wind
3 direction follows the roof level wind direction as illustrated in [Fig. 44Figure 4](#).

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

13 3.1.1 The direct contribution:

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

$$15 \int_{x_{start}}^{x_{end}} \frac{dC_{dir}}{dx} dx = \sqrt{\frac{2}{\pi}} \frac{Q}{W \sigma_w} \int_{x_{start}}^{x_{end}} \frac{1}{x + \frac{u_{street} h_0}{\sigma_w}} dx \quad (3)$$

16 Where C_{dir} is the direct contribution, x_{start} is the distance from the receptor where the plume
17 has the same height as the receptor, which can also be zero in case $h_r \leq h_0$, and x_{end} is the
18 upper integration limit as defined in [Table 3Table 3Table 2](#), h_0 is the height of the plume in
19 the wake of a car (usually termed the -“initial dispersion”), h_r is the height of the receptor (the
20 height of the calculated concentration), Q is the emission flux (in $g\ m^{-1}\ s^{-1}$), W is the width of
21 the street, u_{street} is the street level wind speed, and σ_w is the vertical turbulence flux
22 calculated as a function of the street level wind speed and the traffic produced turbulence.

23 The integration is performed along a straight line path against the wind direction as illustrated
24 in [Fig. 55Figure 5](#). Equation [\(33\) 3](#) is used for calculating the direct contribution on both the
25 leeward side and the windward side; however, the length of the integration paths can differ
26 likewise as illustrated in [Fig. 55Figure 5](#).

27 In [Fig. 55Figure 5](#) it is assumed that $x_{end} = L_{rec}$, the length of the recirculation zone,
28 however, as shown in [Table 3Table 3Table 2](#) this needs not be the case. The calculation of

L_{rec} as a function of the upwind building height (H_u) and the shortening function (f_{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 (σ_z) equals the general building height (H_g) (Ketzler et al., 2014) of the canyon. This point is called x_{esc} and is defined as (Hertel and Berkowicz, 1989):

$$x_{esc} = \frac{u_{street}(H_g - h_0)}{\sigma_w} \quad (4)$$

Where H_g is the general building height of the canyon.

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

$$\int_{x_{esc}}^{x'_{end}} \frac{dc_{dir}}{dx} dx = \sqrt{\frac{2}{\pi}} \int_{x_{esc}}^{x'_{end}} \frac{Q}{u_{street}WH_g} e^{-\frac{\sigma_{wt}}{H_g u_{street}}(x - x_{esc})} dx \quad (5)$$

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

For close to parallel wind directions the integration length (x_{end}) for the leeward side receptor (1) (marked with "1" in Figure 5) is extended from L_{rec} to L_{max} to account for concentration resulting from emissions outside the recirculation zone. The calculation of L_{max} as a function of the street width (W), the wind direction with respect to the street axis (θ_{street}), and the length to the end of the canyon is defined in Table 4. This is done extended when the factor $f_{ext} \theta_{street}$ is greater than 45° , and the contribution to the concentrations from the path outside the recirculation zone is then multiplied by f_{ext} (Hertel and Berkowicz, 1989)¹:

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

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_{red} is defined as $f_{red} = 0.5u_{street}$ for $u_{street} < 2 \frac{m}{s}$. This has subsequently been changed to $f_{red} = \sqrt{0.5u_{street}}$ for $u_{street} < 2 \frac{m}{s}$.

1 (6) Where θ_{street} is the angle between the street and the street level wind direction.

2 **3.1.2 The recirculating contribution**

3 The recirculating contribution is parameterized as a box model, where it is assumed that the
4 inflow of pollutants equals the outflow of pollutants as illustrated in [Fig. 66Figure-6](#).

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

$$7 \quad Q_{in} = \frac{Q}{W} L_{base} \quad (7)$$

8 Where $L_{base} = \min(L_{rec}, L_{max})$. The recirculation zone is modelled as a trapezium with the
9 upper length being half of the baseline length. The outflow from the box model is thus the
10 ventilation at the top of the recirculation trapezium ($\sigma_{wt}L_{top}$) plus the ventilation at the
11 hypotenuse of the trapezium ($\sigma_{hyp}L_{hyp}$) as illustrated in [Fig. 66Figure-6](#) (Berkowicz et al.,
12 1997):

$$13 \quad Q_{out} = C_{rec}(\sigma_{wt}L_{top} + \sigma_{hyp}L_{hyp}) \quad (8)$$

14 Where C_{rec} is the recirculating concentration contribution and σ_{hyp} is the average turbulence
15 at the hypotenuse. Equations [7-\(7\)](#) and [8-\(88\)](#) can now be solved for the recirculating
16 concentration by setting the inflow equal to the outflow:

$$17 \quad C_{rec} = \frac{\frac{Q}{W}L_{base}}{\sigma_{wt}L_{top} + \sigma_{hyp}L_{hyp}} \quad (9)$$

18 **3.1.3 Summarizing the dispersion module in OSPM**

19 For regular street canyons (height to width ratio close to one) the recirculation zone will
20 occupy the majority of the canyon. This means that, for a large wind direction interval, the
21 integration length for the leeward receptor will be significantly longer than the integration
22 length for the windward receptor. Furthermore the leeward receptor will be exposed to the full
23 recirculating contribution, ~~which will only to a minor extent influence the~~ while the windward
24 receptor only receives a further diluted recirculating contribution. These two effects mean that
25 the leeward receptor will experience significantly higher concentrations than the windward
26 receptor for a large wind direction interval.

1 3.2 The inhomogeneous emission dispersion scheme

2 In order to facilitate the modelling of streets with inhomogeneous emission distributions, the
 3 street was divided into a number of parallel segments as illustrated in [Fig. 77Figure 7](#). The
 4 model user will define the width and the emission strength of each segment. At run-time the
 5 model calculates a variable number of several distances generated by the flow (L_{rec} , x_{esc} etc.)
 6 that depend on wind flow conditions. The user-defined emission segments are subsequently
 7 split into one or more segments with constant emission at these pointsdistances. ThisTo
 8 calculate the concentration from the user-defined and flow generated segments ~~means that~~ the
 9 above presented integrals become divided into a number of integrals and subsequently
 10 summed to yield the final concentration. The direct contribution thus becomes:

$$11 \int_{x_{start}}^{x_{end}} \frac{dc_{dir}}{dx} dx = \sqrt{\frac{2}{\pi}} \frac{1}{\sigma_w} \sum_{i=n_{start}}^{n_{end}} \frac{Q_i}{W_i - W_{i-1}} \int_{W'_{i-1}}^{W'_i} \frac{1}{x + \frac{u_{street} h_0}{\sigma_w}} dx \quad (10)$$

12 Where n_{end} is the segment number of the last segment influencing the receptor, n_{start} is the
 13 first segment to influence the concentration at the receptor, W_i is the accumulated width of the
 14 segment calculated from the receptor, and W'_i is the accumulated width of the segment
 15 calculated along the integration path from the receptor. The segments defined by W_i and W'_i
 16 can be either user-defined or dynamically generated.

17 The exponentially decaying concentration contribution from segments further away than x_{esc}
 18 from the receptor becomes:

$$19 \int_{x_{esc}}^{x'_{end}} \frac{dc_{dir}}{dx} dx = \sqrt{\frac{2}{\pi}} \sum_{i=n_{start}}^{n_{end}} \frac{Q_i}{u_{street}(W_i - W_{i-1})H} \int_{W'_{i-1}}^{W'_i} e^{-\frac{\sigma_w t}{H u_{street}}(x - x_{esc})} dx \quad (11)$$

20 The recirculating contribution becomes:

$$21 C_{rec} = \frac{1}{\sigma_w t_{top} + \sigma_{hyp} L_{hyp}} \sum_{i=n_{start}}^{n_{end}} \frac{Q_i}{W_i - W_{i-1}} (W'_i - W'_{i-1}) \quad (12)$$

22 In the homogeneous emission scheme the limits of the integrals are determined by the street
 23 geometry and the recirculation zone geometry. In the inhomogeneous scheme the limits of the
 24 integrals are always W'_{i-1} and W'_i . Instead the limits of the sum determine which segments
 25 contribute to the concentration at the receptor.

26 As seen from the lack of y-dependence in [Eq. equation 3-\(33\)](#) and [-10\(10\)](#), the model does not
 27 contain expressions for horizontal dispersion. In the original model this was unnecessary since

1 the emissions were homogeneous in the entire canyon. In order to model sidewalks or similar
2 segments with zero emission, horizontal dispersion has to be implemented in the model. This
3 is the case due to the geometry of ~~the~~ canyon with zero emission segments on the sides,
4 meaning that as the wind direction approaches parallel, the integration length quickly
5 approaches zero thus leading to zero concentration as illustrated in Fig. 7. Introducing
6 horizontal dispersion in OSPM was however deemed outside the scope of the present study.
7 In the following cases the streets are therefore divided into segments covering both the traffic
8 lanes and the sidewalks. It would be possible to divide the street into more segments to model
9 the individual traffic lanes. However, either the emission of the inner lane had to be
10 distributed over the sidewalk as well, leading to a too low emission density, or the two lanes
11 would have to be of equal width meaning that the segment division would not correspond to
12 the traffic lane division. To avoid these methodological difficulties, it was decided to model
13 the streets as two segments.

14 **4 Results and discussion**

15 **4.1 Hornsgatan**

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

20 As can be seen from Table 5Table 5Table 5 and Table 6Table 6Table 6, there is a noticeable
21 change in the performance of the model when moving from homogeneous emissions to
22 inhomogeneous emissions, but only very little between the two approaches for modelling
23 inhomogeneous emissions. This confirms the assumption made in Sect.section 2.1 that the
24 emission distribution at Hornsgatan is not, to any significant extend, influenced by diurnal
25 variations. It is also noticeable that the increase in performance is especially pronounced for
26 the North side receptor where the FB is markedly improved and the NMSE is improved as
27 well. For the South side receptor a smaller improvement is seen in FB. Conversely, moving
28 from homogeneous emissions to inhomogeneous emissions has almost zero impact on the
29 correlation coefficient on both sides and only a smaller effect on the NMSE on the north side.

1 The results are, however, confounded by the modelled street level contributions to the
2 concentrations decline whereas the measured concentrations are almost stable. This effect is
3 especially seen on the North side receptor and to a smaller extent on the South side receptor.
4 This effect can most likely be ascribed to the emission model performance, since the effect is
5 time dependent, and no interannual change in wind speed or direction is found (data not
6 shown). Most likely the emission model is predicting too optimistic reductions for the modern
7 EURO 5/6 vehicles that are not abated under real-world driving conditions as reported in
8 literature (Carslaw et al., 2011) This is also underlined by the fact that the traffic counts from
9 the inductive loop technology matches fairly well with the camera recordings from 2009. The
10 camera recordings were done over three months where individual cars were identified and
11 compared with register data (Burman and Johansson, 2010). This means that the total traffic
12 counts must be considered reasonably accurate. Since the vehicle distribution for the year
13 2009 is known very accurately from the camera recordings, this is probably not the
14 explanation either. This leaves a change in traffic flow situation (levels of service) or a
15 difference between the actual and modelled vehicle fleet; in terms of age composition,
16 emissions as a function of slope, or other factors; over time as possible explanations for this
17 discrepancy.

18 The wind direction dependency of the concentrations is shown in [Fig. 88](#)~~Figure 8~~. As can be
19 seen, the impact of moving from homogeneous emissions to inhomogeneous emissions is
20 largest for parallel wind directions, where each receptor is only exposed to one emission
21 segment. For perpendicular wind directions there is a small difference when the uphill
22 emissions are close to the North side receptor and no difference when it is further away. A
23 similar pattern is seen for the South side receptor with 180° displacement. The wind
24 direction plot shows a noticeable discrepancy between the model and the measurements
25 around 200° for both receptors. Gidhagen et al. (2004) states that horizontal dispersion is
26 underestimated in the applied κ - ϵ CFD model, and that this is the cause of this discrepancy. If
27 this is the case the underestimation will also appear in the present wind direction plots due to
28 the lack of horizontal dispersion in OSPM.

29 The weekly variation in concentrations is shown in [Fig. 99](#)~~Figure 9~~. The general diurnal
30 variation plus the difference between weekdays and weekends are reproduced well by the
31 model. As can be seen, the two approaches to inhomogeneous emission modelling are almost
32 indistinguishable. It can also be seen from the figure that the impact of inhomogeneous

1 emissions is largest during day time where the concentrations are largest. ~~Figure 9~~Figure
2 ~~9~~Figure-9 shows as well that the diurnal variation is not reproduced in detail. On the north
3 side, the morning rush hours and the evening hours are still underestimated, whereas the night
4 time concentrations are underestimated. Moreover, the figure indicates a faster diurnal change
5 in the modelled concentrations as compared to the measured concentrations. This probably
6 has to do with the way the traffic flow situation is modelled as four discrete categories,
7 whereas real traffic will behave like a continuum. This is a potential area of improvement for
8 a future study.

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

12 **4.2 Jagtvej**

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

20 The diurnal variations in measured and modelled concentrations for weekdays for the two
21 years ~~is~~are shown in ~~Fig. 11~~Figure-11. As ~~can be seen~~expected, the change from
22 homogeneous to inhomogeneous emissions only ~~have~~has an ~~small~~influence on the
23 concentrations around rush hour from 8-9 am, where also traffic is inhomogeneous. ~~Here~~
24 However the difference between the homogeneous and the inhomogeneous emissions is
25 relatively small, approximately 6 ppb. As also seen from the graph, the model tends to
26 overestimate the emissions in 2003, whereas the 2013 emissions seem fairly correct. The poor
27 model performance for 2003 ~~has~~ve to do with the way the model has previously been
28 calibrated to match the measurements. This means that the emissions used in the present study
29 are markedly different from the emissions used when the model was designed, and isAdapting
30 the model to the new emissions was deemed outside the scope of the present study and an area
31 of improvement for a future study.

1 The average concentration as a function of wind direction for the morning rush hour for the
2 two years is shown in [Fig. 1212Figure-12](#). As can be seen, the difference between the
3 homogeneous and the inhomogeneous emission is approximately homogeneously distributed
4 among the different wind directions with difference up to 7 ppb. When averaging over the two
5 years, the emission biases ~~equilibrate~~~~balance~~ each other, and gives a clearer picture of the
6 wind direction dependency. When looking carefully at the graph it can be seen that the
7 difference in concentration between homogeneous and inhomogeneous emissions is slightly
8 larger for parallel compared to perpendicular directions. The spike in the measurements
9 around 100 degrees is likely a result of a random error, since this spike is not seen in the data
10 for the full diurnal cycle (data not shown). Both the homogeneous and the inhomogeneous
11 emission model have difficulties capturing the measurements from approximately 260°
12 degrees to 360° degrees. From 290 to 345 there is an opening in the street canyon and the
13 difficulties of the model to capture this phenomenon was reported in an earlier study (Ottosen
14 et al., 2015). It was thus deemed outside the scope of the present study to develop a solution
15 to this issue as well.

16 4.3 Theoretical calculations

17 A set of theoretical calculations were performed to clearer illuminate the impact of
18 inhomogeneous emissions without the confounding variables influencing the results of the
19 real street canyons. The calculations isare performed with a wind speed of $3.5 \frac{m}{s}$, total
20 emissions of $250 \frac{\mu g}{ms}$, and no urban background concentration. These ~~C~~conditions are are
21 corresponding approximately to the average conditions at Hornsgatan. The results of the
22 theoretical analysis of the concentration dependency of the emission inhomogeneity are
23 shown in [Fig. 1314Figure-13](#). As can be seen, ~~thea~~ larger ~~the~~ emission difference between the
24 two segments also results in , -thea larger ~~the~~ difference in concentration. As ~~also~~ earlier
25 shown for Hornsgatan, the largest difference is seen for near-parallel wind directions.
26 However, bearing in mind the scale of the y-axis, the differences are small. The
27 inhomogeneity at Jagtvej corresponds to approximately 10 ppb and for Hornsgatan to
28 approximately 20 ppb, orders of magnitude also confirmed by [Fig. 89Figure-8](#) and [Fig.](#)
29 [1213Figure-12](#). The comparison with measurement will however give a smaller difference,
30 since the real world data are averages of many different wind speeds and emissions.

1 The impact of the street canyon aspect ratio on the concentrations resulting from
2 inhomogeneous emissions is shown in ~~Fig. 14~~~~Figure 14~~. ~~As seen,~~ the impact is largest for
3 high aspect ratio (building heights larger than street width) canyons. This is ~~natural-expected,~~
4 since “the street canyon effect”, where the impact of the recirculation zone means larger
5 concentrations for the leeward side compared to the windward side, is larger for high aspect
6 ratio canyons. As such, the impact of inhomogeneous emissions will also be larger for high
7 aspect ratio canyons.

8 **5 Conclusions**

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

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

24 **6 Future work**

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

- 28 • At present the receptor is located at the wall of the street. In reality measurement
29 stations are often located several meters from the wall leading to a shorter dilution of
30 the emissions and thereby a higher concentration. Being able to move the receptor

1 freely in the cross-canyon direction could potentially lead to a model performance
2 improvement.

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

8 **Author contribution**

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

18 **Code availability**

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

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

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

24 e-mail: ospm@au.dk

25 Operational System: Microsoft Windows 7 or later

26 Software requirements: None

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

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

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

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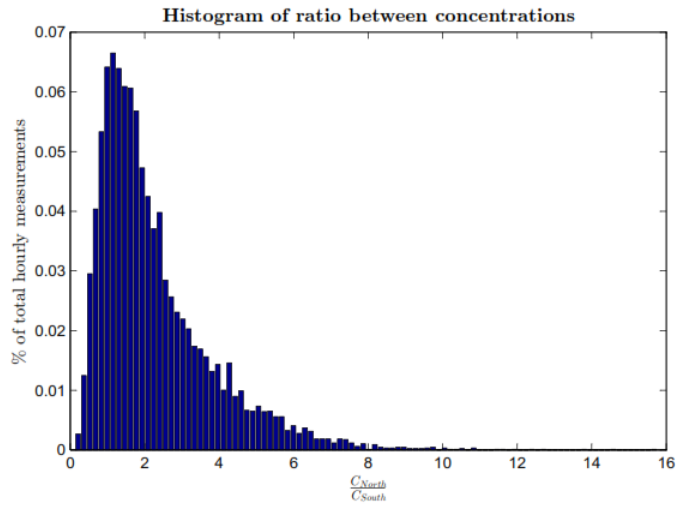
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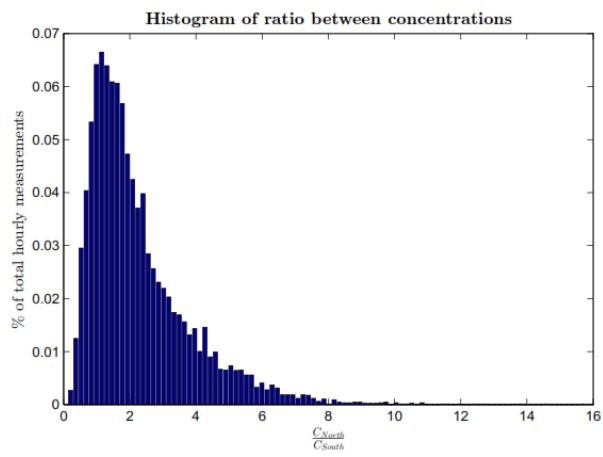
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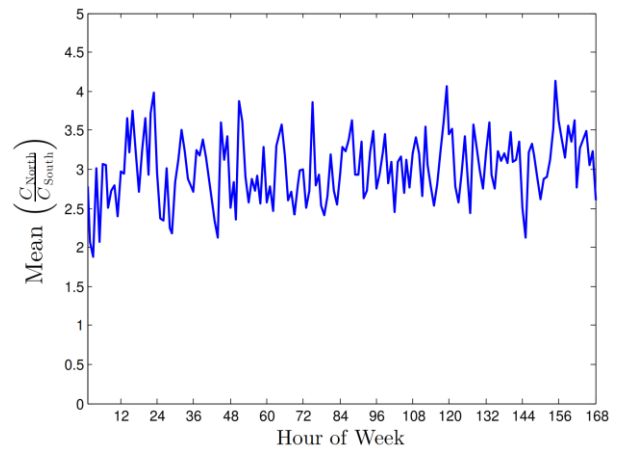
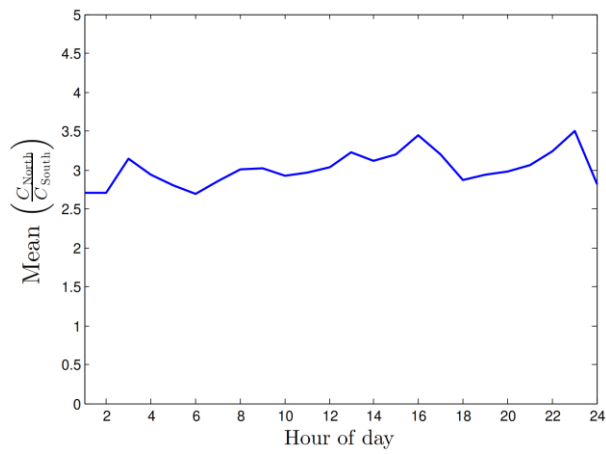
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2 Figure [14](#) Histogram of ratio between North- and South side receptor for near-parallel wind
3 directions [for Hornsgatan, Stockholm](#).

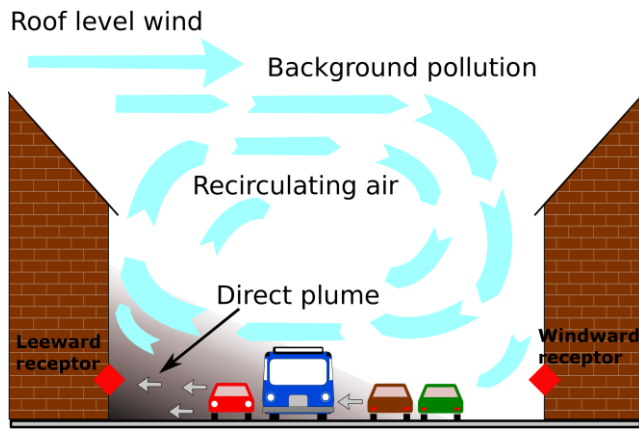
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2 Figure [222](#) Diurnal and weekly variation in the mean ratio between the concentrations for the
 3 north- and south side receptor for near-parallel wind directions with wind speeds above $2 \frac{\text{m}}{\text{s}}$
 4 [for Hornsgatan, Stockholm](#).

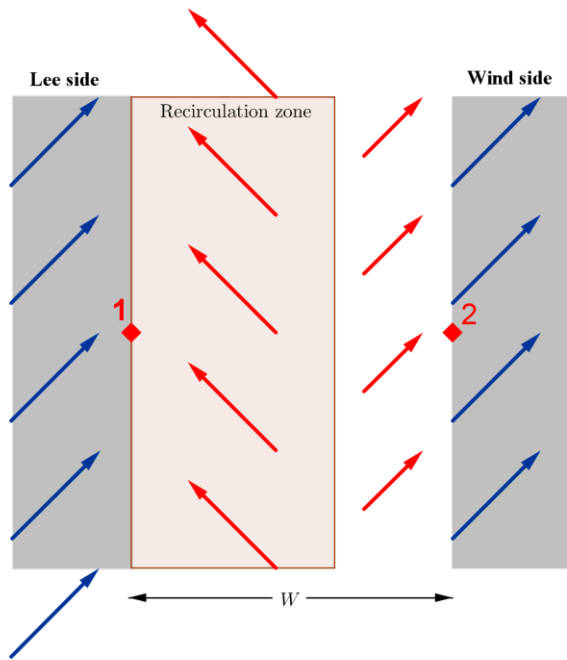
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2 Figure 333 Cross-section of a street canyon. The figure illustrates the governing flow patterns
 3 as modelled in OSPM. The two receptors are marked with red diamonds. In the figure the
 4 recirculation zone occupies the whole canyon although this need not be the case as e.g. shown
 5 in the following figures. Figure modified from Silver et al. (2013).

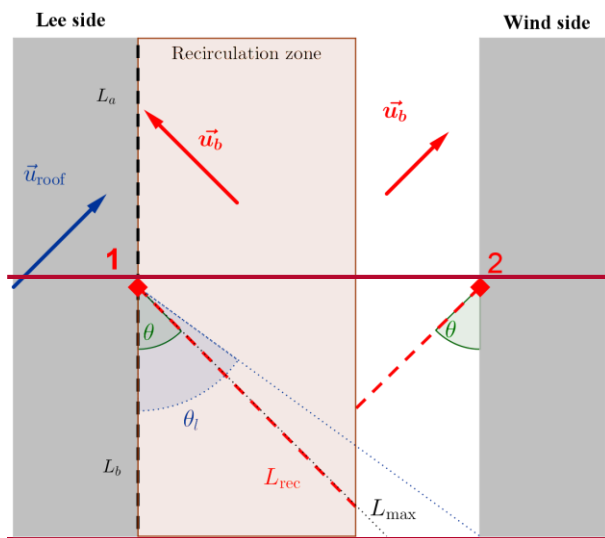
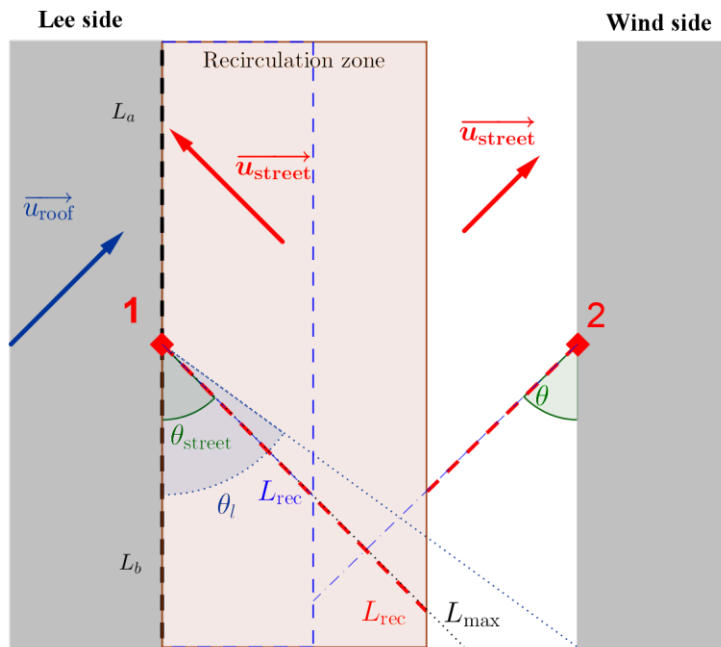
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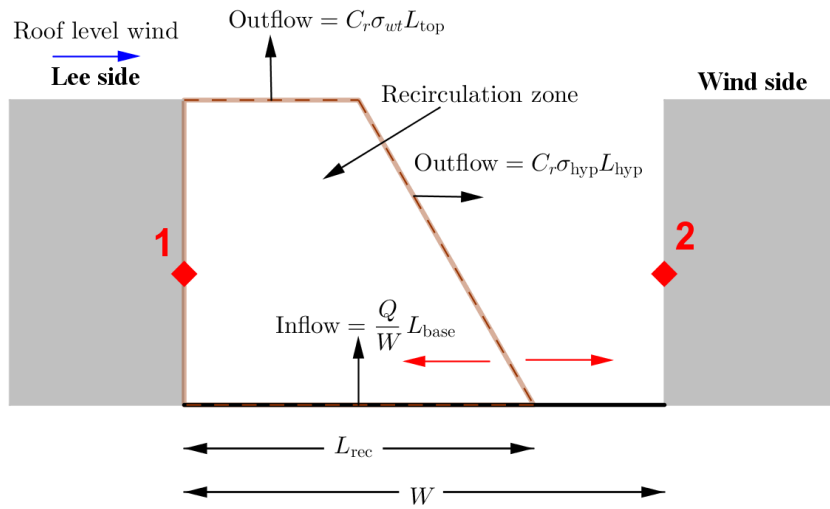
2 Figure 444 Schematic view of a street canyon seen from the top. The arrows represent the
 3 wind directions as modelled in OSPM. The length of the arrows are not proportional to the
 4 wind speed. The blue arrows are rooftop wind directions and the red arrows are street level
 5 wind directions. The receptors are marked with red diamonds.

6



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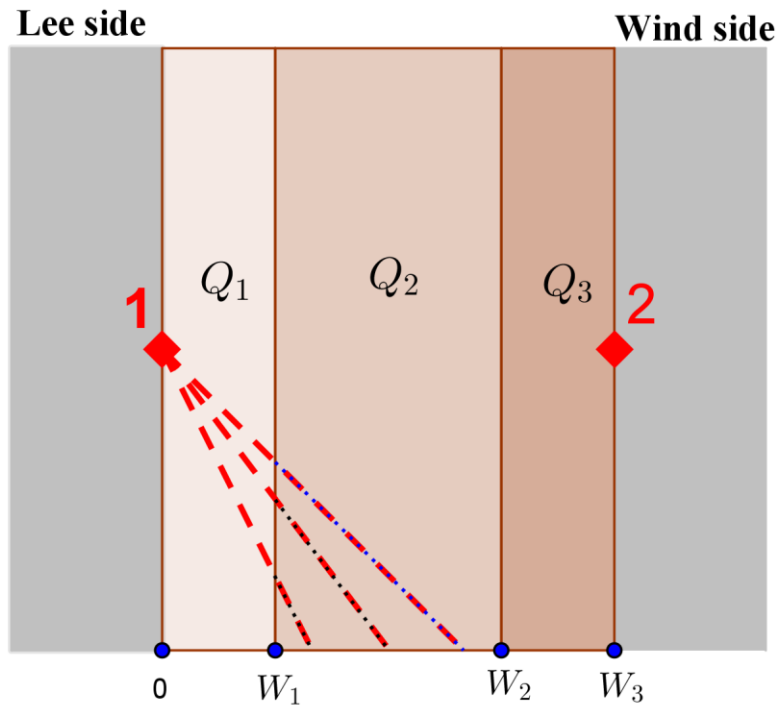
Figure 555 Illustration of the integration paths (red dotted lines) for an arbitrary wind direction for the two receptors in the canyon. The upper blue dotted line marks a critical wind direction (θ_l) which affects the calculation of the integration path length, and L_b is at the length to the end of the canyon used to calculate the maximum integration length (L_{max}). L_{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.



1

2 Figure 666 Cross-section of a street canyon with the dimensions of the recirculation zone
 3 illustrated. The red arrows represent the street level wind direction. Based on (Hertel and
 4 Berkowicz, 1989) p. 69

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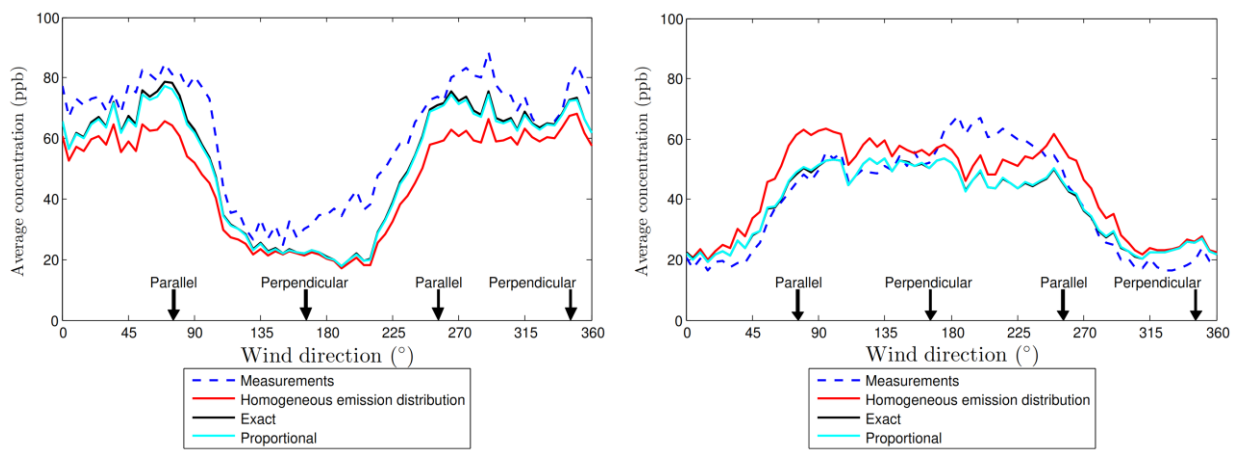


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2 Figure 777 Illustration of the division of the street canyon into a number of segments with
 3 accumulated widths W_1, W_2, W_3, \dots and emission strengths Q_1, Q_2, Q_3, \dots . The red dotted
 4 lines represent the integration path for receptor 1 for different wind directions. The blue
 5 dotted lines represent the contribution from segment Q_2 .

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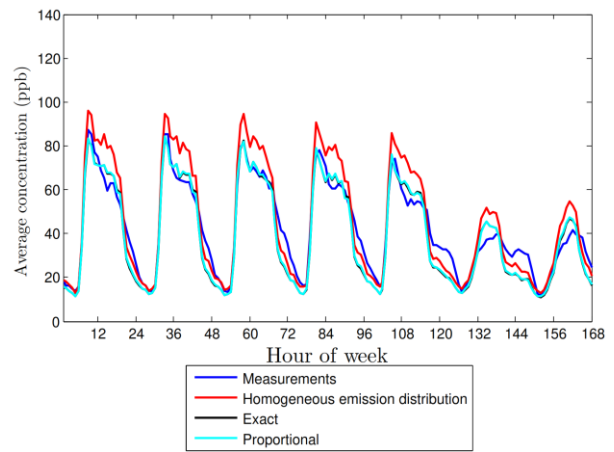
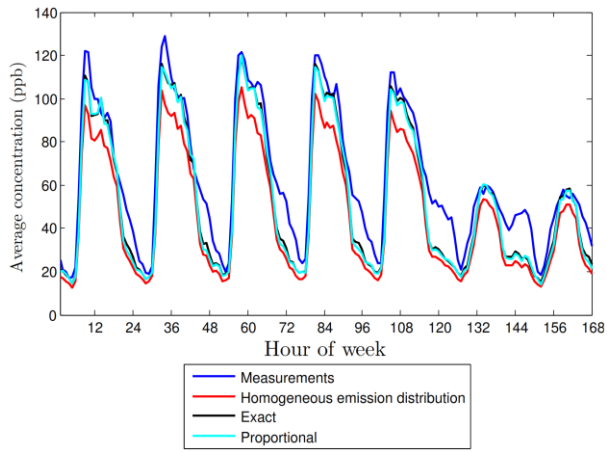
| 1 ~~dotted~~
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2 Figure 888 Mean NO_x concentrations as a function of wind direction for the period 2007-2009
 3 for the North side receptor (left side) and the South side receptor (right side). Where the black
 4 curve is hardly visible it is identical to the cyan curve.

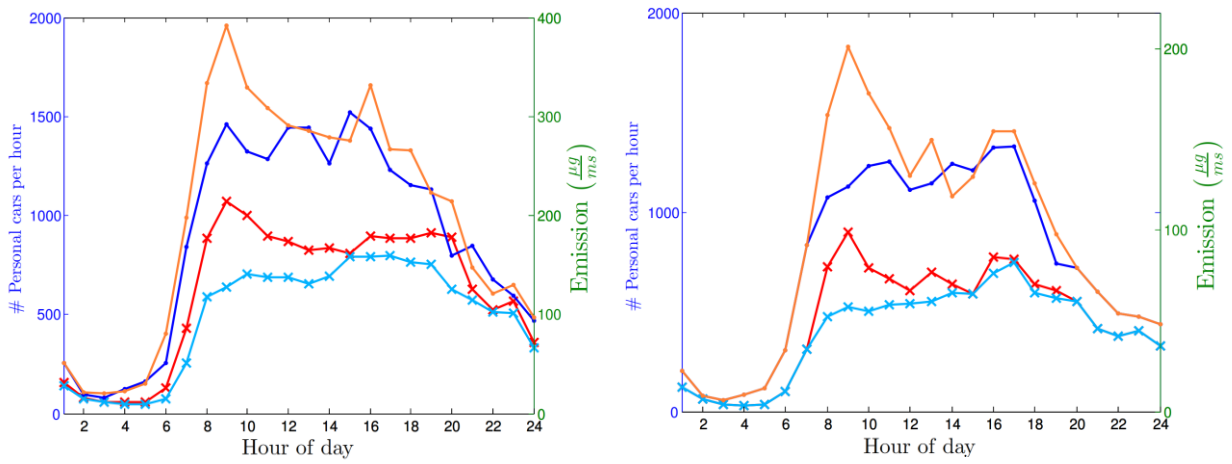
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2 Figure 999 Weekly variation in NO_x concentrations for the period 2007-2009 for the North
 3 side receptor (left) and the South side receptor (right). Where the black curve is not visible it
 4 is below the cyan curve.

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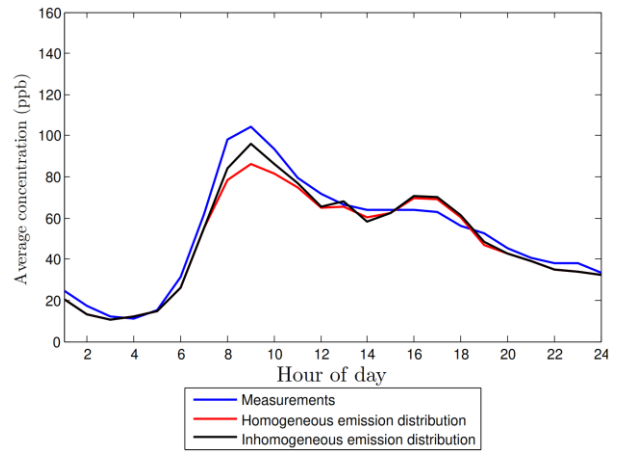
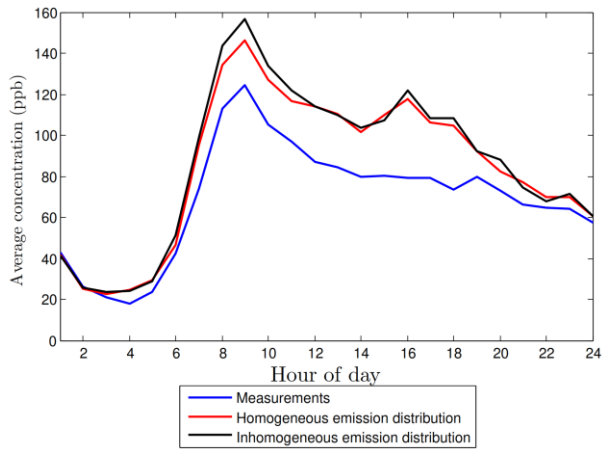


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2 Figure ~~101010~~ Diurnal variation for weekdays in personal cars per hour and total NO_x
 3 emissions for for all vehicles for 2003 (left) and 2013 (right). The red and orange graphs are
 4 for the northeast direction and the blue graphs are for the southeast direction. The curves
 5 marked with dots are the emissions and the curves marked with crosses are the number of
 6 personal cars per hour.

7

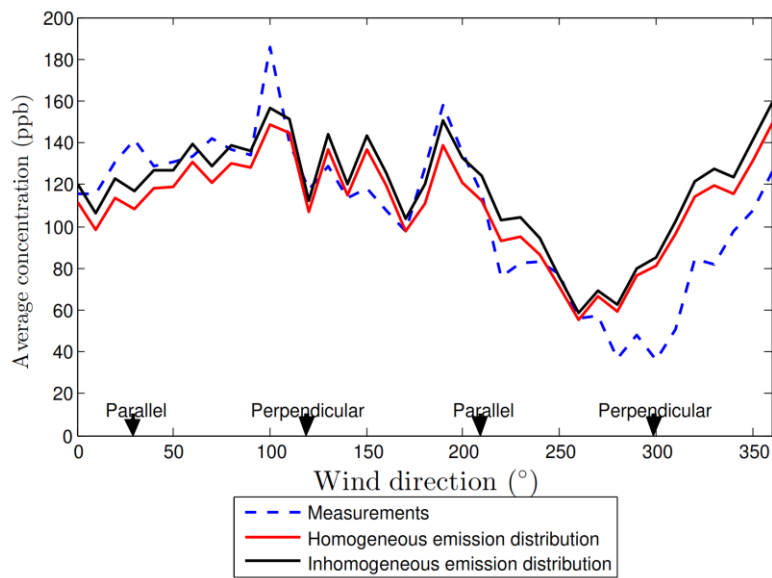
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2 Figure 111111 Diurnal variation in NO_x concentrations on weekdays for 2003 (left) and 2013
 3 (right).

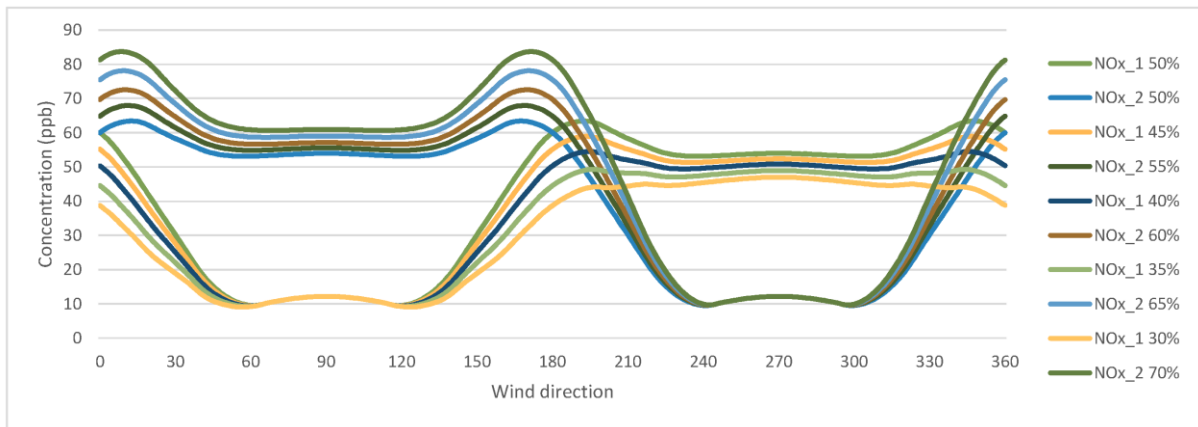
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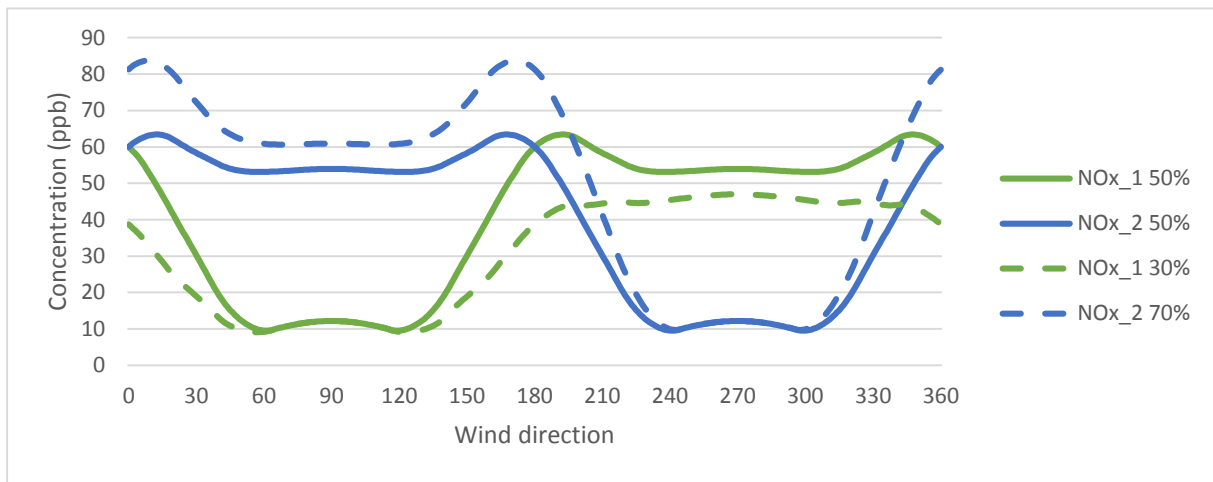
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2 Figure [121212](#) Average NO_x concentrations as a function of wind direction for the morning
 3 rush hour 7am-9am for both 2003 and 2013.

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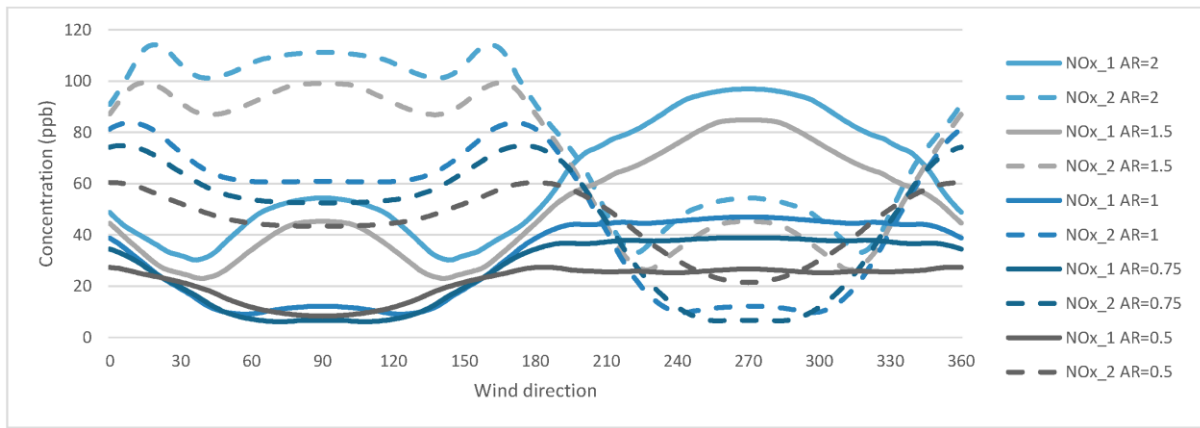
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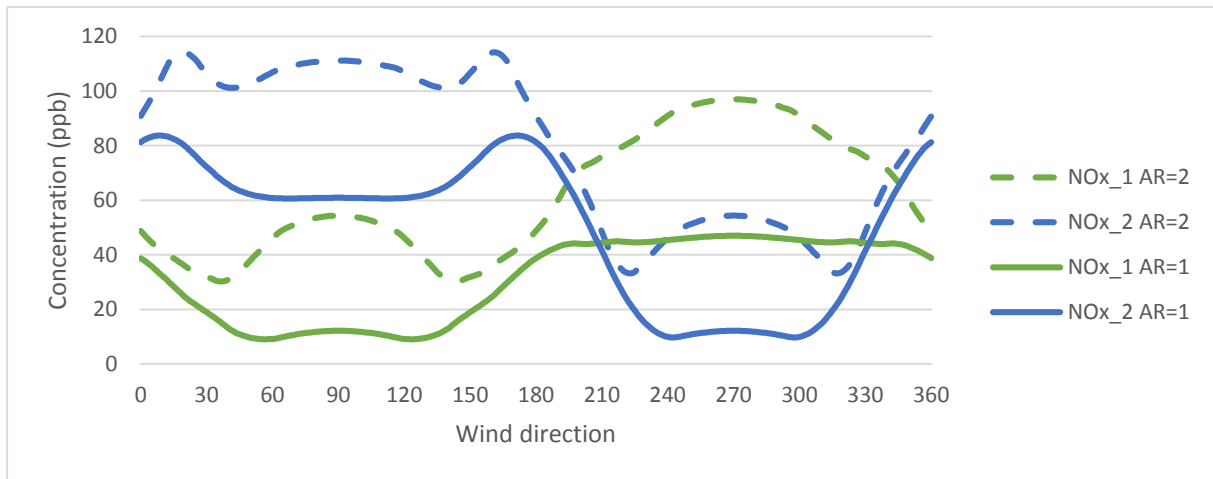
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3 Figure ~~131313~~ Theoretical calculation of the concentration for the two receptors for a street
 4 canyon with two emission segments each covering half the street width and an aspect ratio of
 5 one as a function of the emission inhomogeneity and wind direction. Receptor 1 is marked
 6 with green colour and receptor 2 is marked with blue colour. The inhomogeneity is given as
 7 percentages of the total emission for the two segments and the inhomogeneous case is marked
 8 with dotted lines. ~~The street orientation is 0° so the street runs North-South. The calculation~~
 9 ~~is performed with a wind speed of $3.5 \frac{m}{s}$ a total emissions of $250 \frac{\mu g}{ms}$, and no urban background~~
 10 ~~concentration. Conditions are corresponding approximately to the average condition at~~
 11 ~~Hornsgatan.~~

12



1



2

3 Figure 141414 Theoretical calculation of the concentration for the two receptors for a street
 4 canyon with an emission inhomogeneity of 70% (north going) / 30% (south going) as a
 5 function of aspect ratio (AR) and wind direction. Receptor 1 is marked with green colour and
 6 receptor 2 is marked with blue colour. The case with high aspect ratio is marked with dotted
 7 lines. The calculation is performed with a wind speed of $3.5 \frac{m}{s}$, total emissions of $250 \frac{g}{ms}$, and
 8 no urban background concentration. Conditions are corresponding approximately to the
 9 average conditions at Hornsgatan.

10

1 Table 146 Overview of the properties of the two street canyons used for validation of the
 2 dispersion schemes in the study. There is a measurement station (receptor) at each side of the
 3 street in Hornsgatan, but only one measurement station on the East side of Jagtvej.

Name:	Hornsgatan	Jagtvej
City	Stockholm	Copenhagen
Country	Sweden	Denmark
Latitude	55 ° N	59 ° N
Width	24m	25m
Height	24m	22m
Years in analysis	07, 08, 09	03, 13
Street orientation	76 °	30 °
Average daily traffic	35.500	20.000
Mean vehicle speed (km/h)	45	29
Heavy duty share	4%	3%
Receptor height	3.0m(North) 3.3m(South)	3.6m (East)

4

5

1 Table 2 Level of service as a function of total number of vehicles per hour based on
2 (Vägverket and SMHI, 2007)

Level of service	Total number of vehicles per hour
Freeflow	<601
Heavy	601 – 899
Saturated	900 – 1399
Stop + Go	>1400

3

4

1 Table 3 Table of upper integration limits for respectively ~~equationEq. 3(33)~~ (x_{end}) and
 2 ~~equationEq. 5(55)~~ (x'_{end}). The definition and calculation of the lengths can be found in [Table](#)
 3 ~~4Table4Table 4~~.

Magnitude:	x_{end}	x'_{end}
$L_{rec} > x_{esc} > L_{max}$	L_{max}	-
$L_{rec} > L_{max} > x_{esc}$	x_{esc}	L_{max}
$x_{esc} > L_{rec} > L_{max}$	L_{max}	-
$x_{esc} > L_{max} > L_{rec}$	L_{rec}	-
$L_{max} > x_{esc} > L_{rec}$	L_{rec}	-
$L_{max} > L_{rec} > x_{esc}$	x_{esc}	L_{rec}

4

5

1 Table 4 Table of the critical lengths along the integration path. These lengths determine the
 2 upper and lower limit of the integrals in the homogeneous emission dispersion scheme and of
 3 the sums in the inhomogeneous emission dispersion scheme. Moreover, they determine if the
 4 dispersion should be calculated according to [equation Eq. 3-\(33\)](#) or [equation Eq. 5-\(55\)](#) plus
 5 whether the concentration should be multiplied with f_{ext} as defined in [Eq. equation-6 \(6\)](#). f_{red}
 6 is the shortening function as defined in [equation Eq. -6\(6\)](#), H_u is the upwind building height,
 7 θ_{street} is the wind direction compared to the street direction, θ_l is the critical wind direction
 8 as illustrated in [Figure 5Figure-5Figure-5](#), W is the street width, L_b is the length from the
 9 receptor to the end of the street as illustrated in [Figure 5Figure-5Figure-5](#), and h_r is the height
 10 of the inlet of the receptor above street level.

Name:	Expression:			Description:
L_{rec}	$2 \cdot f_{red} \cdot H_u$			Length of the recirculation zone
x_{esc}	$\frac{u_{street}(H_g - h_0)}{\sigma_w}$			Length where the plume starts to disperse vertically out of the canyon.
x_{start}	$\frac{u_{street}(h_r - h_0)}{\sigma_w}$:	$h_r \geq h_0$	Length where the vertical dispersion of the plume equals the height of the receptor.
	0	:	$h_r < h_0$	
L_{max}	$\frac{W}{\sin(\theta_{street})}$;	$\theta_{street} > \theta_l$	Maximum integration path length.
	$\frac{L_b}{\cos(\theta_{street})}$;	$\theta_{street} < \theta_l$	

11

12

1 Table 5 Correlation coefficient, Fractional Bias, and Normalised Mean Square Error for the
 2 years 2007-2009 for the North side receptor. “Exact” and “Proportional” refer to the emission
 3 modelling approaches described in section 2.1. Moreover, the measured and modelled annual
 4 mean NO_x concentrations for the individual years are also shown. These are calculated as
 5 local street contribution only i.e. the background concentration subtracted from the

	Measured	Homogeneous emissions	Inhomogeneous emissions	
			Exact	Proportional
Correlation coefficient (R^2)		0.85	0.85	0.85
Fractional Bias (FB)		-0.30	-0.16	-0.17
Normalised Mean Square Error (NMSE)		0.36	0.26	0.26
Annual mean 2007 (ppb) (ΔC)	56.8	44.3	53.0	51.3
Annual mean 2008 (ppb) (ΔC)	53.9	37.7	44.2	44.2
Annual mean 2009 (ppb) (ΔC)	53.9	35.0	40.5	40.2

6 measured/modelled street concentration to reflect the street contribution.

7

8

- 1 Table 6 Statistical quantities for the South side receptor. Same definitions as in [Table 5](#)
- 2 [Table 5](#).

	Measured	Homogeneous emissions	Inhomogeneous emissions	
			Exact	Proportional
Correlation coefficient (R^2)		0.83	0.84	0.84
Fractional Bias (FB)		0.08	-0.08	-0.07
Normalised Mean Square Error (NMSE)		0.27	0.28	0.28
Annual mean 2007 (ppb) (AC)	32.7	41.2	33.1	33.6
Annual mean 2008 (ppb) (AC)	34.5	37.2	31.0	31.0
Annual mean 2009 (ppb) (AC)	34.6	34.5	29.1	29.2

1

	<u>Measured</u>	<u>Homogeneous emissions</u>	<u>Inhomogeneous emissions</u>	
			<u>Exact</u>	<u>Proportional</u>
<u>Correlation coefficient (R^2)</u>		<u>0.83</u>	<u>0.84</u>	<u>0.84</u>
<u>Fractional Bias (FB)</u>		<u>0.08</u>	<u>-0.08</u>	<u>-0.07</u>
<u>Normalised Mean Square Error (NMSE)</u>		<u>0.27</u>	<u>0.28</u>	<u>0.28</u>
<u>Annual mean 2007 (ppb) (ΔC)</u>	<u>32.7</u>	<u>41.2</u>	<u>33.1</u>	<u>33.6</u>
<u>Annual mean 2008 (ppb) (ΔC)</u>	<u>34.5</u>	<u>37.2</u>	<u>31.0</u>	<u>31.0</u>
<u>Annual mean 2009 (ppb) (ΔC)</u>	<u>34.6</u>	<u>34.5</u>	<u>29.1</u>	<u>29.2</u>

2