Response to anonymous Reviewer #1

We would like to thank the anonymous Reviewer #1 for his/her comments and suggestions for improving this manuscript. Our response to the reviewer's comments is provided below. The reviewer's comments are written in italic.

This paper has used road dust emission models to investigate the impact of studded tyre use on PM10 concentrations. The science is sound and the paper warrants publication once the following have been addressed:

Introduction In the Introduction it is mentioned that non-exhaust emissions are one of the most important causes of high roadside PM10 concentrations for several decades. However not details their overall contribution is given. Recent figures from the European Environment Agency state that ". In 2016, the non-exhaust emissions of
PM2.5 constituted 42 % of emissions from the road transport sector, compared with17 % in 2000 (for PM10, the contribution increased from 30 % in 2000 to 60 % in2016)". https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-ofair-pollutants-8/transport-emissions-of-air-pollutants-6

Answer:

The reviewer is correct. Overall contribution from the suggested source has been included in the revised manuscript with a sentence: 'Estimated relative contribution of non-exhaust emissions to the emissions of PM_{10} from road transport increased from 30 % in 2000 to 60 % in 2016.' Reference to the European Environment Agency will be included.

Traffic data It's not clear what traffic speed was used in the models. A number of mentioned (weekday daytime, night-time, weekly and monthly). Given that emissions are speed dependent this is important. If there's increased braking and accelerating) this results in additional wear of both the tyre and the road surface. As such would one solution to reduce PM10 concentrations be a lower speed limit? It is noted that it is acknowledge that the NORTRIP model does not account for congested driving conditions but what likely error does this introduce?

Answer:

In order to clarify derivation of the traffic speed for Hämeentie, we have rewritten the sentence in question in the following manner: 'The vehicle speeds for the night-time hours and weekend days were evaluated using the measured diurnal and weekly cycles of vehicle speeds in Runeberginkatu (located 2 km southwest from Hämeentie) in 2004.' Fig. 1 below shows derived average diurnal cycle of traffic volume and speed for years 2007-2009 and 2014. Modelled emissions and PM10 concentrations resemble the diurnal cycle of traffic volume.

We agree with the reviewer that the reduction of the speed limit would be a potential abatement measure for the ambient air PM10 concentrations. However, for Hämeentie where average daily vehicle speed is already very low (26 km/h), and its further reduction would not be possible in practise. We therefore considered it more important to investigating impact of studded tyre reduction and traction control measures.

The congestion could be a source of error but no measurements are available to quantify this. The treatment of the road wear in the NORTRIP model is based on vehicular speed and not on acceleration. Additionally, as acknowledged in the section 3.2.1 of the revised manuscript, the form of the dependency of road wear on vehicle speed in low speed conditions is uncertain.

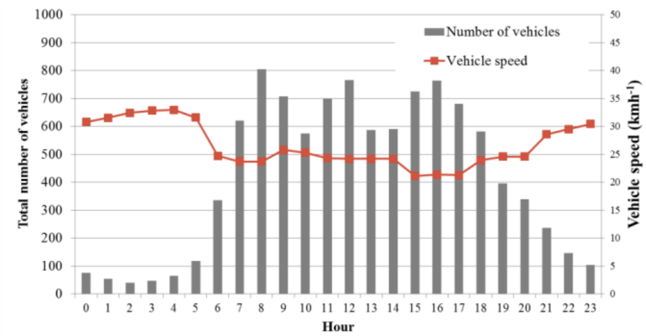

Figure 1. Diurnal cycle of traffic volume and vehicle speed at Hämeentie averaged over the four years (2007-2009 and 2014).

Meteorological data How is snowfall taken into account with total precipitation?

Answer:

In NORTRIP model input, precipitation is included as either rain (mm/h) or snow (mm/h). In case when only information about the total precipitation is available, snowfall is defined as being precipitation for atmospheric temperatures below zero. However, if data is available separately for the precipitation of rain and snow, these values can be used as such in the NORTRIP model input. The FORE model allows one input value for precipitation (mm/h), i.e., it does not separate between solid and liquid water precipitation. We will include a description of these to the revised manuscript.

Road maintenance data Are the roads washed during the summer? Street cleaning is shown in Table 3 but not Figure 3 Does snow ploughing have any impact?

Answer:

Information about the street cleaning and ploughing events will be added to the Figure 3 in the revised manuscript. Street cleaning is typically conducted after the cold season, as soon as weather permits, i.e. when freezing temperatures subside in spring. For the years considered in this study, all street cleaning activities took place from mid-March until the end of April. In the road dust emission modelling, ploughing was taken into account only by the NORTRIP model. Ploughing reduces the amount of dust on the street surface with the predefined efficiency factor, which is expected to be very low. In the NORTRIP model application for Hämeentie, this is set to be 1% and 0.1% for the non-suspendable and suspendable fraction of the road dust, respectively. The same efficiency has been assumed for the street cleaning. We have included a description of the street cleaning and ploughing efficiencies to the section 2.2.1 in the revised manuscript.

The road dust emission model NORTRIP Need to justify why the amount of suspendable material in sand was set to 2%.

Answer:

Measurements of the sand size distribution are required in order to identify fraction of the sanding material that is available for suspension. The data concerning this aspect of sanding material quality is often limited, if available at all. In this study we have used information about the size distribution for sand used in Helsinki Metropolitan Area reported in Kulovuori et al. (2019) that have found amount of suspendable fraction (<200µm) to range from 0.4 % to 2.5 %. Lower suspendable fraction has been found for wet sieved sanding material and higher for the sand with unknown sieving status. We have assumed value of 2%. The reference has been added to the revised manuscript and quality of sanding material will been discussed in Section 3.3.

Evaluation of the vehicular exhaust emissions given that the paper relates to PM10 emissions why not use PM10 emissions instead of those of PM2.5?

Answer:
LIPASTO emission modelling system that was used for evaluation of the exhaust emissions does not separate PM_{10} and $PM_{2.5}$ exhaust particle emissions. These emissions are addressed as 'exhaust particulate matter emissions', i.e. 'exhaust PM emissions'. Only a very small fraction (or none) of the exhaust emissions are in the coarse particle range (larger than 2.5 micrometres). This has been corrected in the revised manuscript.

Results and discussion To save any confusion for readers specify seasons as winter (1 Jan to 14 March etc)
Answer:
The suggested correction has been included in the revised manuscript.

Comparison of predicted and measured PM10 concentrations state the statistical significance of R2 values.
Answer:
More detailed statistical analyses, and their interpretation, have been included as annex in the revised manuscript.

General discussion There should be some consideration of alternatives to road salt given the numerous papers which have highlighted the environmental impact of it.
Answer:
In Finland, sanding is considered as the main alternative traction control method in the areas with sensitive environment to the use of salt (e.g., in areas, in which the ground water supplies could be contaminated). The use of wood chips has been examined by the Finnish Transport Infrastructure Agency as an alternative traction control method but only for the bicycle lanes. This will be mentioned in the section 3.3 in the revised manuscript.

Studless winter tyres are becoming more popular – should Finland make this on option?
Answer:
The reduction of studded tyre use is a feasible option for the road dust abatement, also in Finland. However, policy measures, such as studded tyre charges in Norway or studded tyre ban in individual streets in Sweden, have not been introduced in Finland. Non-studded winter tyres have not gained a wider popularity among drivers, apart from their moderate increasing trend in the Helsinki metropolitan area. Average share of light duty vehicles with studded tyres observed between December and February (inclusive) decreased from 80% in the season2014/2015 to 75% in the season 2018/2019 in favour of the non-studded winter tyres.

In this study, we have demonstrated the potential to reduce the impact of non-exhaust traffic induced particle emissions on ambient air PM10 concentrations, with transition from studded to non-studded winter tyres (Section 3.3). In studied cases with reduced number of vehicles using studded tyres, studded tyres were reduced in favour of non-studded winter tyres. More discussion will be added on this subject to the revised manuscript.

There should be a discussion about the impact of different road surfaces onPM10 emissions (e.g. concrete, more durable asphalt). It is also important to highlight that the wear of the road surface increases with moisture level. Additionally after salting the road surface remains wet for longer periods and so road wear increases.
Answer:
The reviewer is correct. We have expanded Section 3.2.1 with more information about the wear rates used in this study in context of the road surface characteristics. At the same time, impact of road surface moisture on the wear is mentioned. Added paragraph is as follows:' In this study, we have used wear rates derived for the reference pavement type (SMA16 with porphyry from Älvdalen) in the Swedish road wear model (Jacobson and Wågberg, 2007) which is one of the most wear resistant asphalt pavements used in Sweden. The wear rates in the Swedish road wear model are based on laboratory and field experiments and provide an average under both dry and wet conditions. However, influence of surface moisture that increases the wear is not directly considered in the model calculations. Denby et al. 2013a estimated the typical wear rates to be from 2 to 5 g km^{-1} veh^{-1} and acknowledged significantly variation of these values depending on the material used with increased wear rates for roads with the poor quality surfaces.'

Additionally, improvement of pavement quality in terms of the rock aggregate size and durability, or use of alternative pavements has been mentioned as a factor that will enhance air quality benefits along with the studded tyre reduction. Following paragraph has been added to the section 3.3: 'The effect of the studded tyres reductions can be enhanced by improving the quality of road surfaces. Larger aggregate size from rocks that are more resistant to wear in the asphalt pavements, or use of alternative pavements can reduce PM10 emissions (Gustafsson et al. 2009; Gustafsson and Johansson 2012) and therefore, have positive effect on the ambient air PM10 concentrations.'

Typographical Check the spelling of "tyres" as in some places there is "tires". I would also prefer the use of "roads" rather than "pavements"

Answer:

Suggested corrections regarding the spelling and terminology have been included in the revised manuscript, e.g. 'pavement wear' has been replaced with 'road wear'.

The road dust emission model FORE The model uses empirical reference emission factors which depend on the : : :. (note factors and depend)

Answer:

The sentence in question has been replaced with the following: 'The model uses empirical reference emission factors, which have different values depending on the time of the year, the mass fraction of particles (PM_{10} or $PM_{2.5}$), and the traffic environment (urban or highway). The reference emission factor will be higher for the time of the year when sanding and studded tyres are commonly used (referred to as 'sanding period') compared to the rest of the year ('non-sanding period').'

References:

Gustafsson, M., Blomqvist, G., Gudmundsson, A., Dahl, A., Jonsson, P., Swietlicki, E.: Factors influencing PM10 emissions from road pavement wear. Atmospheric Environment 43 (31), 4699e4702, 2009.

Gustafsson, M. and Johansson, C.: Road pavements and PM10. Summary of the results of research funded by the Swedish Transport Administration on how the properties of road pavements influence emissions and the properties of wear particles, Trafikverket, Report 2012:241, 2012.

Kulovuori, S., Ritola, R., Stojiljkovic, A., Kupiainen, K., Malinen, A.: Katupölyn lähteet, päästövähennyskeinot ja ilmanlaatuvaikutukset – Tuloksia KALPA-tutkimushankkeesta 2015–2018. HSY publications 1/2019, in Finnish, summary in Endglish, URL: https://www.hsy.fi/sites/Esitteet/EsitteetKatalogi/Julkaisusarja/1-2019-katupolyn-lahteet-paastovahennyskeinot-ja-ilmanlaatuvaikutukset-KALPA-2015-2018.pdf

Response to anonymous Reviewer #2

We would like to thank the anonymous Reviewer #2 for his/her comments and suggestions for improving this manuscript. Our response to the reviewer's comments is provided below. The reviewer's comments are written in italic.

General comments

1. This manuscript presents some interesting results, but the paper itself is currently written insufficiently well to be published in ACP. Examples of this include:

a. References to tables in the text without any explanation of what is in the table e.g. P3 L31 'The traffic data is summarized in Table 1'. A good quality paper would say what traffic data are summarised, and comment on the values in the table. References to all tables and figures should be reviewed.

Answer:

The reviewer is correct. We have carefully checked the presentation of all the figures and tables, and added a proper discussion to all of these.

We have also removed one table that contained results that were already presented in a figure (Table 8 in the reviewed version of the manuscript). The key information in Table 6 in the reviewed manuscript was condensed to one sentence of text, and that table was removed.

b. The paper takes a standard format 'Intro, data, models etc'. However, information is not always provided in the right sections. e.g. some details of the modelling parameters are given in the introduction, and some more general text is given later in the paper, when it should come earlier. Some examples of where this has been done are given in the technical comments section below, but this list is not exhaustive. The paper should be read carefully by the authors to make sure that all information is in the correct section. This would make the paper easier to follow.

Answer:

We have carefully checked the whole manuscript, and tried our best to place all the information into the proper sections.

For instance, the comments on when winter tyres are obligatory were removed from the introduction (this has been presented in section 2.1.2), and part of the text that was in 'methods' (containing results) has been moved to 'results'.

2. There are some sections where insufficient information is provided regarding terminology. This makes comprehension difficult for a reader not familiar with the topic of Northern European non-exhaust. If terminology was better explained, the paper would be of interest to a wider readership.

Answer:

Regarding 'the street increment of PM_{10}', we have added a brief characterisation to the abstract. The detailed definition of this concept is in the beginning of section 3 (Results). Additionally, explanation of the non-exhaust increment of PM_{10} has been added to section 3 in the revised manuscript.
However, it is not totally clear to us, which concepts the reviewer is referring to; key concepts of non-exhaust emissions are given in the introduction.

Specific comments

3. The title says road dust, but by P1 L17 the text talks about PM10 – and from then on the pollutant is also exclusively referred to as PM10. PM2.5 is mentioned later, but this distracts from the focus of the paper – if this is mentioned, more needs to be said on the proportion of PM10 that is PM2.5 during the episodes. There needs to be an explanation of how these relate; consider changing the manuscript title to refer to PM10.

Answer:

We have improved the title of the manuscript (as per reviewer comment) to be more specific, the revised version reads: "… ambient air PM_{10} concentrations originated from road dust …. ". In the whole of the manuscript, we have also checked the terminology throughout the text. It is made clear in the revised version that we address PM_{10}. All the references to $PM_{2.5}$ are removed as unnecessary.

4. The measurements recorded at the study site need to be put into context early on in the paper e.g. values compared to EU and WHO AQ standards.

Answer:

In this study, we have focused on the street increment PM_{10} concentrations; thus we have not addressed measured kerbside PM_{10} concentrations in the context of the EU and WHO air quality standards. However, paragraph has been added to the section 3.1 in the revised manuscript relating measurements to the air quality standards.~~, and total observed kerbside PM_{10} concentrations will be included in Table 5 together with the street increment concentrations~~.

5. The figures and tables should be improved to make the paper more attractive e.g.:

a. Figure 1 could be made less wide, so that there is an insert which shows more detail of the actual site – either in schematic form or a photograph. Increase text size. Hospitals are shown in pink not red.

b. Figure 2 is poor – consider text size and legend location.

Answer:

We have carefully re-drawn all the figures in the manuscript. We have also added a new panel to Fig. 1 that shows the immediate surroundings of the measurement site. In our view, all the revised figures are more attractive and understandable, and also technically of a better quality.

6. Include a summary table comparing the FORE and NORTRIP models, including the strengths and weaknesses. Mention dependence on parameters e.g. vehicle speed, traffic volume, HGV/LGV proportions.

Answer:

We have included summarised comparison of the two road dust emission models in the revised manuscript, however, in form of a paragraph. We have chosen this approach since it would be difficult to directly compare these two models that are very much conceptually different, i.e. use different approaches in the calculation of the non-exhaust emissions. A detailed inter-comparison of the structures of the two models would be an extensive task, and that is outside the scope of this study. The included paragraph is as follows: 'The NORTRIP model is a process based model that describes wear processes, traffic induced suspension of accumulated road dust and impact of road maintenance activities (salting, sanding, dust binding, cleaning and ploughing) on both dust load and road surface moisture. It includes dependences on vehicle speed, tyre type, vehicle category (light and heavy duty vehicles) and road surface properties that enable comprehensive evaluation of the road dust abatement measures. The NORTRIP model requires extensive input data that is often not available (e.g. road maintenance data, properties of the road surface). This may present a challenge in application of the NORTRIP model. The FORE model requires relatively much less input data. However, it relies on the reference emission factors which need to be computed based on the local air quality measurements. The FORE model considers two road dust sources, viz. road wear and traction sand. The model does not account for the dependence of emissions on vehicle speed and traffic fleet composition, which limits application of the model for the evaluation of a wider range of measures to reduce road dust.'

7. Section 3.2 on sensitivity analysis is poor – analyses that impact on both non-exhaust models need to be considered. e.g. different met inputs (precipitation), removing brake and tyre wear (this would only affect NORTRIP, but still is shows FORE is insensitive to this, and demonstrates the importance of this component).

Answer:

It is correct that this section was actually not at all a (comprehensive) sensitivity analysis. We have re-written the whole section, and also replaced the previous title by a more descriptive one, i.e., "Evaluation of the uncertainties of the modelling". Our aim here was to analyse both qualitatively and in part quantitatively how large the effects of various key sources of uncertainty could be, but not to present a comprehensive and harmonised sensitivity analysis.

The main aim of this study was to evaluate the effectiveness of mitigation options, not to present a thorough sensitivity analysis. Such an analysis, in a harmonised manner for the both suspension emission models, and for the OSPM model, would be a very extensive research task. For instance, a sensitivity analyses solely for the OSPM model have already been previously published. Sensitivity of the NORTRIP model to a range of parameters (including meteorological parameters) has been studied by Denby et al. 2013. Sensitivity of the FORE model to precipitation and traction sanding input is available from by Kauhaniemi et al. 2011.

8. Consider adding more statistics or analyses that show the improved correlation of NORTRIP over FORE, e.g. an average diurnal profile?

Answer:

The R2 values of hourly mean concentrations have been added in the revised manuscript.
More detailed statistical analyses, and their interpretation, have been included as annex in the revised manuscript.

9. The section describing the NORTRIP model needs significant improvement (P5 L9-34):
a. The paragraph needs to eb expanded to explain what has been taken from previous literature, how relevant these values are, and what assumptions are made in the model.

Answer:

We have revised the section describing the NORTRIP model and tried our best to improve it according to the reviewer's suggestion, however keeping the description brief. The reader is therefore referred to other sources for more detailed description of the model. For example, we clarified that used brake and tyre wear rates were taken from the literature; we included more information about the derivation of the suspension factor; and we added assumption made for the efficiency of ploughing and street cleaning for the removal of the road dust.

b. Is Boulter the right reference here - aren't these the EMEP factors?

Answer:

Boulter is the correct reference that has also been used in the NORTRIP model documentation.

c. How busy is the street? Can you comment on how accurate you think the brake and tyre wear factors are?

Answer:

Tyre and brake weak factors were taken from Boulter (2005) which provides a review of tyre and brake emission factors, generally, with a significantly wide range of values. In the NORTRIP model reasonable values have been taken within this range. It would be possible to, for example, investigate accuracy of modelled contribution of the brake and tyre wear against the source apportionment studies for the ambient air PM_{10} samples, e.g., using the method described by Kupiainen et al. 2016. Unfortunately, such analyses were not available.

d. Sentence starting 'In model formulation...' is not a sentence.

Answer:

The sentence in question has been revised in the following manner: 'The road wear and suspension are assumed to be linearly dependent on vehicle speed.'

e. L13 – say 'The road dust model emission calculation…'

Answer:

The suggested correction has been included in the revised manuscript.

f. L28 How does 'ploughing' relate to the activities in Table 2?

Answer:

Information about ploughing events during the study period has been included in the Table 2 and in the Figure 3 in the revised manuscript.

g. P29 provide reference for 2%.

Answer:

Measurements of the sand size distribution are required in order to identify fraction of the sanding material that is available for suspension. The data concerning this aspect of sanding material quality is often limited, if available at all. In this study we have used information about the size distribution for sand used in Helsinki Metropolitan Area reported in Kulovuori et al. (2019) that have found amount of suspendable fraction (<200µm) to range from 0.4 % to 2.5 %. Lower suspendable fraction has been found for wet sieved sanding material and higher for the sand with unknown sieving status. We have assumed value of 2%. The reference has been added to the revised manuscript and quality of sanding material will been discussed in Section 3.3.

10. P6 L15 This is a very high roughness value. Justify comparing to values in the literature for similar urban environments. Are you sure that this z0 represents the vicinity of the site, and is not just a value derived from the building heights on the street in question?

Answer:

The average building height is 26 m on the studied street canyon (including study site and immediate surroundings). Thus, the value of z0 is derived from the average building height in the street canyon in question. The value of z0 represents local conditions (i.e. studied street canyon and immediate neighbourhood within the distance scale of about hundred meters), not wider area (e.g. scale of kilometres) around the studied street canyon.

11. Section 2.1.3 Comment on the representativeness of the met for the study area. Could 'spring' be indicated on Figure 2; also the concentration time series should be put on this graph.

Answer:

Comment regarding the representativeness of the meteorological data has been included in the revised manuscript with the paragraph: 'Using meteorological data at two urban stations could result in reduced representatives of the micrometeorological processes. Particularly, small-scale rain showers could be detected at the urban meteorological stations, but not at the study site, or the other way around.'

The observed street increment of PM_{10} has been presented in Fig. 4 for years 2009 and 2014. We felt that as Fig. 2 is in our view busy as it is (already a curve and a histogram, with two vertical axes), adding additional concentration and other information could make it more difficult to read. The total observed PM_{10} concentrations will be included in table 5 as answer to the reviewer's comment #4.

Technical corrections

12. P1 L18 says 'Both models', but 3 models have been listed.

Answer:

In order to clarify to which models we imply, sentence has been modified in the revised manuscript.

13. Last two sentences of the abstract need to be made clearer.

Answer:

Last two sentences of the abstract have been modified in the revised manuscript as follows: 'Modelled contributions of traction sand and salt to the mean annual non-exhaust increment of PM_{10} ranged from 4% to 20% for the traction sand, and from 0.1 % to 4 % for the traction salt. The results presented here can be used to support development of optimal strategies for reducing the high springtime particulate matter concentrations originated from the road dust.'

14. P1 L31 and elsewhere, the manuscript refers to 'pavements' – usual English term is road.

Answer:

The suggested correction has been included in the revised manuscript.

15. Improve spelling e.g. tires in P1 L33.

Answer:

The corrections in spelling have been included in the revised manuscript.

16. Could mention street furniture (P1 L35)

Answer:

In the sentence in question which describes how the road dust particles are commonly formed, street furniture can be considered to be part of the surrounding environment that was listed as a more general miscellaneous source.

17. P2 L12 say what temporal period winter tyres are mandatory.

Answer:

The sentence in question has been removed in the revised manuscript. However, temporal period when winter tyres are mandatory is included in section 2.1.2.

18. P3 L7 – is 'it' building-to-building width?

Answer:

Building-to-building width of the selected segment of Hämeentie is 32 m. Description of the site has been improved in the revised manuscript.

19. P3L7 say why building height relevant, and provide approx. heights. State aspect ratio and comment on porosity.

Answer:

Information about the aspect ratio and porosity of the street canyon has been included in the revised manuscript in the Section 2.2.3.

20. P3 L8 say why the proportion of HDVs is relevant.

Answer:

We have placed information about the HDVs share to section 2.1.2. Relevance of the HDVs will be mentioned in the revised manuscript.

21. P3 L10-12 are the high trees really relevant? Doesn't the low roughness of the sea have more impact on dispersion that a few trees. If mentioning the trees can be justified, make sure they are clear in Fig. 1.

Answer:

Section 2.1.1 describes the structure of the studied street canyon (i.e. building heights and in this case also tree heights) which is used for construction of the street canyon in OSPM model. Thus, in this case, the tree heights are relevant, to properly construct the street canyon right next to the studied street segment. It is not possible to provide roughness value for OSPM and the model considers only the street canyon in question, but not the surroundings of the street. Thus, the sea area that is located several hundred meters from the canyon cannot be considered in model input. Fig. 1 has been revised to include trees.

22. P3 L17-18 Information about what is done in the modelling should be in the modelling section.

Answer:

The sentence in question has been modified in the revised manuscript as follows: 'The average height of the surrounding buildings in the studied segment of the street is 26 m.'

23. P3 L31 The traffic data ARE … ditto P4 L4

Answer:

The suggested correction has been included in the revised manuscript.

24. P3 L35 which vehicles

Answer:

Studded tyres are used only on the light duty vehicles. This has been clarified in the revised manuscript.

25. P4 L1 Is this at the beginning or the end of the season?

Answer:

The transition between summer and winter tyres happens at the beginning and at the end of the winter tyre season. In order to clarify this in the revised manuscript, the sentence in question has been replaced with the following: 'For other considered years (2007-2009), such detailed information was not available, and the winter tyre season was therefore set to last from 23 October until 30 April. The transition between winter and summer tyres is assumed to be linear over a one-month period at the beginning and at the end of the winter tyre season.'

26. P4 L6 usually refer to cloud cover rather than cloudiness

Answer:

The suggested correction has been included in the revised manuscript.

27. Section 2.1.4 1st para, should this be in the Introduction?

Answer:

The paragraph has been moved to the Introduction in the revised manuscript.

28. Section 2.1.4, last sentence – should be later in manuscript.

Answer:

The last to sentences have been removed in the revised manuscript. Information about the road maintenance considered by the road dust emission models has been included in the section 2.2.1.

29. P4 L30 'made' not 'done'.

Answer:

The suggested correction has been included in the revised manuscript.

30. Section 2.1.5 re-word last sentence to make clearer.

Answer:

The sentence in question has been moved to the results section in the revised manuscript. The sentence has been rewritten as follows: 'The urban background contribution to the concentrations measured at the street level in Hämeentie was substantial, i.e., 64%, averaged over the two years with available data (2009 and 2014).'

31. P6 L4 justify use of reference emissions factors for the current study,

Answer:

The paragraph regarding the reference emission factor in FORE has been revised and currant version reads: 'We have adopted the reference emission factors evaluated for Stockholm estimated and further explained by Omstedt et al. (2005); i.e., 1200 and 200 µg veh^{-1} m^{-1}, for the sanding (Oct-May) and non-sanding (Jun-Sep) period, respectively. The climatic conditions, studded tyre shares and the procedures of using traction sand are fairly similar in Stockholm and Helsinki, although the difference in the used amounts of sand and salt can be significant.'

32. P6 L10/11 – sentence doesn't make sense.

Answer:

The sentence in question has been modified in the revised manuscript as follows: 'The dust layer is reduced by the resuspension of particles due to the air flow and by runoff due to precipitation.'

33. P6 L12-14 explain further

Answer:

The sentences in question have been replaced with the following:

'The suspension of road dust particles in the air is controlled by road surface moisture that is based on modelling of precipitation, runoff, and evaporation. The effect of terrain on wind is defined by roughness length which is needed for the evaluation of the evaporation (Omstedt et al. 2005).'

34. P6 L16 Why quote/use different units if they are equivalent?

Answer:

The units have been removed in the revised manuscript.

35. P6 L16 – 28 – Is any of this relevant to the NORTRIP model – if it is, it is in the wrong section.

Answer:

Adjustment of the studded tyre share has been done only for FORE model. The content has been replaced in the revised manuscript with the following paragraph: 'The model does not allow for the dependencies of emissions on vehicle speed and fleet composition. As studded tyres are only used in light duty vehicles (LDV's), the share of studded tyres in the total traffic fleet is relatively lower in Hämeentie. In the FORE model, we have used as input the studded tyre share of the whole traffic fleet of Hämeentie, including both light duty and heavy duty vehicles. For instance, assuming that 80%, 50%, 30% or 0% of the LDV's uses studded tyres, the studded tyre share of the whole traffic fleet is approximately 57%, 35%, 21% and 0%, respectively.'

36. P6 L16-19 – this section is supposed to be on FORE, not the study.

Answer:

The reviewer is correct. Sentences describing the study site have been removed in the revised manuscript.

37. Section 2.2.2 Last sentence: explain why not and how much uncertainty this introduces e.g. is the traffic stop-start, or continuous?

Answer:

Detailed information about the speed dependence of PM exhaust emission factors was not available in LIPASTO data base. The LIPASTO exhaust emission factors were only available for so-called "street" and "road" speeds. These so-called "street speed" emission factors consider non-continuous driving style.

38. General comment: mention if the traffic in the model given a time-varying emission profile. This may be important due to the non-linear relationship between emissions, meteorology and resultant concentrations.

Answer:

Yes, the modelled non-exhaust and exhaust emissions have time-varying profile, due to the dependency on the hourly traffic data. This has been mentioned in the revised manuscript.

39. P7 L3-4 How have these 9 street crossing geometries been taken into account?

Answer:

The geometry of street crossings is considered by wind sectors and so-called building height exceptions in the OSPM model.

40. P7 P6 – why mention NOx in this paper? Chemistry not relevant. Has this section of text been copied from elsewhere without consideration of its applicability to this particular application?

Answer:

The sentence has been removed in the revised manuscript.

41. P7 L8-10 comment on meteorological and background pollutant data capture rates.

Answer:

The comment on meteorological and background pollutant data capture rates has been included with two sentences: 'Meteorological and background concentration data used for the OSPM calculations were very well covered. Data coverage for wind speed and direction, and background concentrations was 97% and 98%, respectively.'

42. P7 L12 specify 'other' models

Answer:

We have revised section 2.2.3 according to the reviewer's comments 19, 21 and 29-41. Significant modifications have been made and sentence in question has been removed in the revised manuscript.

43. P7 L15-16 3 instances of poor punctuation and spelling.

Answer:

We have revised section 2.2.3 according to the reviewer's comments 19, 21 and 29-41. Significant modifications have been made and sentence in question has been removed in the revised manuscript.

44. P7 L19 – 'used as input to the model' rather than 'implemented'

Answer:

The suggested correction has been included in the revised manuscript.

45. P7 L21 say what the model sensitivity analyses demonstrate.

Answer:

As answered to reviewer's comment #7, we have re-written the whole section, and also replaced the previous title by a more descriptive one, i.e., "Evaluation of the uncertainties of the modelling". We have analysed and numerically evaluated selected key uncertainties related to the application of the two road dust emission models, and to the street canyon modelling for the Hämeentie site. This has been stated in the section 3.2.

46. P7 L20-22 – refer to sections

Answer:

References to sections have been added in the revised manuscript.

47. P7 L28, first sentence – but this section starts with a time series?!

Answer:

The notation mentioned in the reviewer's comment #48 has been corrected.

48. P7 L29 is this ACP notation?

Answer:

The notation has been corrected and the sentence in the revised manuscripts reads as follows: 'Seasons were defined as follows: winter (1 Jan to 14 Mar), spring (15 Mar to 31 May), summer (1 Jun to 30 Sep) and autumn (1 Oct to 31 Dec).

49. Table 5 might be more interesting as a bar chart. Stats (NMSE, R, Fac2, Max values) could be of interest because the NORTRIP correlation is better than FORE.

Answer:

More detailed statistical analyses, and their interpretation, have been included as annex in the revised manuscript. However, we will keep the mean annual and seasonal observed and modelled street increments of PM_{10} as a table.

50. P7 L38 – say what 'late' means for those less familiar with the cycle.

Answer:

The sentence has been modified in the revised manuscript and it now reads: '**Night frosts postponed the street cleaning that commonly starts in March, to the beginning of April.'**

51. P8 L5 Improve sense.

Answer:

The sentence has been removed in the revised manuscript.

52. P8 L11-14. These correlation stats are of interest. Are sub-daily observed concentration values available? Inspect the average diurnal variation to see if there is any relation to congestion.

Answer:

The R2 values of hourly mean concentrations have been added in the revised manuscript. As expected, correlation on the hourly level is lower compared with the daily level. This can be attributed to differences in diurnal cycle of the modelled and observed concentrations and to the higher uncertainties in predictions of the surface moisture on hourly level.

We have inspected average diurnal cycles of observed and modelled street increments of PM_{10}, and traffic volume and speed for years 2009 and 2014. The observed concentrations exhibit more pronounced peak during the evening rush hours, whereas diurnal cycle of the modelled PM_{10} concentrations follow closely the diurnal cycle of the traffic volume and demonstrates peaks of the similar order of magnitude.

53. P9 L1 May be non-linear due to congestion.

Answer:

The sentence has been modified in the revised manuscript and reads as follows: 'The dependency on vehicle speed may be non-linear for the lower traffic speeds encountered in this study (< 30 km h^{-1}) due to congestion.'

54. P9 L14-19 Doesn't need a table.

Answer:

Table 6 has been replaced with one sentence of text.

55. P9 L29 Compounds or configurations?

Answer:

The correction has been included in the revised manuscript.

56. P9 last sentence – remove, not of relevance.

Answer:

The sentence has been removed.

57. P10 L11 remind readers not in FORE.

Answer:

This has been clarified in the revised manuscript.

58. P10 Don't need Table 8.

Answer:

Table 8 has been removed.

59. P10 around the 2nd paragraph – say something about the consistency of concentrations. If the models predict consistent concentrations why is there a massive difference in predictions in the Feb / March period?

Answer:

We will revise this section.

60. P10 L19 which met parameters?

Answer:

We refer here to the meteorological conditions in general. This paragraph will be revised.

61. P10 L37 Us the term hypothetical?

Answer:

Correction has been included in the revised manuscript.

62. P10 Can some emissions and concentration source apportionment analyses for the road be presented? i.e. in terms of road wear, tyre wear, brake wear, exhaust, resuspension, winter tyres – for both models?

Answer:

Contribution estimation from different sources to the PM_{10} emissions and concentrations, and separation between direct and suspension emissions are possible only by the NORTRIP model. Such results are important; however, we feel that they are beyond the scope of this study.

63. Section 4, once other revisions to the paper have been completed , Section should be reviewed e.g. P11 L14-15 – the substantial differences need to be made clearer.

Answer:

We will carefully review and revise section 4. We have included a paragraph with comparison of the two road dust emission models as answer to the reviewer's comment #6. This provides also clarification of the substantial differences.

64. P11 L17 Yes!

Answer:

The sentence will be removed in the revised manuscript.

65. Table 3 – where does the '5 and 10' referred to in the caption come from? What does the last sentence in the caption mean? How do these values relate to the road? Are any of these values from EMEP?

Answer:

The factor 5 is based on an estimate of the increased number of tyres and studs for a HDV compared to an LDV. The factor of 10 for suspension is taken from other studies where they have derived this value from measurements and regression. The references to this are given in Denby et al. 2013a.

66. Table 5 (possibly elsewhere) as the models are introduced as NORTRIP then FORE, they should be presented accordingly in the table.

Answer:

Suggested correction has been included in the revised manuscript.

67. Figure 4 – explain why FORE does badly Jan-Mar i.e. predicts much larger values than NORTRIP for that period.

Answer:

During Jan-March occurrence of the clustered precipitation and dry days was recorded. Dust is accumulated during the wet days and released during the dry days, which is in the model controlled by the reduction factor for moisture content. Large values for this period can be a result of not well reproduced impact of real world surface wetness. From Figure 3 it can be noticed that there are several salting events during Jan-Mar in 2009 and 2014. Application of traction salt can keep surface wet for longer periods. Impact of salt is not considered in the FORE model. Some uncertainty can also occur because the snowfall is treated similarly as rainfall in the model. This is a very good question and extensive analyses would be required for more comprehensive answer.

68. Reduce the caption length for Figure 5.

Answer:

The caption of the Figure 5 is modified in the revised manuscript as follows: 'Modelled relative changes in the non-exhaust street increment of PM_{10} for analysed cases described in Table 6, averaged over the four years (2007-2009 and 2014). Line markers show values for the individual years.'

References:

Boulter, P. G.: A review of emission factors and models for road vehicle non-exhaust particulate matter, Wokingham, UK, TRL Limited, TRL Report PPR065, URL: http://uk-air.defra.gov.uk/reports/cat15/0706061624_Report1__Review_of_Emission_Factors.PDF, 2005.

Denby, B.R., Sundvor, I., Johansson, C., Pirjola, L., Ketzel, M., Norman, M., Kupiainen, K., Gustafsson, M., Blomqvist, G., Omstedt, G.: A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (NORTRIP). Part 1: road dust loading and suspension modelling, Atmospheric Environment, 77, 283-300, 2013a

Denby, B.R., Sundvor, I., Johansson, C., Pirjola, L., Ketzel, M., Norman, M., Kupiainen, K., Gustafsson, M., Blomqvist, G., Kauhaniemi, M., Omstedt, G.: A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (NORTRIP). Part 2: Surface moisture and salt impact modelling, Atmospheric Environment, 81, 485-503, 2013b.

Kauhaniemi, M., Kukkonen, J. Härkönen J., Nikmo J., Kangas L., Omstedt G., Ketzel M., Kousa A., Haakana M., Karppinen A.: Evaluation of a road dust suspension model for predicting the concentrations of PM10 in a street canyon, Atmospheric Environment, 45, 3646-3654, 2011.

Kulovuori, S., Ritola, R., Stojiljkovic, A., Kupiainen, K., Malinen, A.: Katupölyn lähteet, päästövähennyskeinot ja ilmanlaatuvaikutukset – Tuloksia KALPA-tutkimushankkeesta 2015–2018. HSY publications 1/2019, in Finnish, summary in Endglish, https://www.hsy.fi/sites/Esitteet/EsitteetKatalogi/Julkaisusarja/1-2019-katupolyn-lahteet-paastovahennyskeinot-ja-ilmanlaatuvaikutukset-KALPA-2015-2018.pdf

Kupiainen, K., Ritola, R., Stojiljkovic, A., Pirjola, L., Malinen, A., Niemi, J.: Contribution of mineral dust sources to street side ambient and suspension PM10 samples, Atmospheric Environment 147, 178-189, 2016.

The impact of measures to reduce ambient air PM_{10} concentrations originated from road dust, evaluated for a street canyon in Helsinki

Ana Stojiljkovic[1], Mari Kauhaniemi[2], Jaakko Kukkonen[2], Kaarle Kupiainen[1], Ari Karppinen[2], Bruce Rolstad Denby[3], Anu Kousa[4], Jarkko V. Niemi[4], Matthias Ketzel[5]

[1]Finnish Environment Institute (SYKE), Helsinki, P.O.Box 140, FI-00251, Helsinki, Finland
[2]Finnish Meteorological Institute, Helsinki, P.O. Box 503, FI-00101, Helsinki
[3]Norwegian Meteorological Institute, P.O. Box 43, Blindern, NO-0313 Oslo, Norway
[4]Helsinki Region Environmental Services Authority, P.O.Box 100, FI-00066, Helsinki, Finland
[5]Department of Environmental Science, Aarhus University, P.O. Box 358, DK-4000, Roskilde, Denmark

Correspondence to: Ana Stojiljkovic (*ana.stojiljkovic@ymparisto.fi)*

Abstract. We have evaluated numerically how effective ~~a few~~ selected potential measures would be for reducing impact of road dust~~.~~ on ambient air particulate matter (PM_{10}). The selected measures included ~~the~~ reduction of the use of studded tyres in light-duty vehicles and ~~the~~ reduction of the use of salt or sand in traction control. We have evaluated these measures for a street canyon locat~~ioned~~ed in central Helsinki~~,~~ for four years (2007-2009 and 2014). Air quality measurements were conducted in the street canyon for two years, 2009 and 2014. Two road dust emission models, NORTRIP and FORE, were applied in combination with the street canyon dispersion model OSPM to compute the street increments of PM_{10} (i.e. fraction of PM_{10} concentration originated from traffic emissions at the street level) within the street canyon. The predicted concentrations were compared with the air quality measurements. Both road dust emission models reproduced ~~the~~fairly well seasonal variability of the PM_{10} concentrations, but under-predicted the ~~yearly~~annual mean values. It was found that the largest reductions of concentrations could potentially be achieved by reducing the fraction of vehicles that use studded tyres. For instance, a 30~~% percent~~ % decrease in the number of vehicles using studded tyres would result in an average decrease of the non-exhaust street increment of PM_{10} from 10 to 22 %, depending on the model used and the year considered. ~~The corresponding decrease after removal~~Modelled contributions of ~~sanding~~traction sand and ~~salting would be~~salt to the annual mean non-exhaust street increment of PM_{10} ranged from 4% ~~and~~to 20% for the traction sand, and from 0.1 % to 4~~%, respectively.~~ % for the traction salt. The results presented here can be used ~~for finding~~to support development of optimal strategies for reducing the high springtime particulate matter concentrations originated from the road dust.

1 Introduction

During the last couple of decades, strict regulations and technological innovations have led to a significant decrease of exhaust particulate emissions from road traffic. However, at the same time the decreases of non-exhaust traffic emissions have been much more moderate or even negligible, partly caused by the fact that these emissions have remained mostly unregulated~~.~~ (e.g., Kukkonen et al., 2018). Estimated relative contribution of non-exhaust emissions to the emissions of PM_{10} from road transport increased from 30 % in 2000 to 60 % in 2016 (EEA, 2018).

The non-exhaust emissions of respirable particles, PM_{10}, include particles formed due to the wear of ~~pavement~~road surface, brakes and tyres, and the suspension of particles that have been accumulated on the road surface~~.~~ and are commonly referred to as road dust. The latter category is ~~commonly~~ originated from (i) the wear of the road surface and the t~~i~~yres, (ii) traction control materials (sand and salt) and (iii) a range of other miscellaneous sources, such as the deposited material from, e.g., road and building construction sites or surrounding environment, and the deposition of materials to the surface from ambient air.

In northern European countries, the non-exhaust emissions have been one of the most important causes of high ambient air PM_{10} concentrations for several decades (e.g., Kukkonen et al., 1999, 2018; Kauhaniemi et al., 2014). These have also resulted in exceedances of the daily PM_{10} limit values set by the European Union (according to these, there should be no more than 35 days with concentrations exceeding 50 µg m^{-3}), especially during spring. In brief, the mechanisms leading to such exceedances are (i) the accumulation of road dust on the ~~street~~road surfaces in winter, (ii) the melting of snow and ice ~~on the street surfaces~~ in spring, and (iii) the release of substantial amounts of suspended dust to the atmosphere from the ~~street~~road surfaces during dry periods.

In the Nordic countries, it is necessary to use traction control measures (winter tyres, traction sanding and salting) during the colder seasons to ensure traffic safety in snowy and icy weather.

The road wear ~~of pavements~~ associated with the use of studded winter tyres has been found to be the most significant source of road dust (Kupiainen, 2007; Denby et al., 2013a; Kupiainen et al., 2016) that contributes to the high PM_{10} concentrations. The use of traction sanding and salting contribute to a lesser degree to the amount of suspended street dust; however, also these contributions may be significant (Denby et al., 2013a; Kupiainen et al., 2016).

~~The use of winter tyres (studded or friction tyres) on light duty vehicles is mandatory by legislation in Finland. In the Helsinki Metropolitan Area, the maximum share of the studded tyres on light duty vehicles is 80 % (~~Salt is commonly the preferred of the two traction control materials, but sanding has to be used in specific weather conditions. ~~REDUST, 2014).~~

~~In the Nordic countries, it is necessary to use traction control materials during the colder seasons, to ensure traffic safety in snowy and icy weather.~~These include in particular the conditions, for which the ambient temperatures are below -5 °C. Salting would then result in the freezing of the salt-water solution, and would not contribute to improving the friction between the tyres and the street surface. The traction sand can directly contribute to the suspendable road dust, if it contains particulate material that has specific grain sizes. There are also other processes, by which traction sand can contribute: (i) via crushing of larger sand grains into smaller particles due to the passage of tyre, and (ii) via abrasion of ~~pavement~~road surface by the contact of crushed stone and sand, and the tyres of passing vehicles. The latter is commonly called ~~as~~ the sandpaper effect (Kupiainen, 2007). According to Denby et al. (2016), approximately 0.5 % of the total salt distributed on the roads can be released to the air as PM_{10}. As approximately 200 000 tons of salt is spread out every year on the roads and streets in Finland, road salt can be a significant source of the elevated PM_{10} concentrations.

For the design of successful mitigation strategies for road dust, it would be valuable to assess contributions of different sources to the PM_{10} concentrations. Then it would also be possible to evaluate the efficiency and impacts of potential abatement measures. Various modelling tools have been developed to facilitate such analyses.

The aim of this study is to evaluate the effectiveness of ~~a range of~~ selected potential ~~mitigation~~ measures for reducing the ~~emission of~~emissions and concentrations of PM_{10} originated from road dust. These measures include the reduction of the use of studded tyres and the minimization of traction control material use. We have evaluated the effects of these measures for a street canyon location in central Helsinki, for four years (2007-2009 and 2014). We have also compared the predictions of the modelling system with the measured concentrations in the street canyon for two years, 2009 and 2014. The non-exhaust PM_{10} emissions associated with vehicular traffic were computed using the road dust emission models NORTRIP (Denby et al., 2013a, 2013b) and FORE (Kauhaniemi et al., 2011). Both emission estimates were then implemented in the OSPM street canyon dispersion model (Berkowicz, 2000) to simulate the concentrations of PM_{10} at the street level.

2 Materials and methods

2.1 Measurements

2.1.1 ~~Description of the measurement~~Study site description

The study was carried out for a ~~selected~~ segment of a major street called Hämeentie, located in central Helsinki. The street segment is extending from south-west to north-east (at an angle of 56 degrees clockwise from the north). The building block that surrounds the air quality measurement site extends over a distance of 91 m. The air quality measurement site was at distances of 56 m and 35 m from the nearest junctions to the north-east and to the south-west, respectively. The average height of the surrounding buildings in the studied segment of the street is 26 m. The location of the study site in the city, and the applied meteorological and air quality stations are presented in Fig 1a. The location of buildings and park areas in the immediate vicinity of this street segment is presented in Fig. ~~1. The street canyon segment contains four lanes paved with stone matrix asphalt (SMA), two to both directions, and it is 32 m wide. The street canyon is surrounded by six and seven-storey buildings. This street is one of the major routes for public transport to the centre of the city; the proportion of heavy duty vehicles is therefore high, approximately 30 % of all the traffic.~~

1b. There is an open area and a small park to the north-east of the measurement site at distances of approximately 60 and 200 m, respectively. There are several high trees in those areas that were estimated to be approximately 10 m high. The street canyon is 32 m wide and it contains four lanes, two to both directions.

~~The street segment is extending from south-west to north-east (at an angle of 56 degrees clockwise from the north). The building block that surrounds the air quality measurement site extends over a distance of 91 m. The measurement site is at a distance of 56 m and 35 m from the nearest junctions to the north and to the south, respectively. The building heights vary from 24 to 25 m in the studied street segment, and from 23 to 28 m in its immediate vicinity. As the variation of these building heights was only few meters, all building heights in the modelling were set to be equal to 26 m for simplicity.~~

2.1.2 Traffic data and the use of studded tyres

The traffic volume data and, weekly and monthly variations of the traffic volume ~~a~~were based on the estimations made by the Helsinki City Planning Department. The ~~yearly~~measured annual average weekday traffic volume is available for 2015 for Hämeentie, and for 2007, 2008, 2009, and 2014 for a street that is a continuation street of Hämeentie, located 600 m south-west from the site, called Pitkäsilta. ~~These values were estimated using the~~

~~measured traffic data from the traffic counting days at these locations and from several permanent traffic counting stations. Yearly~~Annual average weekday traffic volume measured at Hämeentie in 2015 ~~is used~~was adopted for year 2014. For ~~the~~ other considered years, we have used ~~the~~ measured traffic volumes at Pitkäsilta, scaled by the ratio of ~~yearly~~annual average weekday traffic volumes at Hämeentie in 2015 and at Pitkäsilta in 2014.

The average hourly weekday daytime vehicle speeds are based on the values measured ~~at~~during the monitoring campaigns in Hämeentie~~,~~ in 2007, 2009 and 2011. Measured values for 2007 and 2011 were adopted for years 2008 and 2014, respectively. ~~Measured values for 2007 and 2011 were adopted for years 2008 and 2014, respectively.~~ The vehicle speeds for the night-time~~, weekly~~ hours and ~~monthly variations of traffic speed~~ weekend days were ~~adopted from~~evaluated using the ~~data~~ measured diurnal and weekly cycles of vehicle speeds in ~~Runeberg Street~~Runeberginkatu (located ~~2km~~2 km southwest from Hämeentie) in 2004. The traffic data ~~is~~for Hämeentie for years 2007-2009 and 2014 are summarized in Table 1.

~~The drivers are legally obliged~~ The average speeds of vehicles are clearly below the speed limit value (40 km h^{-1}), due to several junctions and frequently occurring traffic congestion. This street is one of the major routes for public transport to the centre of the city; the proportion of heavy-duty vehicles is therefore high, ranging annually from 29 to 30 %.

The use of winter tyres ~~in Finland~~(studded or non-studded) is mandatory from December to February~~.~~ (inclusive) by legislation in Finland. The studded tyres are allowed from~~ the beginning of~~ November until the last day of March, or until Monday one week after Easter, if it falls on a later date. ~~Studded tyres are used only on light duty vehicles.~~ However, studded tyres can be used also outside of this period, if required by the weather conditions. Studded tyres are used only on light-duty vehicles. The maximum annual share of light-duty vehicles using studded tyres ~~is 80 %. In~~during the ~~input information for the models, the winter tyre season was set to last from late October until the end of April with one month transition~~study period~~. For the years 2007-2009, the transition between winter and summer tyres is assumed to be linear, as there is no more detailed information.~~ was 80 %. For year 2014, the transition from summer to winter tyres is based on the weekly counting of the vehicles with studded tyres in Helsinki (REDUST, 2014). For other considered years (2007-2009), such detailed information was not available, and the winter tyre season was therefore set to last from 23 October until 30 April. The transition between winter and summer tyres is assumed to be linear over a one-month period at the beginning and at the end of the winter tyre season.

2.1.3 Meteorological data

The meteorological data ~~is~~were obtained from two weather stations located at Kaisaniemi and Kumpula (Fig.~~1~~1a) at distances of 1.0 and 2.4 km from the Hämeentie site, respectively. The data includes ambient temperature, relative humidity, precipitation, wind speed, wind direction, total ~~cloudiness~~cloud cover and global radiation. The monthly mean temperature and total precipitation values for the study period are presented in Fig. 2. In terms of the meteorological conditions relevant for the suspension emissions and dispersion conditions, all the years ~~covered here~~addressed in this study can be considered to be commonly occurring ones for this climate zone.

Using meteorological data at two urban stations could result in reduced representatives of the micrometeorological processes. Particularly, small-scale rain showers could be detected at the urban meteorological stations, but not at the study site, or the other way around.

2.1.4 Road maintenance data

Winter time road maintenance for improving traction includes sanding and salting. Salting is commonly the preferred method, but sanding has to be used in specific weather conditions. These include in particular the conditions, for which the ambient temperatures are below -5 °C. Salting would then result in the freezing of the salt-water solution, and clearly, this would not contribute to improving the friction between the tires and the street surface. There are also measures that are designed to mitigate road dust emissions: dust binding and street cleaning. Dust binding is achieved by keeping the road surface moist; street cleaning removes the dust load on the street and thus reduces suspension.

The information about The total number of the relevant road maintenance activities per yearis presented in Table 2 for different years during the study period is presented in Table 2.. The salting and sanding events are the most and the second most frequent ones, respectively. Street cleaning is commonly done only once per year. The approximate seasonal timing of these activities has beenis presented in Fig. 3. The complete data for the autumn months (period from October- to December) was available only for one year 2008. Most of the traction control measures (i.e., sanding and salting) have been done in winter and early spring, from January to March. Dust binding has been done mostly in spring, during March and April.

The information on the timing of road maintenance activities was available within an accuracy of six hours. The estimated dry masses of sand, traction salt (NaCl) and dust binding salt ($CaCl_2$) per application were 100 g m^{-2}, 10 g m^{-2} and 6 g m^{-2}, respectively. The traction salting, dust binding and street cleaning was included in the NORTRIP model input data. The FORE model does not take into account the effects of these road maintenance activities.

2.1.5 Air quality measurements

Kerbside air quality measurements were conducted in the street canyon at Hämeentie in 2009 and 2014 (Fig. 1).. Urban background air quality measurements were madone at the station of Kallio, which is located at a distance of 700 m north-west from the Hämeentie site. Mean contribution of the urban background concentrations, as measured at the station of Kallio, to the total observed PM_{10} concentrations at the kerbside station was 64 % during the study period.

2.2 Models

2.2.1 The models for evaluating the suspension emissions

The non-exhaust PM_{10} emissions for 2007-2009 and 2014 were computed using the NORTRIP and FORE models. A brief overview of the models' structure and their application in this study is presented in the following. More detailed description of the models can be found fromthis section. The reader is referred to Denby et al. (2013a, 2013b) (NORTRIP) and Berkowicz (2000Kauhaniemi et al. (2011, 2014) (FORE).) for comprehensive description of the models and parameter definitions.

The road dust emission model NORTRIP

The NORTRIP model (NOn-exhaust Road TRaffic Induced Particle emissions) ~~as~~is described in Denby et al. (2013a, 2013b) and comprises two sub-models~~,~~ that describe the road dust and surface moisture ~~model~~mass balance. Coupled they are used to predict emission of the road dust, which results from the direct emissions of vehicle related wear (~~pavement~~road, brakes and tyre) and suspension of wear products, salt and sand accumulated on the road surface.

The road dust emission calculation is based on the total wear rates and the size distributions of the different wear sources. The ~~total~~basis road wear rate for studded tyres is determined using the Swedish road wear model (Jacobson and Wågberg, 2007~~). Total~~) and can be adjusted for different pavement types. The basis brake and tyre wear rates and size ~~distribution~~distributions used in this study are ~~based on the literature (~~taken from Boulter~~,~~ (2005). The suspension of road dust induced by passing vehicles is accounted for in the NORTRIP model using a suspension factor. ~~In model formulation, traffic volume and speed will enhance the wear and suspension linearly. Table 3 shows parameters relevant for calculation of emissions from wear and suspension.~~The suspension factor in NORTRIP was initially derived by optimising the model against ambient air measurements that clearly show the decay in PM emissions at the end of the studded tyre season and is described in Denby et al. (2013a). Application of the model to many datasets since then does not indicate the need for significant changes to this suspension factor.

Table 3 shows parameters relevant for calculation of emissions from wear and suspension for light-duty vehicles used in this study at reference speeds of 70 km h^{-1} for wear, and 50 km h^{-1} for PM_{10} fraction and suspension. The road wear and suspension are considered to be linearly dependent on vehicle speed. The wear and suspension rates for the heavy-duty vehicles are assumed to be 5 and 10 times larger than those for light-duty vehicles, respectively.

The surface moisture, as calculated by the surface moisture model, determines the suspension and retention of the road dust and salt. The surface moisture is a product of precipitation, condensation and wetting whereas the removal of surface moisture happens through drainage, evaporation and spray. Additionally, drainage and spray will contribute to removal of dust and salt from the road surface. The energy balance model is used to predict condensation and evaporation from the road surface.

The NORTRIP model input data includes information on street configurations, traffic data (traffic volume and composition, vehicle speed and tyre type), meteorological data (solid and liquid precipitation, wind speed, temperature, radiation, cloud cover, and humidity) and road maintenance activity data.

Road maintenance activities included in the NORTRIP model are traction salting and sanding, dust binding, cleaning and ploughing. Traction sand directly contributes to the suspendable road dust mass, depending on its particle size distribution. Size distribution measurements of traction sand used in the Helsinki Metropolitan Area showed that 0.4-2.5% of the sanding material is in the suspendable fraction (defined as the size fraction < 200 µm) (Kulovuori et al., 2019). In this study, the amount of suspendable material in sand was set to be equal to 2%. Salt contributes directly to the dust loading, when not in solution, and impacts on the predicted surface conditions via surface vapour pressure ~~which inhibits~~depression that reduces evaporation (Denby et al., 2013b). In the model, cleaning and ploughing reduce the amount of road dust and salt on the road surface with a predefined efficiency. The effect of street cleaning will depend on the method used and initial amount of road dust available on the street surface (e.g. REDUST, 2014). In this study, assumed removal efficiency for cleaning and ploughing are set to be 1% and 0.1% for the non-suspendable and suspendable fraction of the road dust, respectively.

The output of the model consists of hourly time series for the emissions~~ (g km^{-1} veh^{-1})~~ from wear sources and from salt and sand in the size fraction of PM_{10}.

The road dust emission model FORE

The FORE model (Forecasting Of Road dust Emissions) has been developed to evaluate the particulate matter emissions from road and street ~~surface. Such~~surfaces. It is based on the particle suspension emission model developed by Omstedt et al. (2005). The model considers emissions ~~can be~~ formed by the wear of road ~~pavement~~surface and from traction sand and the suspension of road dust particles into the atmosphere. The model version does not address the emissions caused by the wear of vehicle components~~.~~ (e.g. brake and tyre wear).

The use of the model requires as input ~~values various~~ hourly meteorological ~~variables,~~data (i.e., total precipitation, temperature, dew point temperature, relative humidity, wind speed, radiation and cloud cover), the roughness length, the share of studded tyres, and the dates of the street sanding.

The model uses empirical reference emission factors, which ~~depends~~have different values depending on the time of the year, the ~~mass~~size fraction of particles~~,~~ (PM_{10} or $PM_{2.5}$), and the traffic environment~~.~~ (urban or highway). The reference emission factor will be higher for the time of the year when sanding and studded tyres are commonly used (referred to as 'sanding period') compared to the rest of the year (referred to as 'non-sanding period').

We have adopted the reference emission factors evaluated for Stockholm estimated and further explained by Omstedt et al. (2005~~).~~); i.e., 1200 and 200 µg veh^{-1} m^{-1}, for sanding (Oct-May) and non-sanding (Jun-Sep) period, respectively. The climatic conditions, studded tyre shares and the procedures of using traction sand are fairly similar in Stockholm and Helsinki, ~~but~~although the difference in used amounts of sand and salt can be significant. ~~The model does not allow for the dependencies of emissions on vehicle speed and fleet composition.~~

The dust layer, which will be accumulated on the street surface during wet conditions, depends on the traction sanding and the road wear. In the FORE model, equal contributions are assumed for the dust layers on the street, originating from the road wear and from the traction sand. The dust layer ~~can be~~is reduced ~~caused~~ by the suspension of particles due to the air flow and by runoff due to precipitation.

The ~~mathematical treatment~~suspension of ~~the moisture on the~~ road dust particles in the air is controlled by road surface moisture that is based on modelling of precipitation, runoff, and evaporation. ~~The~~The effect of terrain on wind is defined by roughness length ~~of the surroundings of the street~~ which is needed for the evaluation of the evaporation~~.~~ (Omstedt et al. 2005). In the present case, the roughness length was ~~determined by considering~~derived from the average building ~~heights~~height (26 m) in the ~~vicinity of the study site~~studied street section. This ~~analysis~~ resulted in the roughness length value of 2.6 m.

The model does not allow for the dependencies of emissions on vehicle speed and fleet composition.~~The model predicts as an output value the suspension emission factor (µg m^{-1} veh^{-1}) for all traffic. For most locations in Helsinki the total traffic fleet mainly consists of light duty vehicles (LDVs). However, at the Hämeentie study site, the share of heavy duty vehicles of the total traffic volume was substantial, approximately 30%).~~

~~As studded tyres are only used in light duty vehicles (LDV's), the share of studded tyres in the total traffic fleet is relatively lower in Hämeentie. The suspension emission of the total traffic fleet, Etot (μg m^{-1} s^{-1}), was computed as~~

$$Etot = \frac{EFtot*TVtot}{3600} \quad (1)$$

~~where EFtot (μg m^{-1} veh^{-1}) is the emission factor that is obtained from the FORE model, and TVtot is the total traffic volume (veh h^{-1}).~~ In the FORE model, we have used as input the studded tyre share of the whole traffic fleet of Hämeentie, including both light-duty and heavy-duty vehicles. As studded tyres are only used in light-duty vehicles at the study site, corresponding share of studded tyres in the total traffic fleet is relatively lower. For instance, assuming that 80%, 50%, 30% or 0% of the ~~LDVs~~light-duty vehicles uses studded tyres, the studded tyre share of the whole traffic fleet is approximately 57%, 35%, 21% and 0%, respectively.

2.2.2 Evaluation of the vehicular exhaust emissions

The ~~vehicular~~ exhaust emission factors ~~for $PM_{2.5}$ used in this study are presented in Table 4. The emission factors~~ were obtained from the LIPASTO emission modelling system (Mäkelä, 2015~~a~~). The LIPASTO emission factors are defined separately for five vehicle categories (personal cars, vans, buses, lorries without a trailer, and lorries with a trailer). The dependencies of emission factors on the vehicle speeds were not ~~taken into account.~~explicitly taken into account; however, they allow for urban driving conditions, i.e., traffic cycles that contain frequent accelerations, decelerations and idling. The vehicular exhaust emission factors for particulate matter used in this study are presented in Table 4. As expected, the emission factors were the largest for lorries equipped with a trailer. The emission factors are an order of magnitude larger for heavy-duty vehicles and vans, compared with the personal cars.

2.2.3 The street canyon dispersion model OSPM

The street canyon dispersion model OSPM is based on a combination of a Gaussian plume model and an empirical box model. For a detailed description of this model, the reader is referred to Berkowicz (2000). A brief overview of the model structure and its application in this study is presented ~~in the following~~here.

The OSPM model requires as input data information on ~~vehicular~~ the street configuration, hourly time series of the traffic data, the exhaust- and non-exhaust emissions, the meteorological parameters~~, the street configuration~~ (wind speed and direction), and the urban background concentrations.

The input information on the street configuration includes the geometry of the ~~surroundings of the~~ studied street segment~~.~~; introduced in Section 2.1.1. The ratio of canyon height (26 m) and width (32 m) gives an aspect ratio of 0.8. Thus, the studied street is considered as a wide street canyon. The aspect ratio of studied street is close to an ideal value in view of the performance of the OSPM model; the model was developed for street canyons with an aspect ratio close to unity.

We have also taken into account the geometries of nine street crossings and two parks that are outside of the studied street segment. ~~The meteorological input data needed for the modelling of particulate matter includes wind speed and direction. The ambient temperature and global radiation are also needed for the modelling of the concentrations of nitrogen oxides. We have used hourly meteorological time series for the target years, 2007-2009 and 2014.~~ These so-called exceptions on canyon walls need to be considered, although they are outside of the studied street segment, as they are situated less than 200 m from the receptor points. Otherwise, the OSPM model will assume that the row of buildings continues over a very large distance (Berkowicz et al., 2003). The geometries of street crossings and parks are considered in the model for various wind sectors and so-called building height exceptions.

The urban background concentrations of PM_{10} (µg m^{-3}) were measured at a height of 4.0 m at the air quality monitoring station of Kallio in central Helsinki. The hourly average concentrations time series for 2007-2009 and 2014 were used.

The hourly exhaust emissions of $PM_{2.5}$ and non-exhaust emissions of PM_{10} (µg m^{-1} s^{-1}) were evaluated by the use of other models, and were used as input values for the OSPM model. The traffic data was used only for the evaluation of the traffic induced turbulence in the OSPM model. Traffic Trees add the porosity of a street canyon, and thus have an influence on dispersion and deposition conditions. However, the OSPM model does not consider any obstacles in the street canyon.

The completeness of the meteorological and background concentration data used as input for the OSPM calculations was excellent. Average data coverage for wind speed and direction, and background concentrations was 98%.

Traffic induced turbulence depends in the model on traffic flow and composition (light and heavy vehicles), as well as on the traffic speed. The hourly average traffic volume (veh h^{-1}) and speed data (km h^{-1}) were used as input separately for LDV'slight-duty vehicles (i.e., passenger cars and vans) and HDV'sheavy-duty vehicles (i.e., busses and lorries).

3. Results and discussion

Two road dust emission models, NORTRIP and FORE, were applied to compute the vehicular non-exhaust PM_{10} emissions that were, together with the exhaust emissions, then implementedused as input in the OSPM street canyon dispersion model to simulate street level PM_{10} concentrations. We address (i) the comparison of measured and predicted concentrations, (ii) perform selected model sensitivity analyses, and (iii) simulate the effects of changes in share of vehicles using studded tyres and the impacts of traction control measures.

We have (i) compared predictions of the models to the measured PM_{10} concentrations (Section 3.1.), (ii) evaluated key uncertainties in the road dust and dispersion modelling for the study site (Section 3.2.), and (iii) simulated the effects of changes in studded tyre share and the impacts of traction sanding and salting on ambient air PM_{10} concentrations (Section 3.3).

For the comparison with the measured concentrations we focushave focused on the street increments of PM_{10}. The measured and predicted street increments were obtained by subtracting the measured urban background concentrations from the measured and predicted concentrations in the street canyon, respectively. Effects of measures intended to reduce road dust emissions were subsequently estimated for the non-exhaust part of the street increments, as a relative difference compared to a selected reference case. Non-exhaust street increment is a fraction of the modelled street increment PM_{10} concertation that originates from the non-exhaust traffic induced particle emissions. The results are presented as yearlyannual and seasonal mean values. Seasons weare defined here as follows: winter (1.1.- January to 14.3.), March), spring (15.3.- March to 31.5.), May), summer (1.6.- Jun to 30.9.) September) and autumn (1.10- October to 31.12.). December).

3.1. Comparison of predicted and measured PM_{10} concentrations

The kerbside air quality measurements ~~at the station of~~in Hämeentie were performed in 2009 and 2014. The total observed annual mean concentrations of PM_{10} were 24 µg m^{-3} and 23 µg m^{-3} in 2009 and 2014, respectively, and were slightly above the WHO guidelines (20 µg m^{-3}). The EU daily limit value (50 µg m^{-3}) was exceeded on 16 days in 2009, and on 21 days in 2014 (Malkki et al. 2010; Malkki and Loukkola 2015). Although the number of exceedances was below the allowed number of 35 days, elevated PM_{10} concentrations caused by the road dust in spring can cause adverse health impacts and reduce the comfort of living. The urban background contribution to the concentrations measured at the street level in Hämeentie was substantial, i.e., 64%, averaged over the two years with available data (2009 and 2014).

The time series of modelled and observed ~~mean~~ daily mean street ~~increments~~increment concentrations of PM_{10} for years 2009 and 2014 are presented in Fig. 4. The ~~mean yearly~~annual and seasonal mean values are presented in Table 5. In 2009, the observed seasonal variation was more pronounced, compared with the corresponding results for 2014~~. The highest increment values occurred in April.~~, as shown both by the results in Fig. 4 and Table 5. The observed street increment in spring was clearly the highest for both years, compared with that in the other seasons.

In 2009, a snow layer was formed on the street in the second half of January, and lasted until the end of March. The month of April was warmer than average and with less precipitation. The observed daily mean PM_{10} concentrations started to increase in the latter part of March and prevailed on a relatively high level until the end of April. Night frosts postponed the street cleaning ~~measures started late~~that commonly starts in ~~2009, due~~March, to ~~frequent night frosts~~the beginning of April. This contributed, together with the lack of precipitation, to the existence of a prolonged ~~street~~road dust season.

On the other hand, the winter of 2014 was milder than average. The snow cover lasted only for a short time between January and February, and the thermal spring started early. ~~The first higher values of~~ The observed PM_{10} concentrations were ~~recorded already in winter. The PM_{10} concentrations were~~ on average substantially lower during spring, compared with those in 2009, caused by both early spring cleaning procedures and fortunately timed precipitation events.

Both models can be considered to have reproduced the seasonal variability fairly well, but they under-predict the ~~yearly~~annual mean values. The street increments of PM_{10} ~~concentrations~~ predicted by the FORE model are higher than the observed values in winter and lower in spring~~.~~, for both years. The NORTRIP model systematically under-predicts the measured concentrations. ~~However, it was found that~~ The NORTRIP model reproduced observed variation of the ~~predicted~~ daily mean street increment concentrations ~~of NORTRIP correlated~~ reasonably well with the ~~measured values (the~~ coefficients of determination R^2 ~~=~~of 0.51 and 0.32 for 2009 and 2014~~).~~, respectively. The corresponding correlations for the FORE model were slightly lower (R^2 = 0.~~24~~25 and 0.20 for 2009 and 2014). The correlation of the hourly mean street increment concentrations, compared with the corresponding values for the daily means, was substantially lower in case of the NORTRIP computations (R^2 = 0.38 and 0.25 for 2009 and 2014, respectively). This was probably due to the higher uncertainties in evaluating the hourly variation of the street surface conditions. In case of the FORE model (R^2 = 0.26 and 0.20, for 2009 and 2014, respectively), the daily and hourly correlations were very similar to each other. Additional results of the statistical analyses for the daily mean street increments of PM_{10} are presented in Appendix A.

3.2 Evaluation of the uncertainties of the modelling

There are significant uncertainties ~~with~~in the modelling of the road dust and dispersion modelling associated to the numerous model input values and parameters used for the model computations. Additionally, uncertainties that can affect the accuracy of the whole modelling system are ~~the~~ potentially missing ~~emission~~road dust sources or source categories. Such sources could be the migration of dust from adjoining streets, the off-road sources (such as sidewalks and parking lots) and the traction sand used by trams.

~~3.2 Sensitivity analyses~~We have analysed and numerically evaluated selected key uncertainties related to the application of the two road dust emission models

~~In order to analyse the results in more detail, we have assessed sensitivity of the models~~, and to ~~key parameters~~the street canyon modelling for the ~~study~~Hämeentie site.

3.2.1 ~~Sensitivity analyses~~Uncertainties of the NORTRIP model

~~There are numerous model input values and parameters used for the NORTRIP model computations.~~ Denby et al. (2013b) previously studied extensively the sensitivity of the NORTRIP model to ~~these~~a wide range of input parameters and demonstrated ability of the ~~NORTRIP~~ model to ~~predict~~reproduce the mean concentrations of PM_{10} within a range of ± 35 % of observations for a number of data sets. However, the results ~~from this~~of the present study ~~fall~~were outside of ~~this~~the above mentioned range of uncertainties.

~~High ambient air concentrations of PM_{10} occur in spring, due to the enhanced suspension of dust load accumulated during the winter period when wet surface conditions prevail.~~ The results ~~suggest~~presented in Section 3.1. show that the NORTRIP model ~~does not generate enough dust during winter and spring months~~ systematically under-predict observed PM_{10} concentrations for Hämeentie.

~~The formation of~~Road wear particles created by the studded tyres ~~that dominates~~dominate in the road dust emissions ~~depends on pavement characteristics (stone sizes and wear parameters).~~. In the NORTRIP model, the wear rate caused by studded tyres depends on the properties of asphalt pavement (such as stone sizes and wear resistance) and vehicle speed. In this study, we have used wear rates derived for the reference pavement type (ABS16 with porphyry from Älvdalen) in the Swedish road wear model (Jacobson and Wågberg, 2007) which is one of the most wear resistant pavements used in Sweden. The wear rates in the Swedish road wear model are based on laboratory and field experiments and provide an average under both prevailing dry and wet conditions. However, influence of surface moisture that increases the wear is not directly considered in the model calculations. Denby et al. 2013a estimated the typical wear rates to be from 2 to 5 g km^{-1} veh^{-1} and acknowledged significantly variation of these values depending on the material used with increased wear rates for roads with the poor quality surfaces. Hämeentie is paved with the stone matrix asphalt ~~(SMA)~~ but further detailed information about road surface parameters ~~is missing~~was not available, which ~~can be~~is a source of ~~a significant~~ uncertainty in evaluating the ~~used~~ studded tyre wear ~~rate.~~rates.

We found that numerically doubling the studded tyre wear rate would increase the mean ~~non-exhaust and~~ street increment concentrations of the PM_{10} computed with the NORTRIP model by ~~61 and 33%, respectively,~~

without significant impact on 34%. This would therefore result in model predictions that would be in better agreement with the measurements. However, this increase would not substantially influence the correlation. of measured and predicted values which is largely dependent on the modelled road surface conditions.

The studded tyre wear rate is also assumed to be linearly dependent on vehicle speed (Denby et al., 2013a). In all previous calculations using the NORTRIP model (Denby et al., 2013b) no roads with), the vehicle speeds lesshave been larger than 40 km h^{-1} were assessed and the . The dependency on vehicle speed may be non-linear assumption may not hold for the lower traffic speeds hereencountered in this study (< 30 km h^{-1}).) due to congestion. The NORTRIP model also does not account for the influences of congested driving conditions where, in which acceleration and deceleration will likely lead toresult in an enhanced road wear.

In summary, it is possible that an underestimation of the studded tyre wear rate in congested low vehicle speed conditions, for this particular road surface, could contribute to the under-predictions by the NORTRIP model.

3.2.2 Sensitivity analysesUncertainties of the FORE model

Regarding the predictions of the FORE model, The key parameter in the FORE model is the reference emission factor, which sets a baseline value for the predicted suspension emissions. In this study, we have used the reference emission factors estimated by Omstedt et al. (2005) forbased on the measurements in Hornsgatan in Stockholm. The average daily Although the climatic conditions were similar during the Hornsgatan measurement campaign and the present study, the different traffic volume in the measurements by Omstedt et al. (2005) in 2000 was 35500 vehicles per day with 5% share of heavy duty traffic. The amounts of sanding events were not known.

In summary, there were some notableconditions could in principle have caused differences between these two measurement campaigns (Hornsgatan, 2000 and this study). that will be reflected in the values of the baseline emissions.

We have therefore estimated numerically, how changesusing the physically largest feasible values of the reference emission values would affectincrease the results predicted bypredictions of the FORE model. We evaluated four additional cases with different sets ofThe base case PM_{10} reference emission factors, and compared the for the sanding and non-sanding periods in Omstedt et al. (2005) were 1200 and 200 µg veh^{-1} m^{-1}, respectively. The assumed numerical results with those of the original model that uses the reference values presented by Omstedt et al. 2005. The set-up of these cases is presented in Table 6. We consider these cases to be conservative in the sense that the range of the assumed cases used the higher PM_{10} reference emission values is as large as was considered to be physically possible.

factors for the sanding and non-sanding periods, i.e., 1500 and 300, and 3200 and 400, respectively. For the assumed numerical cases presented in Table 6, the yearlyannual mean non exhaust and street increment concentrations of PM_{10} would increase from 32 % to 148 % and 23% to 118%, respectively.%.

Clearly, there are also other possible uncertainties in the application of The FORE model. does not address the influences of salting, street cleaning and dust binding. The suspension emissions are also, for simplicity, modelled for the whole vehicle fleet, i.e., . This approach does not take into account the details such asof the vehicle speeds and the composition of the vehicle fleet are not allowed for. In addition, the model does not address the influences of salting, street cleaning and dust binding..

~~3.2.~~In summary, an under prediction of the baseline emissions could have contributed to the under-prediction of suspended PM_{10} concentrations found in this study. Neglecting the effects of salting, street cleaning and dust binding could cause a reduced correlation of the measured and predicted concentration values.

3~~ Sensitivity analyses.~~2.3 Uncertainties of the OSPM model

~~We have also studied the influence of one key parameter in~~ The OSPM model~~,~~ contains the so-called roof parameter (fRoof~~). This parameter relates~~), which is used to relate the measured or modelled wind speed at a meteorological mast with the wind speed at roof level. The value of ~~the fRoof~~this parameter depends on building and roughness situations around the meteorological station~~ and should be adjusted~~. In this study, we have used the roof parameter value of 0.4, which is based on the model-measurement ~~comparisons for several different compounds.~~studies conducted in Copenhagen by Ketzel et al (2012).

~~In this sensitivity analysis, we selected the fRoof parameter values of 0.4 and 0.6. The parameter value of 0.4 was used in this study and is the default value of the OSPM model, based on the model-measurement studies conducted in Copenhagen by Ketzel et al (2012).~~ However, some other studies have suggested ~~that~~ a higher value of 0.6~~ could be more appropriate~~ (OSPM FAQ, 28.03.2017). The numerical computations showed that the ~~yearly~~ mean ~~PM_{10} and $PM_{2.5}$ exhaust~~ street increment PM_{10} concentration~~s~~ over the two years (2009 and 2014) w~~ere~~as approximately 26% lower~~ with fRoof = 0.6~~, using this higher value of the roof parameter, compared to th~~ose~~at with fRoof ~~=~~value of 0.4.~~, for both target years~~. ~~The total concentrations of PM_{10} were about 78% lower with fRoof = 0.6 compared to those with fRoof = 0.4. For total $PM_{2.5}$ the change in concentrations modelled with fRoof = 0.6 was from 65% and 4% lower than those with fRoof = 0.4, in 2009 and 2014.~~

3.3 Impact of the reductions in studded tyre use and ~~the~~ road maintenance measures

We have ~~studied~~assessed numerically the ~~effectiveness of potential mitigation measures for reducing road dust. The selected numerical cases are presented in Table 7. The measures include the reduction of the use of studded tyres and the~~ impact of changes in selected traction control measures~~. The effects of these measures were evaluated for the~~ on the non-exhaust street increments of PM_{10}. The selected numerical cases are presented in Table 6. In the so-called reference case, we have assumed that ~~the~~all reported road maintenance activities have been done, and the maximum share of the light-duty vehicles using studded tyres is equal to the observed value ~~(80%).~~

~~Both suspension emission models (NORTRIP and FORE) were applied to assess the impacts of studded tyres and the traction sanding.~~. The maximum observed share of vehicles using studded tyres (80%) was numerically reduced to 50% (~~st50),~~ST 50%), 30% (~~st30)~~ST 30%) and 0% (~~st0~~no ST). We also assumed that all recorded sanding and salting events would not have been done ~~(noSand). The impact of not including~~ in 'no Sand' and 'no Salt' case, respectively. Both road dust emission models (NORTRIP and FORE) were applied to assess the impacts of the reduced fraction of studded tyres and the impact of traction sanding. The impact of traction salt was studied only using the NORTRIP model~~ (noSalt).~~.

The computed ~~relative~~ changes in the modelled non-exhaust increments of PM_{10}~~ for~~, relative to the ~~selected cases~~reference case are presented in Fig. ~~5 and in Table 8.~~

~~According to these computations,~~5. The largest reductions of concentrations can be achieved by reducing the use of studded tyres~~.~~ in favour of the non-studded winter tyres. For the ~~theoretical~~most extreme case with no studded tyres in traffic, the predicted mean PM_{10} reductions average decreases in the non-exhaust street increments of PM_{10} over four year period were 39% and 40% for the NORTRIP and FORE models, respectively. A 50 % percent decrease inIn case where the share of vehicles usingreference maximum studded tyres would result in an average decrease intyre share was reduced by 30%, average decreases in modelled annual non-exhaust incrementstreet increments of PM_{10} ofwere 16% (NORTRIP) or 17% (FORE).

The yearly PM_{10} concentrations are strongly influenced by meteorology. The Varying effect of the same studded tyre reduction between different years can be attributed to the changing meteorological input data influences the modelled road surface conditions, which control the that influence suspension emissions and theroad dust and salt removal processes. Clearly, the type and number of the road maintenance operations is also directly associated with the meteorological as well as the dispersion conditions. Modelled changes in the PM_{10} concentrations represent the combined impacts of selected measures and meteorology.

The impact of studded tyre reductions can be further enhanced by improving the quality of road surfaces. Larger aggregate sizes that are made from rocks more resistant to wear in the asphalt pavements, or the use of alternative pavements can reduce PM_{10} emissions (Gustafsson et al. 2009; Gustafsson and Johansson 2012).

The number of reported sanding events in Hämeentie was 9 for yearin 2007 and 18 for yearsin 2009 and 2014. (Table 2). In year 2008, all traction control was done by salting. All sanding events occurred during January and February. Salting was extensively used between January and March during the study period with 17 to 49 salting events per year. BothThe results for the 'no Sand' and 'no Salt' cases give an indication of the overall contribution of implemented sanding and salting to the non-exhaust street increments of PM_{10} in Hämeentie. Without taking into account reported sanding events, both road dust emission models predict similar changes in the modelled non-exhaust PM_{10}street increment concentrations after removal of sandingaveraged over the four years; however, with different seasonal variation. The modelled reductioncontribution of sanding to the annual mean non-exhaust street increment of PM_{10} ranges from 4 to 20%, depending on the year and the model considered. The NORTRIP model predicts highest impact of sanding in spring months (-18%) and indicates that sanding influence extends throughout summer. The impact of sanding predicted by the FORE model is limited to winter and, spring, and autumn owing to model's concept regarding the sanding implementation.

The impact of traction salt was studied using the NORTRIP model. The traction salt was assumed to be applied dry. Salting was extensively used between January and March during the study period with 17 to 49 salting events per year. The traction salt is efficiently removed from the street surfaces by drainage and vehicle spray processes, which are affected by precipitation (Denby et al., 2016). In dry conditions, traction salt can significantly contribute to the PM_{10} concentrations. The predicted change in yearlyannual mean non-exhaust street increments of PM_{10} after exclusion of reported salting events ranges from -0.1% to -4%.

It would be difficult or even impossible to implement the selected numerical example cases as presented. For instance, in reducing traction control, one still has to assure a sufficient traffic safety. The results also show that it is not possible to eliminate emissions simply by substituting sanding by salting.

The results demonstrate that traction sanding and salting are potentially significant sources of the road dust. However, immediate restrictions in their use could jeopardize traffic fluency and safety. Optimizing spatially and temporally the use of traction control materials can reduce the impacts of road dust on PM_{10} concentrations. The impact of traction sand on suspended road dust will depend on the frequency of the sanding operations, and the amount and quality of sanding material. The use of sanding material with high resistance to fragmentation and with removed fine particulate fractions will reduce the contribution of sanding to the suspendable road dust (Tervahattu et al., 2006). From an air quality perspective, substituting sand for less dust forming materials, such as salt, would be beneficial. However, this may not be always possible, due to the prevailing weather conditions, and also in areas, which need to be protected from the negative environmental effects of the conventional traction salt, sodium chloride (NaCl). Alternatives to sodium chloride, such as other chlorine based salts and organic salts, have been tested for use in sensitive groundwater areas in Finland (e.g. Hellstén et al., 2001, 2002); however, their widespread use has not been introduced.

4 Conclusions

We have conducted numerical computations regarding the effectiveness of ~~selected~~potential measures to reduce impact of road dust~~.~~ on ambient air PM_{10} concentrations. The ~~evaluated mitigation~~selected measures ~~contained the~~included reduction of the use of studded tyres in light-duty vehicles and ~~phasing out~~reduction of the ~~application~~use of traction ~~sand or salt~~sanding and salting. The effects of these measures were analy~~z~~sed for a street canyon ~~location~~ in central Helsinki. Two road dust emission models, NORTRIP and FORE, were used in combination with the street canyon dispersion model OSPM. ~~The~~ We have compared predictions of the modelling system ~~were also compared~~ with the available street canyon measurements for a period of two years~~.~~ and evaluated variability and uncertainties associated with various modelling approaches. Impact of selected traction control measures was estimated for the non-exhaust street increments of PM_{10}.

The NORTRIP model is a process based model that describes wear processes, traffic induced suspension of accumulated road dust and impact of road maintenance activities (salting, sanding, dust binding, cleaning and ploughing) on both dust load and road surface moisture. It includes dependences on vehicle speed, tyre type, vehicle category (light and heavy-duty vehicles) and road surface properties that enable a comprehensive evaluation of the road dust abatement measures. However, the model requires extensive input data that may not be available (such as, e.g. road maintenance data and the properties of the road surface). This may present a challenge in application of the NORTRIP model. On the other hand, the FORE model requires relatively much less input data. However, it relies on the reference emission factors, which need to be computed based on local air quality measurements. The FORE model considers two road dust sources, viz. road wear and traction sand. The model takes into account neither the dependence of emissions on vehicle speed and traffic fleet composition, nor the influence of traction salting and dust control measures (i.e., dust binding and street cleaning). These factors limit the application of the FORE model for evaluation of a wider range of measures to reduce road dust.

Both road dust emission models reproduced the seasonal variability of the concentrations of PM_{10} fairly well, but ~~the models~~ under-predicted the ~~yearly~~annual mean values. The street increments of PM_{10} ~~concentrations~~ predicted by the FORE model ~~were~~tended to be higher than the observed values in winter and lower ~~than the measured concentrations~~ in spring, whereas the NORTRIP model systematically somewhat under-predicted the measured concentrations. The ~~predicted~~ daily mean street increment concentrations ~~of~~predicted by NORTRIP correlated reasonably well with the measured values; the correlation was better tha~~t~~n the corresponding one for the FORE model. An underestimation of the studded tyre wear rate in congested low vehicle speed conditions, which are common for the Hämeentie site, could contribute to the under-predictions by the NORTRIP model. In case of the FORE model, the main uncertainties were the underestimation of the baseline emission factor and neglecting the effect of salting, street cleaning and dust binding.

There are substantial differences in the structure and mathematical treatments of various processes in the NORTRIP and FORE models. ~~However, ~~Despite the differences, these models predicted a very similar distribution of ~~how effective the selected options would be to reduce road dust. This adds more confidence~~changes in the ~~prediction capacity of these models~~PM_{10} concentrations for ~~analyzing the influence of various measures.~~the studied cases.

The results demonstrate that changes in the current traction control measures can significantly reduce the impact of road dust on ambient air PM_{10} concentrations. The largest reductions ~~of~~in PM_{10} concentrations ~~could potentially~~can be achieved by reducing ~~the fraction of vehicles that use ~~studded tyre use in favour of the non-studded winter tyres. For instance, ~~a 30% percent decrease ~~in case where the reference maximum studded tyre share ~~of vehicles using studded tyres would result in an~~was reduced by 50 %, average decrease ~~of~~in the non-exhaust street increment of PM_{10} was from 16 % to 34 %, depending on the model used and the year considered. ~~The corresponding values for ~~However, the effectiveness of the studded tyre reductions is also dependent on other factors, such as the quality of the road surfaces, vehicle speed and vehicle driving cycles. In addition, both the fluency and safety of vehicular traffic and the implementation of street maintenance measures are substantial economic issues. The reduction of the use of studded tyres would be beneficial also due to the reduced costs for the ~~total removal~~repairing of road surfaces.

Modelled contribution of traction sanding ~~or ~~to the annual mean non-exhaust street increment of PM_{10} during the study period ranged from 4 % to 20 %. The impact of traction salting ~~would range from 4% to 20%, and ~~was estimated using only the NORTRIP model. Completely removing street salting reduced the non-exhaust street increment of PM_{10} from 1% to 4~~%, respectively.~~% on annual level.

~~The selected measures are simple. Clearly, it would be difficult to implement the selected numerical example cases as such, as other considerations, such as traffic safety, economic considerations, and other factors have to be simultaneously considered by the national and local authorities. However, the methods developed and the numerical results ~~Based on the results, optimizing the use of traction control materials can reduce impact of road dust on PM_{10} concentrations. For example, substituting sanding for a less dust forming materials such as salt, whenever possible, would reduce the amount of road dust, but this measure would not completely eliminate road dust emissions. Additionally, the contribution of sanding can further be reduced by choosing the sand materials that are wear resistant and do not contain the finer grain fractions.

We have demonstrated that there is a substantial potential for reducing the impact of road dust on ambient air PM_{10} concentrations, by changing the traction control measures of both vehicles (studded tyre use) and street and road maintenance (sanding and salting). The results presented here can be used ~~as one aspect in finding optimal~~to support the development of feasible strategies for reducing the high springtime particulate matter concentrations~~.~~ originated from the road dust.

Appendix A: Results of the statistical analyses for the daily mean street increments of PM_{10} for Hämeentie in 2009 and 2014.

Table A1 presents the statistical values for daily mean street increment PM_{10} concentrations for 2009 and 2014 calculated on annual and seasonal level. The error of both models is lowest during summer and highest for winter (FORE) or spring (NORTRIP). The RMSE indicates substantial inaccuracies in daily PM_{10} street increment concentrations for both models.

Table A1. Statistical values for modelled daily mean street increment of PM_{10} for the NORTRIP and FORE models for 2009 and 2014, calculated on annual and seasonal level.

NORTRIP 2009						
Statistical parameter		**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
RMSE	Root mean square error	8.4	15.4	3.1	5.5	8.7
IA	Index of agreement	0.50	0.62	0.72	0.49	0.67
F2	Factor-of-two	54	42	75	69	62
R^2	Coefficient of determination	0.06	0.61	0.56	0.15	0.51
FB	Fractional bias	-0.44	-0.74	-0.41	-0.50	-0.57
AvgCp	Average of predicted data	4.6	9.4	4.4	3.7	5.3
AvgCo	Average of observed data	7.2	20.5	6.7	6.1	9.6
N	Number of data points	71	78	122	89	360
FORE 2009						
Statistical parameter		**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
RMSE	Root mean square error	13.7	13.4	2.7	4.7	9.2
IA	Index of agreement	0.21	0.70	0.78	0.63	0.67
F2	Factor-of-two	42	56	80	69	64
R^2	Coefficient of determination	0.00	0.52	0.43	0.23	0.25
FB	Fractional bias	0.55	-0.49	-0.20	-0.08	-0.13
AvgCp	Average of predicted data	12.7	12.4	5.5	5.6	8.4
AvgCo	Average of observed data	7.2	20.5	6.7	6.1	9.6
N	Number of data points	71	78	122	89	360
NORTRIP 2014						
Statistical parameter		**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
RMSE	Root mean square error	9.6	10.6	4.1	9.7	8.5
IA	Index of agreement	0.47	0.62	0.63	0.47	0.58
F2	Factor-of-two	45	44	62	25	45
R^2	Coefficient of determination	0.29	0.44	0.44	0.10	0.32
FB	Fractional bias	-1.11	-0.76	-0.54	-1.17	-0.83
AvgCp	Average of predicted data	2.2	6.9	4.4	2.2	3.9
AvgCo	Average of observed data	7.7	15.3	7.6	8.5	9.5
N	Number of data points	73	78	122	92	365
FORE 2014						
Statistical parameter		**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**

RMSE	Root mean square error	10.5	8.3	3.8	8.7	7.8
IA	Index of agreement	0.42	0.74	0.66	0.48	0.64
F2	Factor-of-two	36	62	68	49	55
R^2	Coefficient of determination	0.02	0.41	0.32	0.15	0.20
FB	Fractional bias	0.16	-0.36	-0.39	-0.80	-0.34
AvgCp	Average of predicted data	9.0	10.7	5.1	3.6	6.7
AvgCo	Average of observed data	7.7	15.3	7.6	8.5	9.5
N	Number of data points	73	78	122	92	365

Acknowledgements

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References

Berkowicz, R.: OSPM-a parameterised street pollution model., Environmental Monitoring and Assessment, 65, 323-331, 2000.

Berkowicz, R., Olesen, R.H., Jensen, S.S.: User’s Guide to WinOSPM Operational Street Pollution Model Draft - March 2003, NERI Technical Report, no. &&, Ministry of the Environment, National Environmental Research Institute, 2003.

Boulter, P. G.: A review of emission factors and models for road vehicle non-exhaust particulate matter, Wokingham, UK, TRL Limited, TRL Report PPR065, URL: http://uk-air.defra.gov.uk/reports/cat15/0706061624_Report1__Review_of_Emission_Factors.PDF, 2005.

Denby, B.R., Sundvor, I., Johansson, C., Pirjola, L., Ketzel, M., Norman, M., Kupiainen, K., Gustafsson, M., Blomqvist, G., Omstedt, G.: A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (NORTRIP). Part 1: road dust loading and suspension modelling, Atmospheric Environment, *77*, 283-300, 2013a.https://doi.org/10.1016/j.atmosenv.2013.04.069, 2013a.

Denby, B.R., Sundvor, I., Johansson, C., Pirjola, L., Ketzel, M., Norman, M., Kupiainen, K., Gustafsson, M., Blomqvist, G., Kauhaniemi, M., Omstedt, G.: A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (NORTRIP). Part 2: Surface moisture and salt impact modelling, Atmospheric Environment, 81, 485-503, 2013b.https://doi.org/10.1016/j.atmosenv.2013.09.003, 2013b.

Denby, B.R., Ketzel, M., Ellermann, T., Stojiljkovic, A., Kupiainen, K., Niemi, J.V., Norman, M., Johansson, C., Gustafsson, M., Blomqvist, G., Janhäll, S., Sundvor, I.: Road Salt Emissions: A comparison of measurements and modelling using the NORTRIP road dust emission model, Atmospheric Environment, 141, 508-522, 2016.https://doi.org/10.1016/j.atmosenv.2016.07.027, 2016.

EEA, Emissions of air pollutants from transport: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-6, last access: 8 May 2019, 2018.

Gustafsson, M., Blomqvist, G., Gudmundsson, A., Dahl, A., Jonsson, P., Swietlicki, E.: Factors influencing PM10 emissions from road pavement wear, Atmospheric Environment, 43 (31), 4699-4702, https://doi.org/10.1016/j.atmosenv.2008.04.028, 2009.

Gustafsson, M. and Johansson, C.: Road pavements and PM10, Summary of the results of research funded by the Swedish Transport Administration on how the properties of road pavements influence emissions and the properties of wear particles, Trafikverket, Report 2012:241, https://trafikverket.ineko.se/Files/sv-SE/11167/RelatedFiles/2012_241_Road_pavements_and_PM10.pdf, 2012.

Hellstén, P. and Nystén, T.: Vaihtoehtoisten liukkaudentorjunta-aineiden kemialliset reaktiot pohjaveteen kulkeutumisessa, Helsinki, Finnish Environmental Institute, The Finnish Environment, 515, 77p., in Finnish, summary in English, ISBN 952-11-0996-3 (PB.), ISBN 952-11-0997-1 (PDF), ISSN 1238-7312, http://hdl.handle.net/10138/40642, 2001.

Hellstén, P., Nystén, T., Kokkonen, P., Valve, M., Laaksonen, T., Määttä, T. ja Miettinen, I.: Vaihtoehtoisten liukkaudentorjunta-aineiden kulkeutuminen pohjaveteen. Helsinki, Finnish Environmental Institute, The Finnish Environment, 552. 63p., in Finnish, summary in English, ISBN 952-11-1126-7 (PB.), ISBN 952-11-1127-5 (PDF), ISSN 1238-7312., http://hdl.handle.net/10138/40453, 2002.

HSY and Metropolitan Area Municipalities, Regional Land Cover Dataset: tree data, File service of open data, Helsinki Region Environmental Services Authority (HSY): https://www.hsy.fi/en/experts/regional-data/Pages/default.aspx, https://kartta.hsy.fi/ (in Finnish), last access: 13 May 2019, 2014.

Jacobson, T. and Wågberg, L. G.: Developing and upgrading of a prediction model of wear caused by studded tyres and an overview of the knowledge of the factors influencing the wear – Version 3.2.03, Linköping, The Swedish National Road and Transport Research Institute, VTI notat 7-2007, in Swedish, summary in English, URL: http://www.vti.se/en/publications/developing-and-upgrading-of-a-prediction-model-of-wear-caused-by-studded-tyres-and-an-overview-of-the-knowledge-of-the-factors-influencing-the-wear--version-3203/, 2007.

Kauhaniemi, M., Kukkonen, J. Härkönen J., Nikmo J., Kangas L., Omstedt G., Ketzel M., Kousa A., Haakana M., Karppinen A.: Evaluation of a road dust suspension model for predicting the concentrations of PM10 in a street canyon, Atmospheric Environment, 45, 3646-3654, 2011.https://doi.org/10.1016/j.atmosenv.2011.04.055, 2011.

Kauhaniemi, M., Stojiljkovic, A., Pirjola, L., Karppinen, A., Härkönen, J., Kupiainen, K., Kangas, L., Aarnio, M.A., Omstedt, G., Denby, B.R. & Kukkonen, J.: Comparison of the predictions of two road dust emission models with the measurements of a mobile van, Atmospheric Chemistry and Physics, 14, 9155-9169: 15s, ~~2014.~~https://doi.org/10.5194/acp-14-9155-2014, 2014.

Ketzel, M., Jenssen, ~~SS~~S.S., Brandt, J., Ellermann, T., Olesen, ~~HR~~H.R., Berkowich, R., Hertel, O.: Evaluation of the Street Pollution Model OSPM for Measurements at 12 ~~Street Station~~Streets Stations Using a Newly Developed and Freely Available Evaluation Tool, Journal of Civil & Environmental Engineering, S1:004~~.~~, doi:10.4172/2165-784X.S1-004, 2012.

Kukkonen, J., Salmi, T., Saari, H., Konttinen, M. and Kartastenpää, R.: Review of urban air quality in Finland, Boreal Environment Research, Vol. 4, No. 1, pp. 55-65, 1999.

Kukkonen, J., Kangas, L., Kauhaniemi, M., Sofiev, M., Aarnio, M., Jaakkola, J.J.K., Kousa, A., and Karppinen, A.: Modelling of the urban concentrations of PM2.5 for a period of 35 years, for the assessment of lifetime exposure and health effects, Atmospheric Chemistry and Physics, 18, 8041–8064, https://doi.org/10.5194/acp-18-8041-2018, 2018.

Kulovuori, S., Ritola, R., Stojiljkovic, A., Kupiainen, K., Malinen, A.: Katupölyn lähteet, päästövähennyskeinot ja ilmanlaatuvaikutukset – Tuloksia KALPA-tutkimushankkeesta 2015–2018, HSY publications 1/2019, in Finnish, summary in English, https://www.hsy.fi/sites/Esitteet/EsitteetKatalogi/Julkaisusarja/1-2019-katupolyn-lahteet-paastovahennyskeinot-ja-ilmanlaatuvaikutukset-KALPA-2015-2018.pdf, 2019.

Kupiainen, K.: Road dust from pavement wear and traction sanding, Monographs of Boreal Environment Research, 26, 50 p., ~~2007.~~http://hdl.handle.net/10138/39334, 2007.

Kupiainen, K., Ritola, R., Stojiljkovic, A., Pirjola, L., Malinen, A., Niemi, J.: Contribution of mineral dust sources to street side ambient and suspension PM10 samples, Atmospheric Environment, 147, 178-189, https://doi.org/10.1016/j.atmosenv.2016.09.059, 2016.

Malkki M., Niemi J., Lounasheimo J., Myllynen M., Julkunen A., Loukkola K.: Ilmanlaatu pääkaupunkiseudulla vuonna 2009, HSY publications 2/2010, in Finnish, https://www.hsy.fi/sites/Esitteet/EsitteetKatalogi/Julkaisusarja/2_2010_ilmanlaatu_paakaupunkiseudulla_vuonna2009_web.pdf, 2010.

Malkki, M. and Loukkola, K.: Ilmanlaatu pääkaupunkiseudulla vuonna 2014, HSY publications 6/2015, in Finnish, summary in English, https://www.hsy.fi/sites/Esitteet/EsitteetKatalogi/Julkaisusarja/6_2015_Ilmanlaatu_paakaupunkiseudulla_vuonna_2014.pdf, 2015.

Mäkelä, K.: LIPASTO. Tieliikenne kunnittaiset päästöt~~.~~, Road traffic emissions for municipalities, ~~URL:~~in Finnish, http://lipasto.vtt.fi/liisa/kunnat.htm, 30.10.2015, ~~(in Finnish),~~ 2015.

MML~~:~~, Land scanning data, File service of open data, National Land Survey of Finland~~, URL~~: http://www.maanmittauslaitos.fi/en~~(~~, last access: 7 November 2012~~), 2012.~~

Omstedt, G., Bringfelt, B., Johansson, C.: A model for vehicle-induced non-tailpipe emissions of particles along Swedish roads, Atmospheric Environment, 39, 6088-6097, ~~2005.~~https://doi.org/10.1016/j.atmosenv.2005.06.037, 2005.

OSPM FAQ: http://envs.au.dk/en/knowledge/air/models/ospm/faq/~~,~~, last access: 28.03.2017~~, URL: http://envs.au.dk/en/knowledge/air/models/ospm/faq/~~

REDUST~~ 2014.~~, Demonstration test final report: Main results and conclusions~~.~~, Deliverable product of the REDUST LIFE+ project Actions 1 and 2, 15.8.2014., http://www.ymk-projektit.fi/redust//files/2015/02/REDUST-Action-1-2-final-report.pdf~~URL: ~~, 2014.

Tele Atlas NV: Mapinfo, StreetPro, Pitney Bowes Software Limited, United Kingdom, 2012.

Tervahattu H., Kupiainen K.J., Räisänen M., Mäkelä T., Hillamo R.: Generation of Urban Road Dust from Anti-Skid and Asphalt Concrete Aggregates, Journal of Hazardous Materials, 132, 30-46, https://doi.org/10.1016/j.jhazmat.2005.11.084, 2006.

Table 1. Summary of ~~the~~ traffic data ~~for~~at Hämeentie ~~during the study period. AADT = annual average daily traffic.~~ for four years.

Year	~~AADT~~ Annual average daily traffic (vehicles day^{-1})	~~Heavy~~ Share of heavy-duty vehicles ~~share~~ (%)	Mean speed (km h^{-1})
2007	11400	29	27
2008	9700	29	27
2009	10110	29	27
2014	9050	30	25

Table 2. The number~~s~~ of ~~the~~ road maintenance measures ~~for~~in Hämeentie for ~~each year, in 2007 – 2009 and in 2014~~four years. Number of ploughing events was computed using the NORTRIP model.

Year	Sanding events	Traction salting ~~events~~ (NaCl)	Dust binding ~~events~~ ($CaCl_2$)	Street cleaning ~~events~~	Ploughing
2007	9	21	1	2	7
2008	0	49	4	1	14
2009	18	40	3	1	19
2014	18	17	10	1	9

Inserted Cells

Table 3. The wear and suspension rates for the light-duty vehicles and the fraction of wear material in the size range of PM_{10} used in the NORTRIP model. ~~The wear and suspension rates for the heavy duty vehicles are assumed to be 5 and 10 times larger, respectively.~~ The reference speed is 70 km h^{-1} for wear and 50 km h^{-1} for PM_{10} fraction and suspension.

	Studded tyres	Winter tyres	Summer tyres	PM_{10} fraction (%)
Road wear (g km^{-1} veh^{-1})	2.88	0.15	0.15	28
Tyre wear (g km^{-1} veh^{-1})	0.1	0.1	0.1	10
Brake wear (g km^{-1} veh^{-1})	0.01	0.01	0.01	80
Road dust suspension rate (veh^{-1})	5.0x10^{-6}	5.0 x10^{-6}	5.0 x10^{-6}	-

Table 4. The vehicular exhaust particulate matter emission factors of $PM_{2.5}$ (g km^{-1} veh^{-1}) in Helsinki for the targetfour years, based on the LIPASTO emission modelling system LIPASTO (Mäkelä, 2015a)..

Vehicle type	2007	2008	2009	2014
Personal cars	0.03	0.03	0.02	0.01
Vans	0.15	0.14	0.14	0.10
Buses	0.29	0.25	0.21	0.12
Lorries, no trailer	0.19	0.16	0.13	0.09
Lorries with trailer	0.55	0.47	0.35	0.23

Table 5. Mean yearlyAnnual and seasonal mean observed and modelled street increments of PM_{10} (µg m^{-3}) for Hämeentie in 2009 and 2014.

Year		Winter	Spring	Summer	Autumn	YearlyAnnual mean
2009	Observed	7.8	20.1	6.9	6.4	10.1
	FORENORTRIP	13.45.3	129.4	4.5.6	6.03.9	8.5.7
	NORTRIPFORE	5.313.4	912.4	4.5.6	3.96.0	8.5.7
2014	Observed	8.2	15.7	7.7	9.0	10.2
	FORENORTRIP	9.2.3	117.2	4.5.3	2.3.7	8.04.2
	NORTRIPFORE	9.2.3	711.2	4.5.3	2.3.7	4.28.0

Table 6. The set-up of the numerical sensitivity cases for the FORE model; the assumed PM_{10} reference emission factors (µg veh^{-1} m^{-1}).

Case	Sanding period (Oct-May)	Non-sanding period (Jun-Sep)
Omstedt et al. 2005 "Base case"	1200	200
Case1	1500	300
Case2	2000	300
Case3	2000	400
Case4	3200	400

Table ~~7~~6. ~~Summary of~~ The selected numerical cases with ~~reduced~~ maximal shares of light-duty vehicles using studded tyres~~,~~ and ~~with applied~~ road maintenance measures~~.~~ for traction control considered by the two road dust emission models. The symbol + refers to 'included' and – to 'not included'.

Model	**Case**	**~~Abbr.~~Abbreviation**	**Studded tyre**	**Sanding**	**Salting**	**~~Dust binding~~**
NORTRIP	1 Reference	Ref	80 %	+	+	~~+~~
	2 Studded tyre share 50	~~st50~~ST 50 %	50 %	+	+	~~+~~
	3 Studded tyre share 30	~~st30~~ST 30 %	30 %	+	+	~~+~~
	4 Studded tyre share 0	~~st0~~ST 0 %	-	+	+	~~+~~
	5 No sanding	~~noSand~~no	80 %	-	+	~~+~~
	6 No salting	~~noSalt~~no	80 %	+	-	~~+~~
FORE	1 Reference	Ref	80 %	+	-	~~-~~
	2 Studded tyre share 50	~~st50~~ST 50 %	50 %	+	-	~~-~~
	3 Studded tyre share 30	~~st30~~ST 30 %	30 %	+	-	~~-~~
	4 Studded tyre share 0	~~st0~~ST 0 %	-	+	-	~~-~~
	5 No sanding	~~noSand~~no	80 %	-	-	~~-~~

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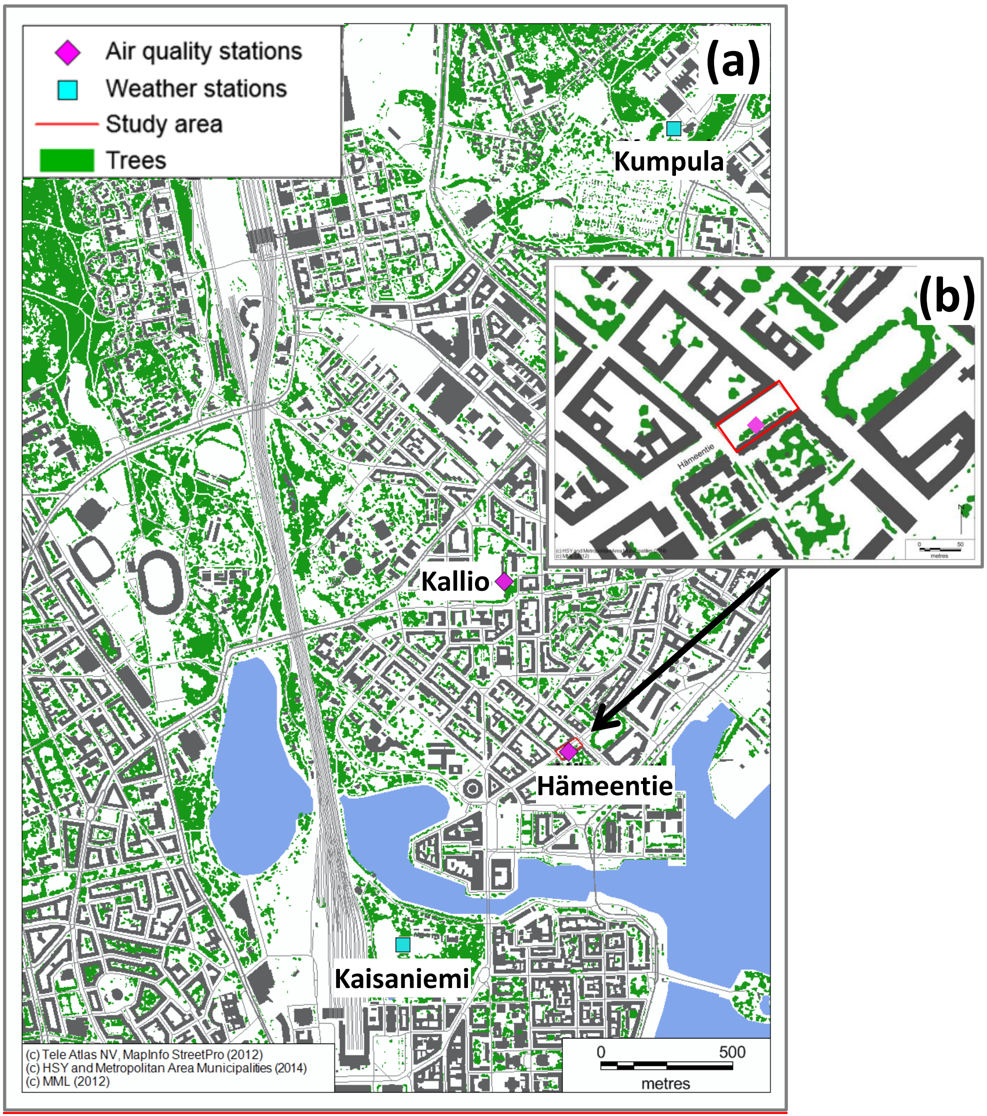
~~Table 8. Changes in modelled non-exhaust PM_{10} concentrations for studied cases predicted by two emission models for different seasons.~~

~~Model~~	~~Season~~	~~st50~~	~~st30~~	~~st0~~	~~noSand~~	~~noSalt~~
~~NORTRIP~~	~~Winter~~	~~-14%~~	~~-21%~~	~~-32%~~	~~-5%~~	~~-2%~~
	~~Spring~~	~~-20%~~	~~-31%~~	~~-47%~~	~~-18%~~	~~-3%~~
	~~Summer~~	~~-10%~~	~~-16%~~	~~-24%~~	~~-13%~~	~~-2%~~
	~~Autumn~~	~~-18%~~	~~-28%~~	~~-44%~~	~~-13%~~	~~-2%~~
~~FORE~~	~~Winter~~	~~-22%~~	~~-36%~~	~~-57%~~	~~-19%~~	~~-~~
	~~Spring~~	~~-25%~~	~~-41%~~	~~-60%~~	~~-11%~~	~~-~~
	~~Summer~~	~~0%~~	~~0%~~	~~0%~~	~~0%~~	~~-~~
	~~Autumn~~	~~-12%~~	~~-16%~~	~~-19%~~	~~0%~~	~~-~~

1 
Air quality stations
Weather stations
Study area
Trees
(a)
Kumpula
(b)
Kallio
Hämeentie
Kaisaniemi
(c) Tele Atlas NV, MapInfo StreetPro (2012)
(c) HSY and Metropolitan Area Municipalities (2014)
(c) MML (2012)
0
500
metres

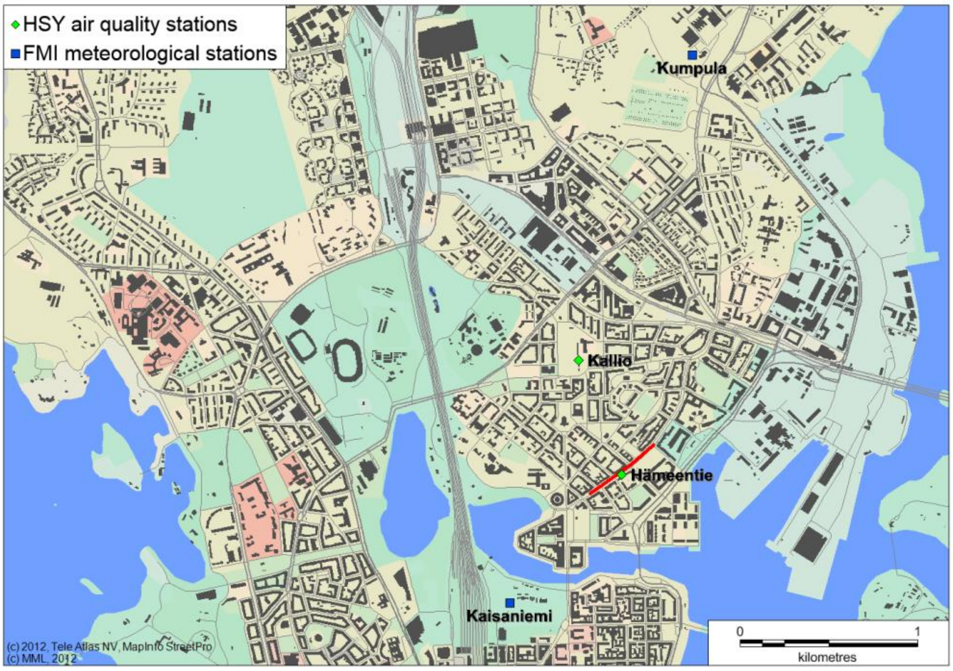
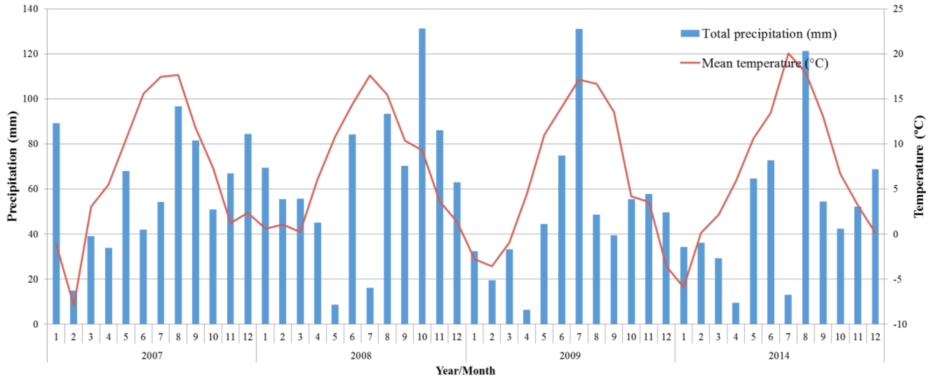


Figure 1. a) The locations of studied street segment (red ~~line~~rectangle) at Hämeentie, kerbside (Hämeentie) and urban background (Kallio) air quality stations (~~green~~pink diamond~~)~~), and weather stations (Kumpula and Kaisaniemi) (blue square) in central Helsinki. ~~Buildings~~Trees have been marked with ~~black~~green circles. b) Close-up view showing building blocks (marked with grey colour~~. The parks have been presented in green, the urban and industrials areas in light brown and grey,~~) and ~~special sites, such as hospitals, in red~~trees in the vicinity of the studied street segment.



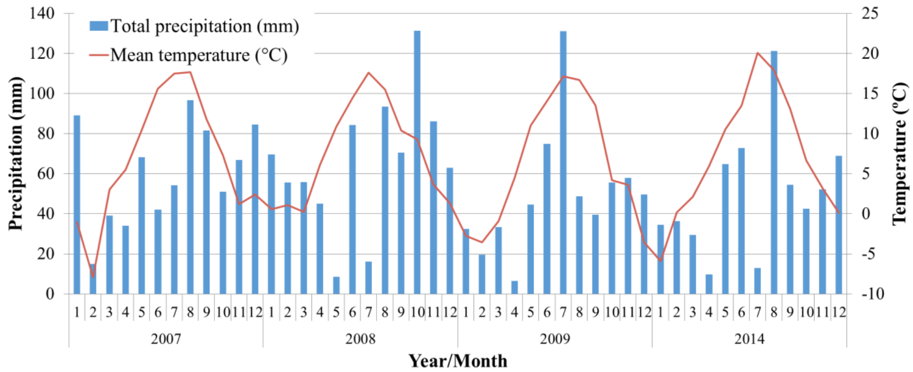
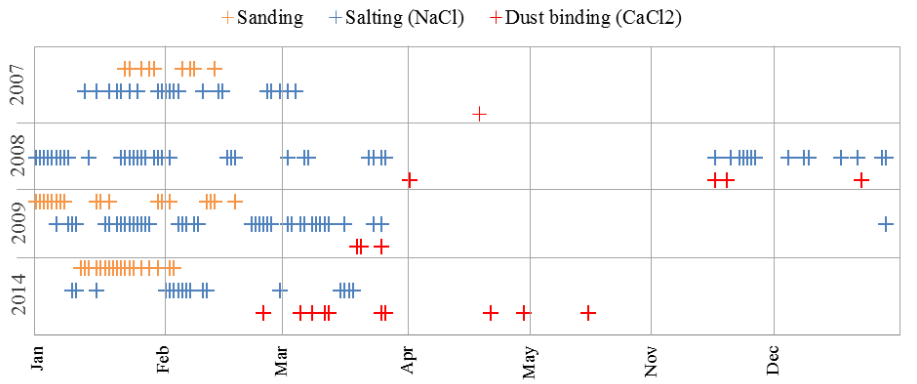


Figure 2. Monthly mean temperature (°C) and total precipitation (mm) ~~during the study period (2007 – 2009 and 2014), as~~for four years, measured at the meteorological station of Kaisaniemi.



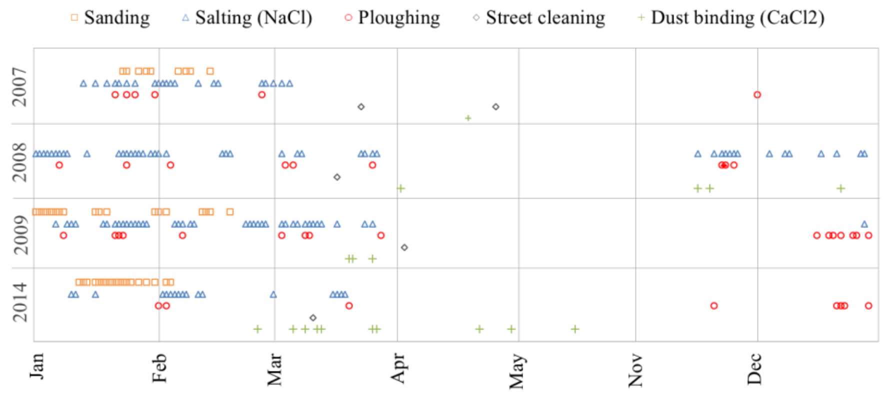
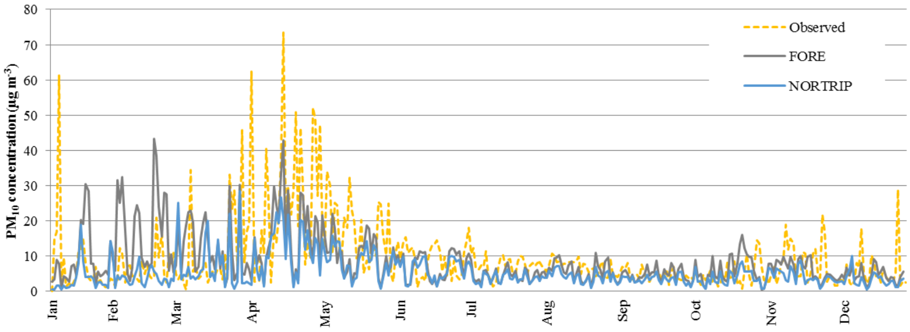


Figure 3. The approximate timing of the road maintenance measures at Hämeentie ~~in 2007-2009 and 2014.~~for four years. All the relevant information for the latter part of the year (from October to December) was available only for 2008.



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PM10 concentration (μg m-3)
Observed
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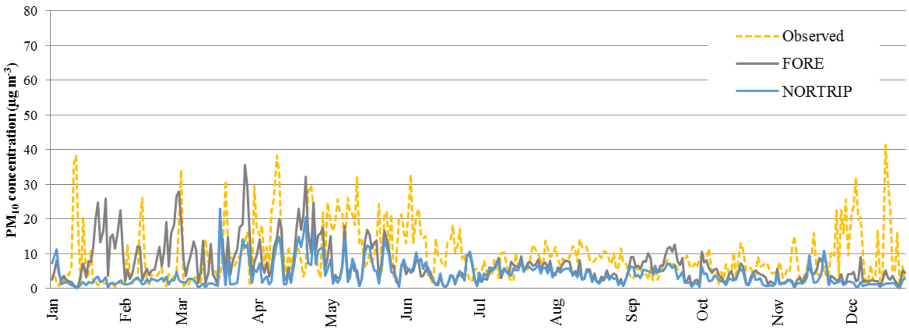

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PM10 concentration (μg m-3)
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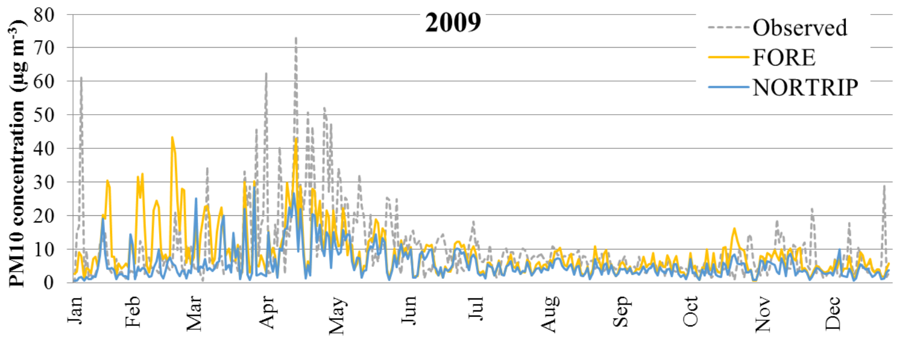

2009
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PM10 concentration (μg m-3)
Observed
FORE
NORTRIP
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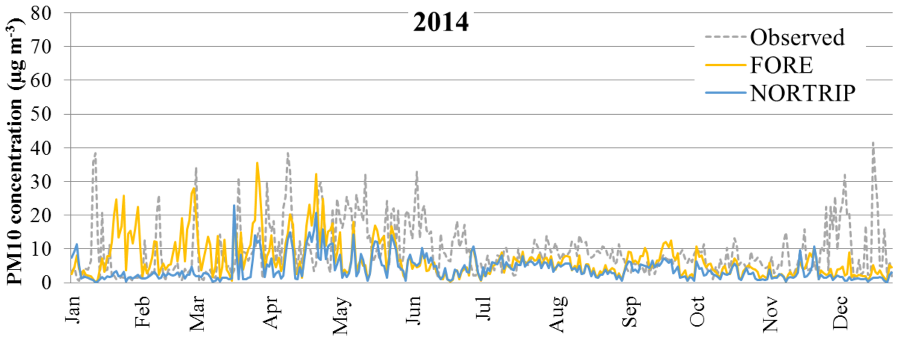

2014
80
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0
PM10 concentration (μg m-3)
Observed
FORE
NORTRIP
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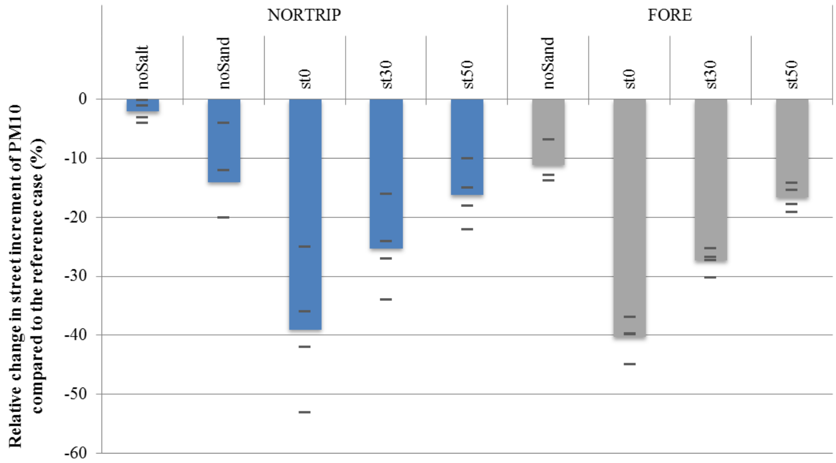
Figure 4. Time series of daily mean ~~modelled and~~ observed and modelled street increments of PM_{10} ~~at~~for Hämeentie ~~in~~for 2009 (upper panel) and 2014 (lower panel).



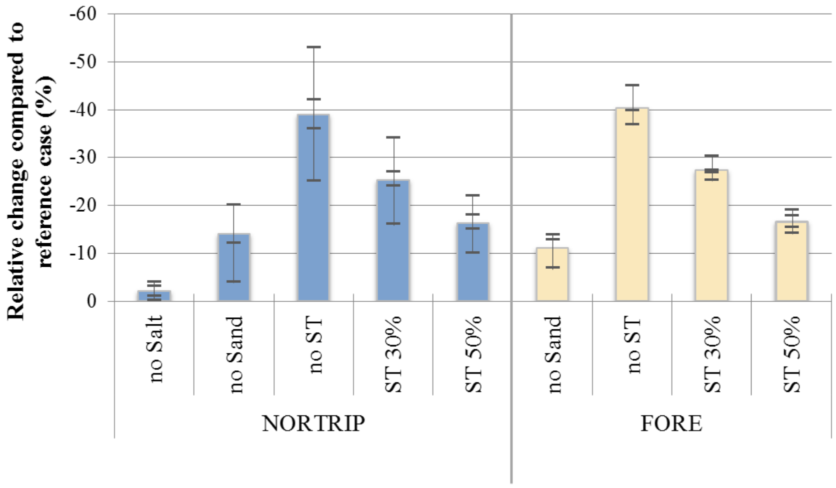


Figure 5. Modelled relative changes in the ~~modelled~~ non-exhaust street increment of PM_{10} ~~concentration due to~~for the ~~reduction in the share of light duty vehicles using studded tyres and with excluding the reported sanding and salting events. The results were computed by the two road dust emission models. Impact of traction salting is estimated using the NORTRIP model. Relative changes compared to the reference case are presented as~~cases described in Table 6, averaged over four ~~-~~year ~~average values with~~period (2007-2009 and 2014). Line markers show~~ing~~ values for the individual years.