Modelling street dust in the Helsinki metropolitan area

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Foreword

Thoracic particles (PM_{10}), especially fine size fraction of them ($PM_{2.5}$), are considered to be the most significant environmental health problem. The association of the mass concentration of fine particles with different health end points and increased mortality has been demonstrated in several studies, also in Helsinki region in spite of fairly low particle concentrations. Lately also adverse health effects of coarse particles i.e. street dust have been recognized.

Street dust concentrations often rise high in spring when streets dry out and particles originating mainly from pavement wear and traction control materials are resuspended into the air. Several studies have been accomplished to find effective means to reduce PM_{10} concentrations (e.g. KAPU and REDUST projects). Dust binding with saline solution has been found to be the most cost-effective way to combat acute street dust problems in spring. Furthermore, efficient cleaning methods, such as street scrubbers and high pressure water flushing, are needed to remove dust from street surfaces. Thanks to continuously improve more effective dust binding and street cleaning measures the EU's daily limit value on PM_{10} has not been exceeded during the past ten years in Helsinki. However, street dust still causes high PM_{10} concentrations and guideline values set by the World Health Organization (WHO) are still exceeded in busy traffic environments.

The formation and emission of street dust is dependent on several factors related to traffic properties, street maintenance actions as well as weather conditions. These parameters are included in the new street dust emission model NORTRIP (NOn-exhaust Road Traffic Induced Particle emissions) that has been developed in cooperation with Nordic experts. This report describes the results of testing and applicability of the NORTRIP model in the Helsinki metropolitan area. The model results also demonstrate potential mitigation options for street dust emissions.

This research report has been compiled by Nordic Envicon Oy in cooperation with Metropolia University of Applied Sciences and HSY. The authors of the report are Ana Stojiljkovic, Kaarle Kupiainen and Roosa Ritola (Nordic Envicon), Liisa Pirjola and Aleksi Malinen (Metropolia) as well as Jarkko Niemi and Anu Kousa (HSY). HSY acknowledges the authors as well all other persons and organizations participated in the project, providing their expertise and various data sets needed for the modelling and evaluation. The project was funded by the City of Helsinki (Public Works Department and Environment Centre) and HSY. This research has also utilized work performed in the Nordic NORTRIP-2 project funded by the Nordic Council of Minister's Climate and Air Pollution group.

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Tiivistelmä

Katupöly on merkittävä hengitettävien hiukkasten (PM_{10}) lähde suomalaisten kaupunkien ilmassa ja pääasiallinen syy erityisesti maalis-toukokuussa havaittaviin korkeisiin hiukkaspitoisuuksiin. Hiukkasten lähdeosuuksien sekä päästövähennysmahdollisuuksien tutkimus auttaa kestävän strategian luomisessa ja edesauttaa saavuttamaan huomattavia parannuksia suomalaisten kaupunkien ilmanlaadussa.

NORTRIP-malli (NOn-exhaust Road TRaffic Induced Particle emissions) on kehitetty yhteistyössä pohjoismaisten ilmanlaatu- ja päästöasiantuntijoiden kanssa. NORTRIP-malli on tällä hetkellä kattavin liikenteen ei-pakokaasuperäisten hiukkasten mallintamistyökalu, joka perustuu hiukkasten syntyyn ja päästöihin liittyvien prosessien tuntemiseen, ja jota voidaan käyttää PM_{10}-päästöjen ymmärtämiseksi ja kontrolloimiseksi. Vaikka jotkin mallin parametrit kaipaavat yhä kehitystyötä, mallin tarjoama mahdollisuus tutkia erilaisten prosessien vaikutusta PM_{10}-pitoisuuksiin tekee siitä erinomaisen työkalun ilmanlaadun tutkimuksessa.

Tässä työssä mallin suorituskykyä testattiin ja arvioitiin erilaisissa katu- ja tieympäristöissä pääkaupunkiseudulla. Lisäksi mallin avulla tarkasteltiin, kuinka herkästi PM_{10}-pitoisuus reagoi erilaisiin liikenteen ei-pakokaasuperäisten hiukkaspäästöjen vähennyskeinoihin.

NORTRIP-malli kuvaa verrattain hyvin PM_{10}-pitoisuuteen liittyvän kausiluontoisen vaihtelun, siihen liittyvän talviaikaisen pölyn kerääntymisen katuympäristöön sekä kevätaikaisen pölyvarastojen pienenemisen kaikissa mallinnetuissa kohteissa. Raja-arvotason ylityspäivien (PM_{10}-vuorokausikeskiarvon pitoisuus >50 µg/m^3) ennustamisessa mallin virhemarginaali kasvaa, sillä kyseinen parametri on herkkä sääolosuhteille sekä muille päästölähteille. Kehäteiden (Kehä I ja Kehä III) osalta malli yliarvioi talvi- ja kevätkausien PM_{10}-pitoisuudet. Jatkossa kyseiseen poikkeavuuteen johtavia syitä on tutkittava lisää. Suurmetsäntien osalta tulokset viittaavat hiekoitusmateriaalin (talviaikainen liukkaudentorjunta) merkittävään osuuteen PM_{10}-lähteenä. Kyseisen prosessin ymmärtämisen ja parametrisoinnin tueksi tarvitaan jatkotutkimusta hiekoitusmateriaalin päästöihin liittyen.

Herkkyystarkastelun tulokset osoittivat katujen kunnossapidon toimilla (hiekoitus, suolaus, puhdistus, pölynsidonta) sekä liikenteen ominaisuuksilla (ajoneuvomäärä, ajonopeus, nastarenkaiden osuus) olevan merkittävä vaikutus PM_{10}-pitoisuuksiin ja raja-arvotason ylityspäivien määrään.

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Sammandrag

Gatudamm är en betydande källa till inandningsbara partiklar (PM_{10}) i luften i finländska städer och den främsta orsaken till skadligt höga partikelhalter särskild i mars–maj. Forskningen kring fördelningen av partikelkällorna samt möjligheterna att minska utsläppen bidrar till framtagandet av en hållbar strategi och hjälper till att uppnå avsevärda förbättringar av luftkvaliteten i finländska städer.

NORTRIP-modellen (NOn-exhaust Road TRaffic Induced Particle emissions) har utvecklats i samarbete med nordiska experter på luftkvalitet och utsläpp. För tillfället är NORTRIP-modellen det mest omfattande verktyget för modellering av icke-avgasbaserade partiklar från trafiken och det baserar sig på kännedomen av de processer som ligger bakom uppkomsten av partiklar och utsläpp. Verktyget kan användas för att förstå och kontrollera PM_{10}-utsläpp. Även om vissa parametrar i modellen ännu behöver utvecklas ytterligare, erbjuder modellen möjligheter att undersöka de olika processernas inverkan på PM_{10}-halterna, vilket gör den till ett ypperligt redskap i forskningen kring luftkvaliteten.

I detta arbete testades och bedömdes modellens prestanda i olika gatu- och vägmiljöer i huvudstadsregionen. Dessutom användes modellen till att undersöka hur lätt PM_{10}-halten reagerar på olika metoder för att minska icke-avgasbaserade partikelutsläpp.

NORTRIP-modellen identifierar relativt väl den säsongsbetonade variationen i PM_{10}-halten, ackumuleringen av dammet vintertid i gatumiljön samt reduktionen av dammlagren under våren för alla modellerade objekt. Vid prognosticering av dagar då gränsvärdsnivån överskrids (halten för PM_{10}-dygnsmedelvärdet > 50 µg/m^3) ökar felmarginalen enligt modellen, eftersom parametern i fråga är känslig för väderleksförhållanden och andra utsläppskällor. För ringvägarnas del (Ring I och Ring III) överskattar modellen PM_{10}-halterna på vintern och våren. I fortsättningen måste orsakerna till denna avvikelse undersökas mer. För Storskogsvägens del antyder resultaten att sandningsmaterialet (halkbekämpningen vintertid) utgör en anmärkningsvärd andel som PM_{10}-källa. För att förstå processen i fråga och kunna parametrisera den behövs fortsatta undersökningar angående de utsläpp sandningsmaterialet ger upphov till.

Resultaten från känslighetsanalysen visade på att gatuunderhållets åtgärder (sandning, saltning, rengöring, dammbinding) samt egenskaperna hos trafiken (fordonsantal, körhastighet, dubbdäckens andel) har en betydande inverkan på PM_{10}-halterna och det antal dagar då gränsvärdet överskrids.

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Abstract

Road dust is an important source of thoracic particle (PM_{10}) concentrations in Finnish urban environments and the main cause of high concentration observed in March, April and May. Studies about the main source contributions and mitigation opportunities of road dust help to formulate robust strategies that can lead to significant improvements in urban air quality in Finnish cities.

NOn-exhaust Road TRaffic Induced Particle emissions (NORTRIP) model has been developed as a Nordic collaboration utilizing the expertise of Nordic air quality modellers and emission experts. The NORTRIP model is currently the most comprehensive process based non-exhaust emission model that can be used for better understanding and controlling of PM_{10} emissions. Although a number of model parameters still need to be refined the possibility to separately study the influence of different processes and factors governing the PM_{10} emissions makes it a useful tool in air quality management.

In this study model performance has been evaluated for different street and road environments in the Helsinki metropolitan area. Furthermore the model has been applied to study the sensitivity of the PM_{10} concentrations to measures that can be used to reduce non-exhaust traffic emissions.

The NORTRIP model captures reasonably well seasonal variation in PM_{10} concentrations along with the dust loading decay during spring and build-up during winter season for all modelled sites. Model error in predicting the number of exceedance days (days with PM_{10} mean daily value >50 µg/m^3) is larger due to higher sensitivity of this parameter to the meteorological conditions and presence of additional emission sources. At both ring road sites model overestimates PM_{10} concentrations during winter and spring period. Issues that may lead to this discrepancy in the result need to be further studied. The Suurmetsäntie street results identified sand as an important source of PM_{10}. For better assessment of its impact parameters and processes related to the sand emissions will need more attention.

The results of the sensitivity analysis demonstrated the significant impacts of different road maintenance activities (sanding, salting, cleaning, dust binding) and traffic properties (volume, speed, the shares of light duty vehicles and studded tyres) on PM_{10} concentrations and number of exceedance days.

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Contents

1 Introduction and project aims

Road dust is an important source of ambient PM_{10} concentrations in Finnish urban environments. It is the main cause of especially high concentrations observed during spring months March, April and May. Identification of the main sources and mitigation opportunities of road dust would lead to significant improvements in urban air quality in Finnish cities.

Formation, emissions and air quality effects of road dust have been studied recently in Finnish national projects KAPU (Kupiainen et al., 2009), REDUST (REDUST 2014) and the STUD research program (Kupiainen et al., 2013). Results and recommendations of those projects have highlighted the need to develop detailed modelling tools for establishing a more holistic and quantitative view of the different factors influencing the road dust issue as well as to support the formulation of strategies for reducing the emissions and air quality effects.

NOn-exhaust Road TRaffic Induced Particle emissions (NORTRIP) model has been developed as a Nordic collaboration utilizing the expertise of Nordic air quality modellers and emission experts (Johansson et al., 2012). The NORTRIP model quantifies the processes affecting the formation and emissions of road dust and couples these with dispersion estimates in urban street environments. Special attention in model development has been paid to emission sources relevant for Nordic conditions, i.e. studded tyres as well as traction sanding and salting.

This study has utilized the NOTRIP model in several street and road environments in the Helsinki metropolitan area during multiple years in 2006-2013. The model results have been compared with local air quality and emission measurements and local winter maintenance characteristics have been taken into account. Although the project has mainly focused at evaluating the model performance in Finnish sites, it has also been utilized to study the contribution of different road dust sources and potential for mitigating the emissions and air quality effects. However, since the model is still under development, the results in this area should be considered as indicative.

2 Overview of the NORTRIP model

The NORTRIP emission model (NOn-exhaust Road TRaffic Induced Particle emissions) has been developed during the NORTRIP project, a cooperative project between the Nordic countries of Norway, Sweden, Finland and Denmark (Johansson et al., 2012). The model consists of two sub-models, road dust and surface moisture model. Road dust sub-model predicts the road dust, sand and salt loading through a mass balance approach and determines the emissions through suspension of these loadings as well as through direct wear of road, tyre and brake sources. Road surface moisture sub-model determines road surface moisture needed for the prediction of suspension and the retention of dust and salt on the road surface. A surface mass balance approach is also applied, coupled to an energy balance model to predict evaporation/condensation. The model is described in detail in Denby et al. (2013a, b) and Denby and Sundvor (2012). Figure 1 shows the key processes included in the model. Sand abrasion and crushing, as well as windblown suspension, are not currently included in the model.

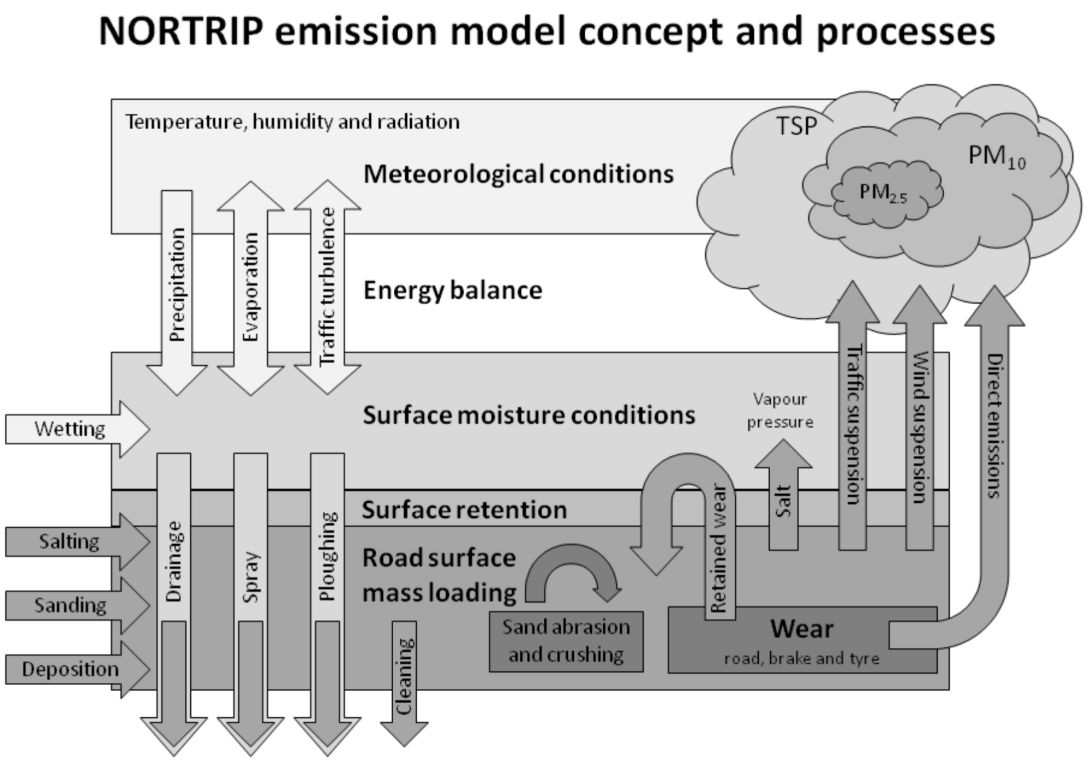

Figure 1. Schematic outline of the NORTRIP emission model (Johansson et al., 2012).

For the road dust sub-model the following major processes are included (Denby, 2013a, b):

- Road wear based on the Swedish road wear model
- Wear and emission of tyre and brake sources
- Direct emission of PM as well as retention of PM on the surface due to surface moisture
- Suspension of accumulated wear during dry periods
- Differentiation between the light and heavy duty contributions to wear and suspension
- Mass balance and suspension of salt
- Mass balance and suspension of sand
- Removal processes for dust and salt including drainage, vehicle spray, cleaning and snow ploughing
- Salting and sanding model for generating salt and sand application to the road, if no information is available

For the surface moisture sub-model the following main processes are included (Denby, 2013a, b):

- Addition of water and/or ice to the surface through precipitation and wetting during salting/sanding activities
- Removal of water through drainage and vehicle spray
- Removal of snow through snow ploughing
- Energy balance model predicting surface temperature, surface melt/freezing and surface evaporation/condensation of moisture
- Impact of salt on the surface freezing temperature and on vapour pressure. Dust binding salt is included as $MgCl_2$

The model requires information on a number of parameters, not all of which are well known. To calculate the road dust emissions, the model requires information concerning total wear rates and the fraction of wear that is in the PM_{10} size which is defined in model input parameter list. Brake and tyre wear rates and size fractions are based on literature, e.g. Boulter, 2005. The road wear rates will depend on tyre type (studded or non-studded), vehicle speed, and vehicle type (heavy or light) as well as on the road pavement characteristics. For studded tyres the wear is calculated based on a Swedish road wear model (Jacobson and Wåberg 2007) coupled with size distribution data to obtain smaller dust sizes. The road wear model has been developed based on wear measurements in a road simulator and it has been validated against pavement wear data collected from several field sites.

Due to a lack of information concerning the road wear characteristic for cobblestone in Mannerheimintie default wear rates based on the Swedish road wear model were used and adjusted in order to approximate the observed mean concentration. We have also assumed that rain is drained off from the cobblestone surface effectively and simulated this in the model.

Sand may also be applied to the road surface in the model, even though there is significant uncertainty in its rate of application, in its size distribution and in the mechanisms for its removal (Denby, 2013a). Model uses a concept of suspendable and non-suspendable sand with the cut off around 200 µm (Denby and Sundvor 2012). In this study suspendable sand fraction is set to be 6% which is the suspendable sand fraction indicated by the VTI measurements of particles size distribution for traction sand used in Stockholm.

Suspension is treated based on a suspension factor that removes a small fraction of the dust with each vehicle passage. Suspension factor may vary from road to road depending on the road surface macro-texture. Previous studies (Denby et al., 2013a) have shown a reasonable range of values to be between 0.5×10^{-6} and 5×10^{-6} veh^{-1}. In this study, value of 2.5×10^{-6} veh^{-1} was used for streets and 1×10^{-6} veh^{-1} for the ring roads. Discrepancy in the results for the highly trafficked roads with high vehicle speed was previously observed (Denby and Sundvor, 2012) and it was suggested that assessment with lower suspension rates is needed in order to improve model results. The wear and suspension rates are assumed to be linearly dependent on vehicle speed.

Sensitivity assessments (e.g. Johansson et al., 2012; Denby et al., 2013a, b) have proved the role of road surface moisture as the most important factor determining variations in road dust emissions. Performance of the model with modelled and measured surface moisture has been compared by Denby et al. (2013 b). In general, use of the measured surface moisture will significantly improve model predictions of PM_{10} concentrations. The moisture sub-model was found to predict the hourly surface state, wet or dry, 85% of the time (Denby et al., 2013 b).

3 Evaluation of NORTRIP model performance for the selected sites in the Helsinki metropolitan area

The NORTRIP model performance was evaluated for different street and road environments using the currently available input data and model parameter set modified to utilize site specific characteristics. The evaluation was done by comparing model predictions to the observed PM_{10} concentrations, source contributions and emissions measured using the Sniffer mobile laboratory (Pirjola et al., 2009; 2012). Model was applied for the following sites: Mannerheimintie (2006-2009 and 2013), Ring I Malmi (2012), Ring III Varisto (10.2012-5.2013) and Suurmetsäntie (10.2011-5.2012 and 10.2012-5.2013).

For the sites with the available kerbside air quality measurements (Mannerheimintie, Ring I and Ring III), modelled PM_{10} concentrations (modelled non-exhaust PM_{10} plus exhaust particles and urban background contribution) and the number of exceedance days (days with PM_{10} mean daily value >50 µg/m^3) were compared to the observations. Comparisons between the observed and modelled concentrations were made for hours when measured kerbside NO_X and PM_{10} concentrations were higher than the background concentrations. The daily mean values were calculated if at least 7 comparable hours were available. Therefore, the observed values used for the comparison may differ from the official statistical records. Comparison was done on annual level and for the spring period (15.3.-31.5.).

Comparison of source contributions was done for the sites where such data was available from the previously conducted projects. These include Suurmetsäntie season 2011/2012 and Mannerheimintie years 2008-2009. A source apportionment study for Suurmetsäntie road dust suspension samples was conducted as a part of the STUD research program (Kupiainen et al., 2013). A similar study was done for the PM_{10} exceedance days in Mannerheimintie for years 2008 and 2009 (Kupiainen and Stojiljkovic, 2009; Kupiainen et al., 2011). Salt content in PM_{10} air quality samples was analyzed for the selected days in Ring III and compared to the model predictions.

Modelled PM_{10} emissions were compared with the data obtained from the measurements in Suurmetsäntie conducted during the REDUST project (REDUST 2014). Measurements were done by the Sniffer mobile laboratory. The measured suspended dust emissions were compared with the model predictions both directly and after conversion to emission factors.

3.1 Model input data

The NORTRIP model requires a range of input data and information on number of parameters in order to calculate non-exhaust emissions of the traffic.

Input data requirements include **metadata** on road and street canyon configurations, **traffic data** (vehicle counts, vehicle types, tyre types and vehicle speeds) and **meteorological data** (wind speed, temperature, radiation, cloud cover, and humidity). Road surface conditions (road surface moisture and temperature) are optional. **Road maintenance activity data** include information about addition of salt and sand to the road surface as well as dust binding, street cleaning and ploughing events. **Air quality data** including measured kerbside and background PM_{10}, $PM_{2.5}$ and NO_X concentrations, estimated NO_X and $PM_{2.5}$ exhaust emissions is required in order to compare modelled PM_{10} concentrations with the observations. The model uses hourly time series of the input data.

Meta data

Mannerheimintie site is a wide (47 m) street canyon surrounded by 6-storey buildings. The number of driving lanes is four. Tram rails are located in the middle of the street. All other study sites were located in open environments. The number of lanes is 4 at Ring I Malmi and Ring III Varisto sites. Suurmetsäntie is a smaller street with 2 lanes.

Traffic input

Hourly traffic distribution was estimated using average daily traffic volume information in combination with the hourly traffic estimates calculated based on the information and data provided by the City Planning Department of Helsinki (Mannerheimintie and Suurmetsäntie) and the Finnish Transport Agency (ring roads). The emission estimates of NO_x and $PM_{2.5}$ exhaust particles were calculated by HSY using emission factors from the Handbook Emission Factors for Road Transport (HBEFA; www.hbefa.net). Summary of the traffic properties for the modelled sites is given in Table 1.

Table1. Average traffic properties for the modelled sites.

Site	Average daily traffic	Share of heavy duty vehicles (%)	Mean speed (km/h)
Mannerheimintie	20495	5.2	22
Ring I	58867	5.7	74
Ring III	40768	9.7	82
Suurmetsäntie	13587	7.4	60

The winter tyre season was set to be from 23 October to 1 May with one month transition period during which winter tyres phase-in in late autumn and phase-out in spring. Studded tyres are used only by the light duty vehicles. The maximum share of studded tyres during the winter tyre season is 80%. For Mannerheimintie 2006-2009, the transition between winter and summer tyres is assumed to be linear, whereas for other sites and modelled periods it is based on the counts of the studded tyre share in Helsinki which started in season 2009/2010 (REDUST 2014).

Road maintenance activity data

Information about the road maintenance activities in Mannerheimintie was taken from the book-keepings compiled during the KAPU (2006-2010) and REDUST (2011-2014) projects. Similar information was also collected for Suurmetsäntie. Activity data for Ring I and Ring III was obtained from Destia Ltd, Finnish infrastructure and construction servicecompany responsible for the maintenance of the ring road sites. Summary of the road maintenance activities for the modelled sites is presented in Table 2.

Table 2. Summary of the road maintenance activities for the modelled sites.

Site	Year	Sanding	Salting	Dust binding	Cleaning	Ploughing*
Mannerheimintie	2006	27	21	2	3	12
	2007	18	19	-	1	9
	2008	2	25	13	1	16
	2009	-	25	24	3	24
	2013	8	38	32	4	**7**
Ring I	2012	-	107	-	-	7
Ring III	10.2012-5.2013	-	83	-	-	36
Suurmetsäntie	10.2011-6.2012	41	41	-	1	4
	2013	16	13	-	-	8

**modelled values*

Due to insufficient data regarding the timing of the road maintenance activities for Mannerheimintie and Suurmetsäntie, all measures are set to take place at 5:00 AM.

Most of the reported sanding events occurred during the period between January and March. Default amount of 100 g/m^2 of traction sand was used unless differently specified in the road maintenance book-keepings. In Suurmetsäntie traction control was mainly done with the 50/50 by volume mixture of sand and salt. Model does not recognize this kind of traction control practice therefore mass of salt and sand were estimated from the reported amounts of the mixture and used as an input.

The road maintenance book-keepings do not provide information about the used amounts of traction and dust binding salts. For this reason the same practice was assumed for all modelled sites. For each salting occasion 20 g/m^2 (dry mass) of NaCl is added to the road surface and for each dust binding occasion 40 g/m^2 (dry mass) of dust binding salt. In both cases salt was assumed to be applied in 16% by weight solution. In the light of the recent findings the amounts of traction and dust binding salt used in practice may be even half of those used in this study.

The effect of street cleaning is simulated in the model by removing dust and salt mass from the road surface with the predefined efficiency. In this study cleaning efficiency of 30% was applied, which might be a too optimistic estimate in reality.

Modelled ploughing events were used for all sites. This means that model applies ploughing automatically when the snow depth is more than 3 mm water equivalent (which for new snow is about 3 cm) removing 80% of the snow.

Meteorology

Summary of the meteorological data used in this study is shown in Table 3. On-site meteorological measurements were available only for Suurmetsäntie for the period between March and June. Modelled road surface moisture was used for all sites except for Suurmetsäntie. Measured surface moisture data (Vaisala Remote Surface State Sensor DSC111) from Suurmetsäntie was available for the period between mid-March and June. Outside of this period the road surface moisture measurements were adopted from the nearby Jakomäki Road 4 site (Centre for Economic Development, Transport and the Environment). The meteorological data from Kaisaniemi and Kumpula was obtained from the Finnish Meteorological Institute.

Table3. Summary of the meteorological data used for the modelled sites and location at which data was collected (station name in the brackets).

Site	Year	Mean temp. (ºC)	Mean global radiation (W/m^2)	Mean cloud cover (%)	Total precipitation (mm)	Dispersion factor ($\mu g/m^3(g/km/hr)^{-1}$)
Mannerheimintie (Kaisaniemi met. station with Kumpula global radiation)	2006	6.8	120	54	250	0.082
	2007	7.1	113	56	722	0.106
	2008	7.6	107	62	790	0.104
	2009	6.2	113	58	605	0.117
Mannerheimintie (Pasila met. station with Kumpula global radiation)	1.-10. 2013	7.1	119	49	330	0.115
Ring I (Pasila met. station)	2012	5.9	112	53	631	0.064
Ring III (Ämmässuo met. station)	10.2012-5.2013	0.2	79	54	374	0.125
Suurmetsäntie (Pasila/Suurmetsäntie met. station)	10.2011-6.2012	2.9	81	55	389	-
	10.2012-6.2013	1.6	87	54	237	-

Air quality data

Air quality data from HSY was available from Mannerheimintie and the ring roads kerbside traffic stations. Kallio, Vartiokylä and Luukki were used as background stations for Mannerheimintie, Ring I and Ring III, respectively. Since there was no measurements of the PM_{10} at the Luukki background station, PM_{10} concentrations were estimated based on the assumption that the $PM_{2.5}/PM_{10}$ ratio is about 0.75 at rural background sites. Exhaust emissions were calculated based on traffic average emission factors.

3.2 Model performance evaluation results

3.2.1 Mannerheimintie

Mannerheimintie modelling results for the total daily mean concentrations and dust loading for all calendar years of the modelled period are shown in Appendix A, Figures A1-3. Statistical summary of the modelling results is given in appendix B, Table B.1. Mean annual and spring PM_{10} concentrations and number of exceedance days are presented in Figure 5 and Figure 6, respectively.

The NORTRIP model was applied over a four-year period, from January 2006 to December 2009 and for year 2013 at Mannerheimintie. Taking into account that the traffic properties remained almost unchanged during the modelled period, differences in model predictions between years can be considered to be due to the year specific meteorological conditions and associated road maintenance. Contribution of the urban background to the total modelled PM_{10} concentrations was significant, on average around 60%.

The model captures well the seasonal variation in PM_{10} concentrations along with dust loading decline during spring and build-up during next winter season. For the period between years 2006 and 2009 the model predicts annual mean PM_{10} concentrations with average fractional bias of -12%, ranging between -6% to -21% for the individual years (see Appendix B for more details).

In spring 2006, a period with very high observed PM_{10} was visible in both background and net (kerbside subtracted by background) concentrations. According to the *Air Quality in the Helsinki Metropolitan Area in year 2006* report (Myllynen et al., 2007) this was due to a number of coinciding factors; the beginning of the road dust season, long-range transport (LRT) episode, poor dispersion conditions and VR (state railways) warehouse fire in the city centre. This period was not well modelled because of the significant influence of these additional sources. The best match with observations both in the mean concentrations and the number of exceedance days was achieved for year 2007. The total modelled and observed daily mean PM_{10} concentrations for years 2006 and 2007 are shown in Figure 2.

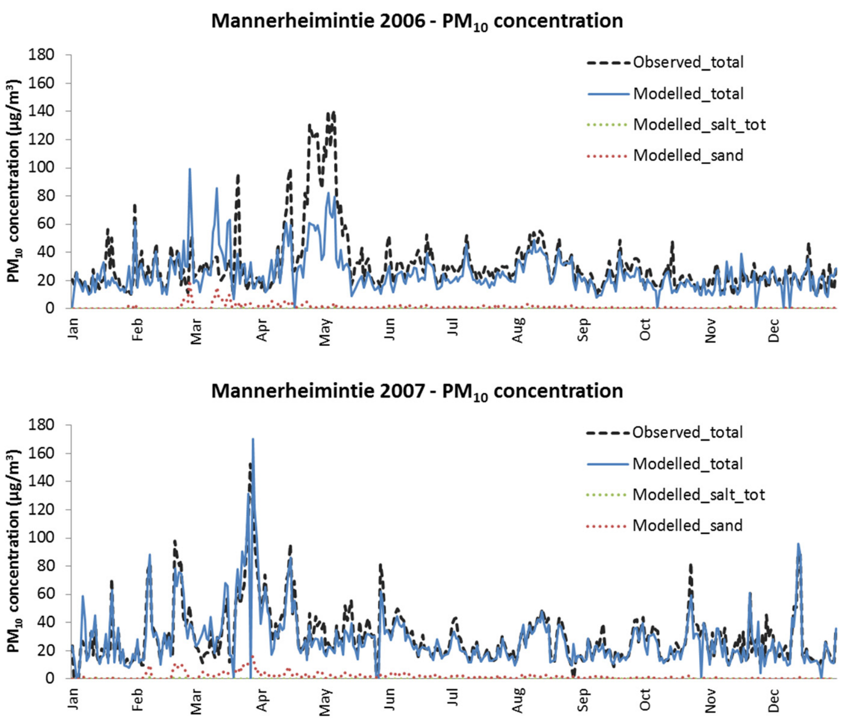

Figure 2. Modelled and observed total daily mean PM_{10} concentrations at Mannerheimintie for years 2006 and 2007.

It is assumed that the construction works, conducted in Mannerheimintie in late spring and in the beginning of summer in both 2008 and 2009, were responsible for the missing modelled mass during these periods. This affected match between the predicted and observed mean concentrations as well as modelled number of exceedance days. The influence of other sources, including construction sites, was demonstrated in the PM_{10} source apportionment studies for the exceedance days in Mannerheimintie in 2008 and 2009 (Kupiainen and Stojiljkovic, 2009; Kupiainen et al., 2011). A comparison of the average modelled PM_{10} concentrations with the source apportionment results for the exceedance days in April 2008 and May 2009 is shown in Figure 3. Similar comparison for all exceedance days for years 2008 and 2009 is given in Figures C.1. and C.2.

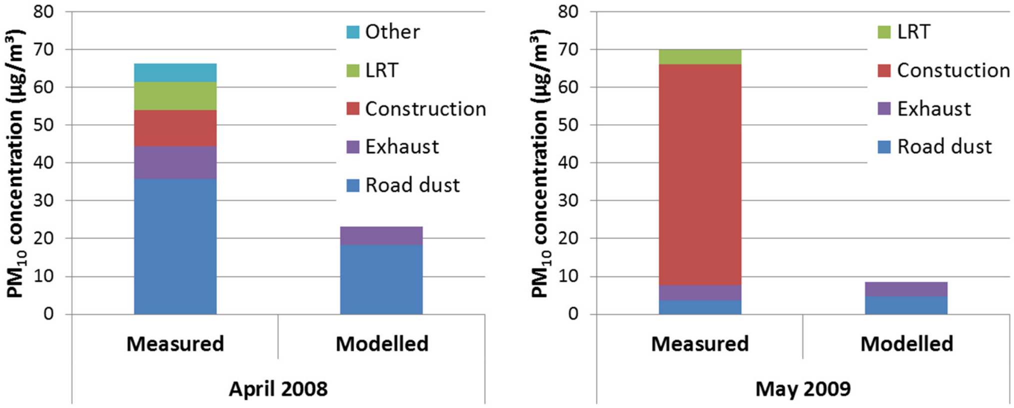

Figure 3. Average PM_{10} source contributions on exceedance days in Mannerheimintie during April 2008 (left) and May 2009 (right). "Measured" refers to the results from the source apportionment studies.

Figure 4 shows the daily mean PM_{10} concentrations for year 2013 at Mannerheimintie. The abundance of snow and lasting temperatures below zero kept the PM_{10} emissions at a low level at the beginning of the year. The beginning of the road dust season and concentration peaks in March and April are captured by the model. The observed values are slightly underestimated in May and June when the high PM_{10} level can partly be explained by the influence of the nearby construction sites.

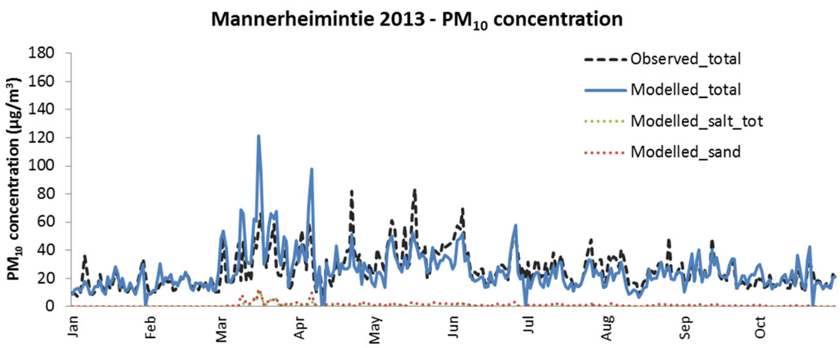

Figure 4. Modelled and observed total daily mean PM_{10} concentrations at Mannerheimintie for year 2013.

Model error in predicting the number of days exceeding the PM_{10} mean daily limit value (50 µg/m^3) is larger than that found for the mean concentrations (Figures 5 and 6). The model underpredicts the number of exceedance days by 27% on annual and 24% for the spring period. The number of predicted exceedance days was higher than the observed only for year 2013. The number of exceedance days was more sensitive to the meteorological conditions and presence of additional PM_{10} sources than the mean concentrations.

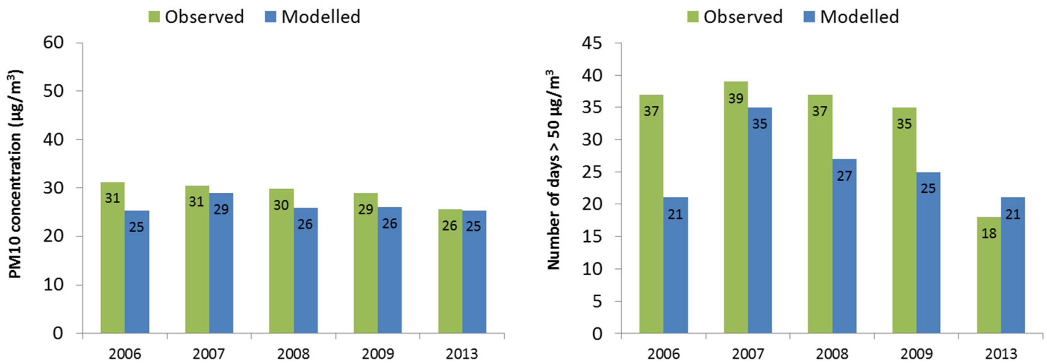

Figure 5. Observed and modelled mean annual PM_{10} concentrations (left) and number of exceedance days (PM_{10} concentration > 50 µg/m³) (right).

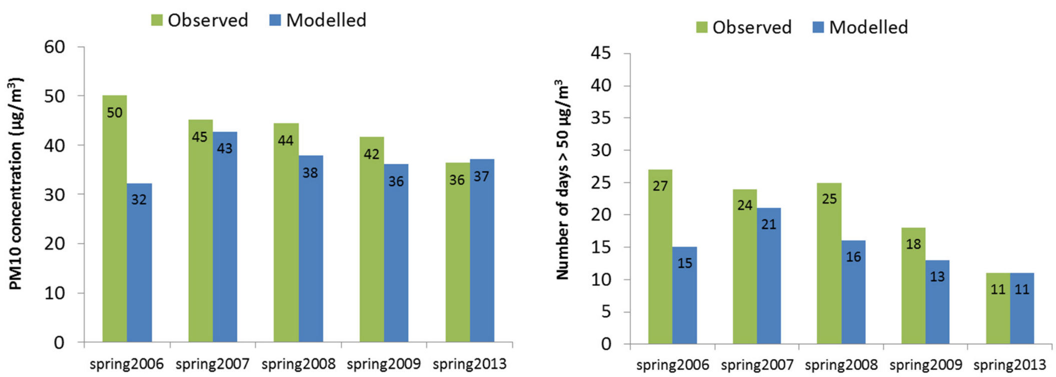

Figure 6. Observed and modelled spring period mean PM_{10} concentrations (left) and number of exceedance days (PM_{10} concentration > 50 µg/m³) (right).

3.2.2 Ring roads (Ring I and Ring III)

The model was applied for year 2012 at Ring I and between October 2012 and May 2013 for Ring III. At Ring III, the kerbside PM_{10} measurements began in January 2013. Modelling results for the daily mean concentrations and dust loading for Ring I and Ring III are shown in Figure A.4 and Figure A.5, respectively. Statistical summary of the modelled PM_{10} concentrations for Ring I is presented in table B.2 and for Ring III in table B.3. The predicted and observed total mean PM_{10} concentrations and number of exceedance days are presented in Figures 7 and 8.

At both ring road sites the model overestimates PM_{10} concentrations during the winter and spring periods. The Ring I annual mean concentration was overestimated with fractional bias of 33% and 14% for the spring period. A high PM_{10} episode at Ring III that occurred from the beginning of March until mid-April after a long wet period was captured by the model. The mean concentration was however overestimated by a factor of 1.8. Because of discrepancy between the modelled and observed PM_{10} concentrations during the winter and spring months, an error in the number of predicted exceedance days was significant on the annual level although it was less pronounced for the spring period, especially for the Ring I.

A possible explanation for the over predictions of the model during the winter and spring months may lie in wet removal processes such as spray, that can be a significant removal process at high speeds. The removal rate of dust and salt by the spray of water (and also possibly snow which is currently not in the model) is not yet well defined. Additionally the wear estimates in high speeds should be evaluated. These issues will be addressed in the future model development work.

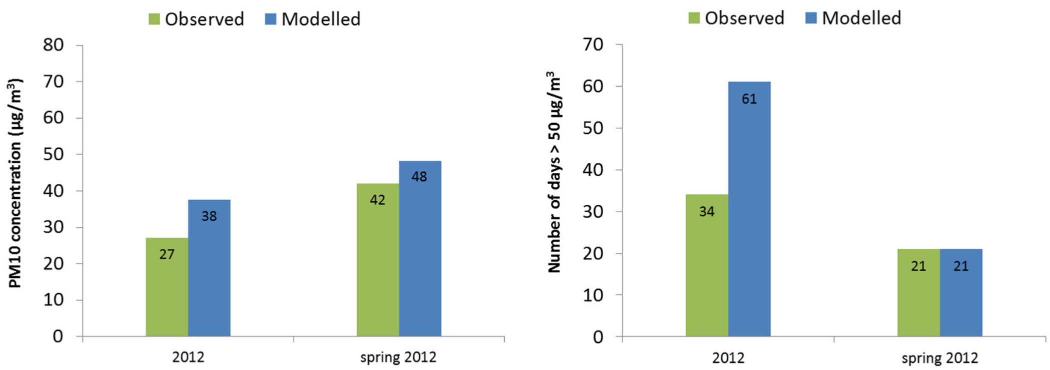

Figure 7. Observed and modelled mean annual PM_{10} concentrations (left) and number of exceedance days (PM_{10} concentration > 50 µg/m³) (right) for Ring I.

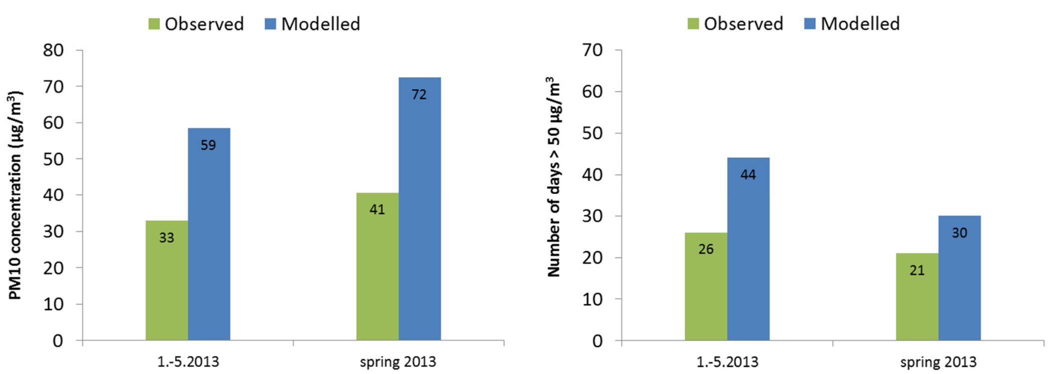

Figure 8. Observed and modelled mean annual PM_{10} concentrations (left) and number of exceedance days (PM_{10} concentration > 50 µg/m³) (right) for Ring III.

Salt content in the Ring III PM_{10} samples was analyzed for the selected days (daily PM_{10} > 50 µg/m^3) in March and April 2013, and compared to the salt concentrations predicted by the model. The results are presented in Figure 9. From October 2012 to May 2013 there were 83 salting events, three of which took place between March and April (12 March, 13 March and 7 April). In general, the results indicate that the model captures reasonably well the dynamics of the measured salt concentration.

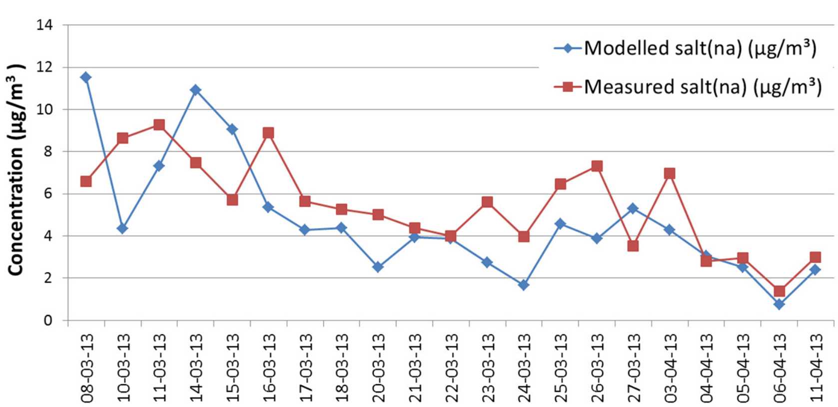

Figure 9. Modelled and measured NaCl salt content in PM_{10} at Ring III for the selected days.

3.2.3 Suurmetsäntie

The Suurmetsäntie non-exhaust PM_{10} emissions were modelled for the period between October and May for the seasons of 2011/2012 and 2012/2013. The modelled PM_{10} emissions from different sources are compared to the results of the source apportionment study for the road dust suspension samples conducted as a part of the STUD research program in 2011 and 2012 (Kupiainen et al., 2013). The PM_{10} samples behind the left rear tyre of the mobile laboratory Sniffer were collected onto the filter of the monitoring instrument (DustTrak) when the Sniffer drove back and forth at Suurmetsäntie. The sampling time was at least one hour. The composition of the dust particles was analyzed by the SEM/EDX method. A comparison of the results for the days when the source apportionment data was available is presented in Figure 10.

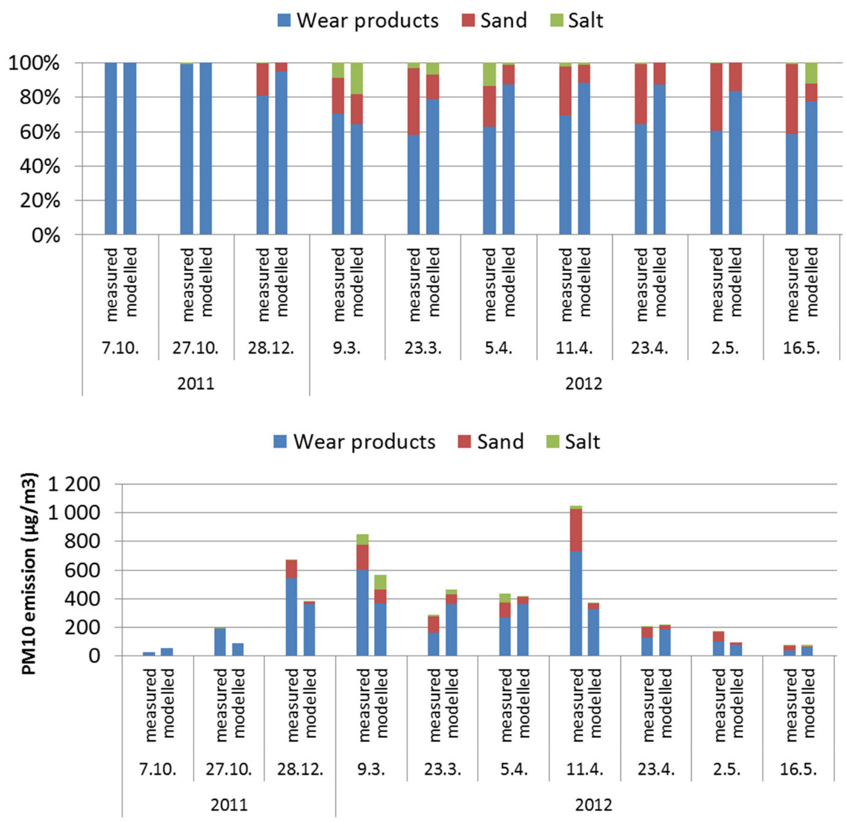

Figure 10. Modelled and measured contributions of different sources to the PM_{10} emissions presented as relative (top) and absolute values (bottom). "Measured" refers to the results from the source apportionment studies. Modelled wear products include road, tyre and brake wear. Measured wear refers to the pavement wear only.

First recorded application of salt in Suurmetsäntie was in November 2011 and first sanding was in December 2011. Two different approaches for identifying PM_{10} emission sources find wear processes as a major source of dust in October samples. Presence of sanding material was identified in the succeeding samples with the modelled share of sand being around half of the measured (Figure 10). Modelled sand and salt emissions are sensitive to the choice of dust removal efficiency for cleaning and wet removal processes (drainage and spray) as well as defined fraction of suspendable sand. It is worth mentioning that the amount of applied sand and salt used as model input were estimated based on the reported mass of sand/salt mixture and may be different from those used in practice.

The modelled emissions are also compared with the data obtained from the Sniffer mobile measurements of the suspendable PM_{10} in Suurmetsäntie during the REDUST project (REDUST 2014). Outcome of the Sniffer measurements is an average concentration of the suspended PM_{10} measured behind the left rear tyre (inlet) with a monitoring instrument TEOM (Tapered Element Oscillating Microbalance) during multiple measurement rounds along the street. These concentrations can be converted to emission factors using the equation derived by Pirjola et al. (2012). First, the modelled daily mean emissions are compared directly to the PM_{10} concentrations measured with the Sniffer. Secondly, the modelled daily mean emission factors were converted to the traffic average emission factors and compared to the Sniffer emission factors. Results are presented in Figures 11 and 12.

Figure 11 shows the results with both modelled emissions and suspended PM_{10} concentration measured by the Sniffer between October and June. Axes are arbitrarily scaled in both figures. In relative terms this results in a very similar trajectory for both modelled and Sniffer measured values. Both approaches indicate a downward trend in spring months (March-May) and a stabilization of the emissions from June onwards.

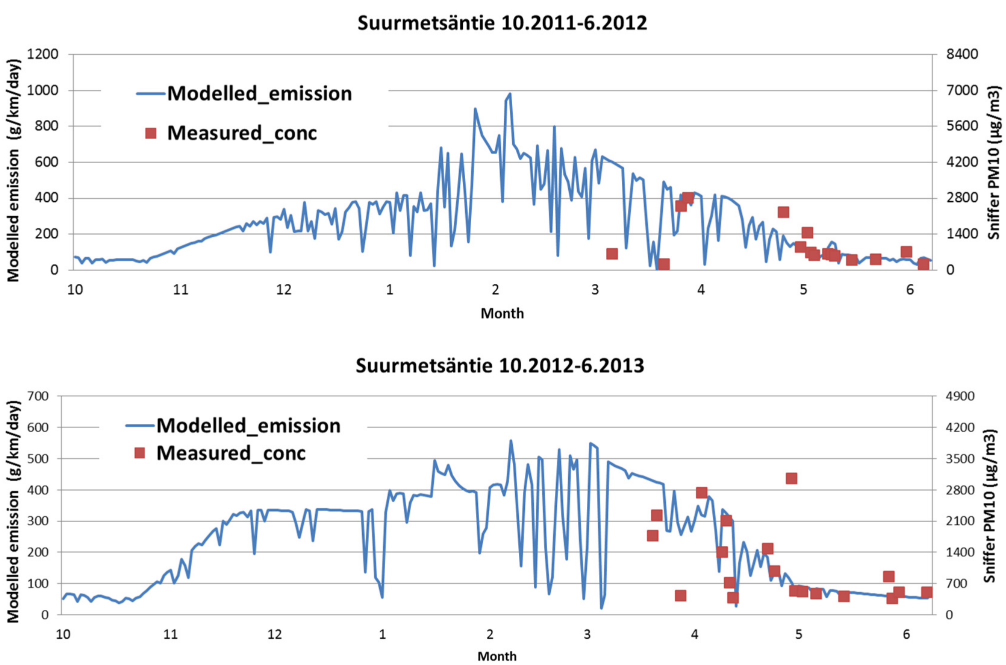

Figure 11. Modelled daily mean PM_{10} emissions and Sniffer PM_{10} concentrations on measurement days in Suurmetsäntie for the seasons 2011/2012 (top) and 2012/2013 (bottom).

Emission factors calculated based on the Sniffer concentrations seem to be on a higher level than the modelled traffic average emission factor values (Figure 12). Similar observation has been made by Kauhaniemi et al. (2014). Some of the possible factors that may be sufficient to create difference between modelled and measured emission factors are uncertainties in the model input data. Additionally, the conversion equation between the Sniffer concentration and emission factor is not yet fully established.

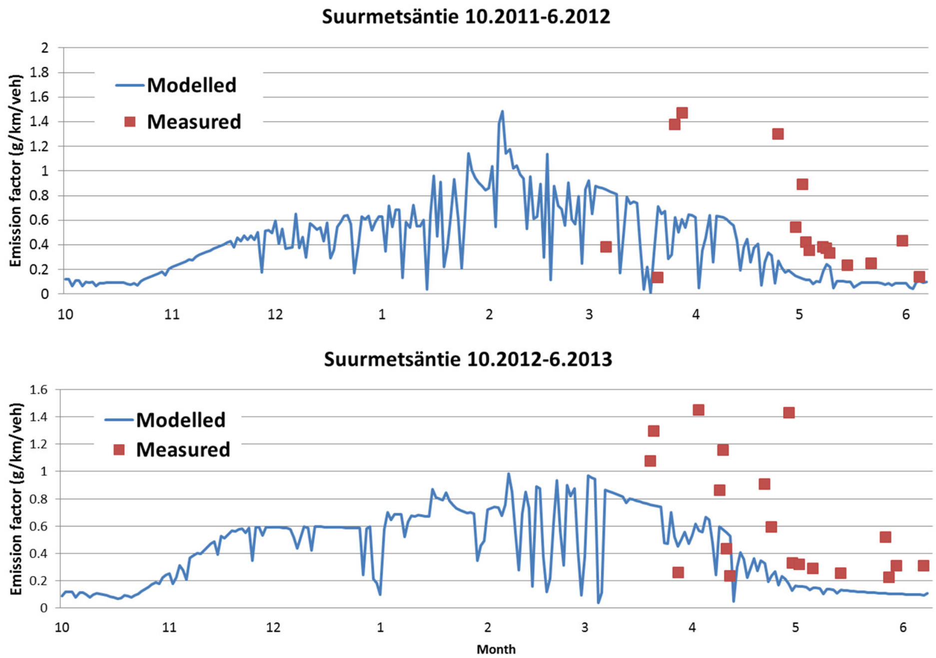

Figure 12. Modelled daily mean emission factors and Sniffer emission factor on measured days in Suurmetsäntie for the seasons 2011/2012 (top) and 2012/2013 (bottom).

3.2.4 PM_{10} from studded tyre wear

Road wear rates in the NORTRIP model depend on tyre type (studded or non-studded), vehicle speed, and vehicle type (heavy or light) as well as on the road pavement characteristics. For studded tyres the wear is calculated based on a Swedish road wear model coupled with size distribution data to obtain smaller dust sizes (Jacobson and Wåberg 2007). The road wear model has been developed based on wear measurements in a road simulator, and it has been validated against pavement wear data collected from several field sites.

In this study, the PM_{10} wear estimates from the on-road emission measurements were compared with those obtained with the NORTRIP model. The results of the on-road PM_{10} emission measurements from the recent projects (REDUST and STUD) were compiled and complemented with some additional emission measurements of studded and studless winter tyres that were made within this study.

In order to estimate how the on-road emission measurements of studded tyres relate to the emission module of the NORTRIP model, measurement results with different speeds were compiled. Figures 13 and 14 illustrate how the on-road measurements and the NORTRIP model relate to each other regarding the speed dependency. In order to make the results comparable, both the measurements and model results have been normalized so that the results with 50 km/h have been set to 100. Since it is unclear whether the travelled distance should be taken into account in on-road measurements, we show the results without (Figure 13) and with (Figure 14) a correction of the longer distance travelled during a time unit.

The speed dependency of the PM_{10} emission from road wear by studded tyres is relatively similar in both the NORTRIP model and the on-road measurements as shown in Figures 13 and 14. The distance correction does not affect this conclusion, although the match with the modeled result seems to be somewhat better.

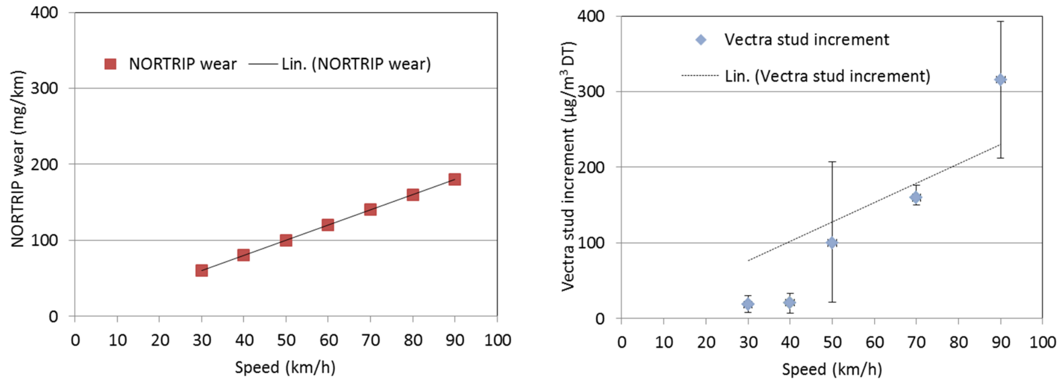

Figure 13. Stud increments measured with different speeds during STUD, REDUST and this project and comparison with NORTRIP/VTI tyre wear PM_{10}. Both NORTRIP wear and stud increments have been normalized so that speed 50 km/h is equal to 100.

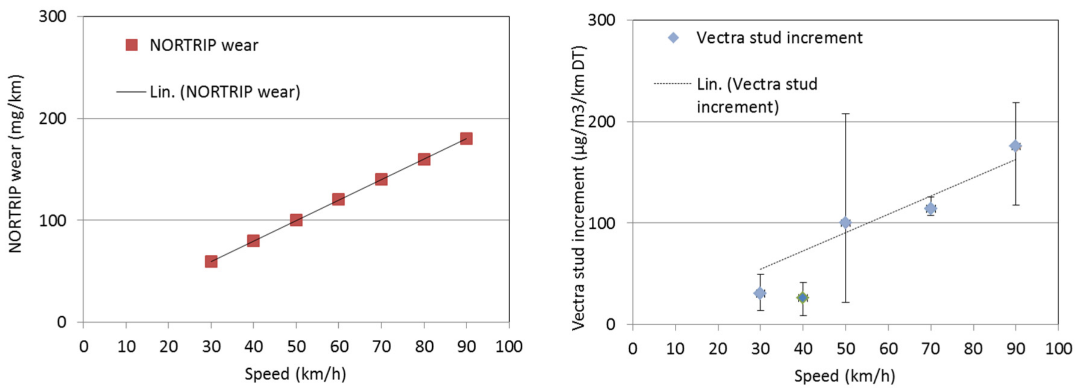

Figure 14. Stud increments measured with different speeds during STUD, REDUST and this project and comparison with NORTRIP/VTI tyre wear PM_{10}. Two adjustments have been made to the original datasets (1) NORTRIP wear and stud increments have been normalized so that speed 50 km/h is equal to 100, (2) Stud increments (mobile measurement) have been normalized to take into account the potential influence of differing travel distance to emission signal speed 50 km/h has been set to 100.

3.3 Summary of the model evaluation results

Evaluation of the NORTRIP model performance at the selected sites in the Helsinki metropolitan area was done by applying model for the five years at Mannerheimintie (2006-2009 and 2013), one year at Ring I (2012) and period between October to May at Ring III (2012/2013) and Suurmetsäntie (2011/2012 and 2012/2013).

The NORTRIP model requires a range of input data and information on number of parameters in order to calculate non-exhaust emissions of the traffic. The main challenge related to the input data was missing or incomplete information about the road maintenance activities, especially timing and amounts of used materials (traction sand as well as traction and dust binding salts). Model parameter set was modified to utilize site specific characteristics. Wear properties of the cobblestone in Mannerheimintie are unknown. Therefore default wear rates based on the Swedish road wear model were adjusted and used. Additionally it was assumed that rain is drained off from the cobblestone surface effectively. For the model application at ring roads reduced suspension rates were used.

All the results in this study apart from Suurmetsäntie are based on the modelled surface moisture which has an influence on variation and timing of modelled road dust emissions particularly during winter and spring months.

The NORTRIP model captures reasonably well seasonal variation in PM_{10} concentrations along with the dust loading decline during spring and build-up during winter season for all modelled sites. At Mannerheimintie traffic properties have been almost unchanged during the modelled period therefore inter-annual changes of PM_{10} concentrations and number of exceedance days can be attributed to the year specific meteorological conditions and associated road maintenance activities. Contribution of the urban background to the total modelled PM_{10} concentrations was significant, on average around 60% on annual level. Model predicts total (modelled non-exhaust PM_{10} plus exhaust particles and background contribution) mean annual PM_{10} concentrations with average fractional bias of -10%, ranging between -1% to -21% for the individual years. Missing mass during late spring and summer months in 2008, 2009 and 2013 can be attributed partly to the influence of the nearby construction sites, as demonstrated in the PM_{10} source apportionment studies, and other sources not included in the model. At Mannerheimintie sand used on tram lines is a potential source of dust, whose influence on PM_{10} concentrations is not yet studied. Number of exceedance days is under predicted by 27% on annual and 24% for the spring period. Daily concentrations are more sensitive to the meteorological conditions and presence of additional PM_{10} sources than the annual or spring mean concentrations.

For both ring roads model captures high PM_{10} periods although discrepancy in the mean concentrations during winter and spring months exists. This has been observed for other high speed roads and the issue will be addressed in the future model development work. Comparison of measured and modelled salt content in PM_{10} indicates that model captures dynamic of measured salt concentration.

Modelled Suurmetsäntie PM_{10} emissions from different sources are compared to the results of the source apportionment study for road dust suspension samples for the period between October 2011 and May 2012. Two different approaches for identifying PM_{10} emission sources find pavement wear processes as a major source of emission at Suurmetsäntie in October 2012 samples and identify presence of sanding material in the succeeding samples with the modelled share of sand being around half of the measured. For better assessment of sand impact on PM_{10} emissions further work will be needed due to the significant uncertainty in its rate of application, in its size distribution and in the mechanisms for its removal. Direct comparison of the modelled daily mean emissions with the Sniffer measurements show very similar trajectory for both the modelled and Sniffer measured values with downward trend in spring months (March-May) and a stabilization of the emissions from June onwards.

In this study PM_{10} wear estimates from on-road emission measurements were compared with those obtained with the NORTRIP model. The speed dependency of the PM_{10} emission from road wear by studded tyres is relatively similar in both the NOTRIP model and the on-road measurements.

4 Sensitivity analyses of options to reduce PM_{10} concentrations

The aim of the analyses was to provide information on the sensitivity of the modelled PM_{10} concentrations to measures that can be used to reduce non-exhaust emissions and consequent ambient PM_{10} concentrations. The NORTRIP model was applied for four years (2006-2009) at Mannerheimintie to investigate sensitivity of mean annual and spring PM_{10} concentrations to changes in road maintenance activities including traction control and dust control activities (dust binding and street cleaning), studded tyre share and traffic parameters. Tested cases can be considered mainly as realistic options for street maintenance. Mean PM_{10} concentrations and source contributions for all tested cases were compared to the modelling results for the current road maintenance practice, henceforth referred to as “current state”. Figure 15 shows approximate timing and number of road maintenance activity events used for the “current state” model input.

In this analysis the focus was on the local traffic contribution, therefore comparisons were done for the modelled non-exhaust PM_{10} concentrations. In order to investigate whether different measures bring concentrations below the limit values, number of exceedance days was calculated taking into account urban background and exhaust emission contributions. Modelling results are presented as non-exhaust mean PM_{10} concentrations, relative change in mean concentrations compared to the “current state” and source contributions including exhaust particles. Number of exceedance days for all tested cases is given in Table B.4. Since the model is still under development, the results of this analysis should be considered as indicative.

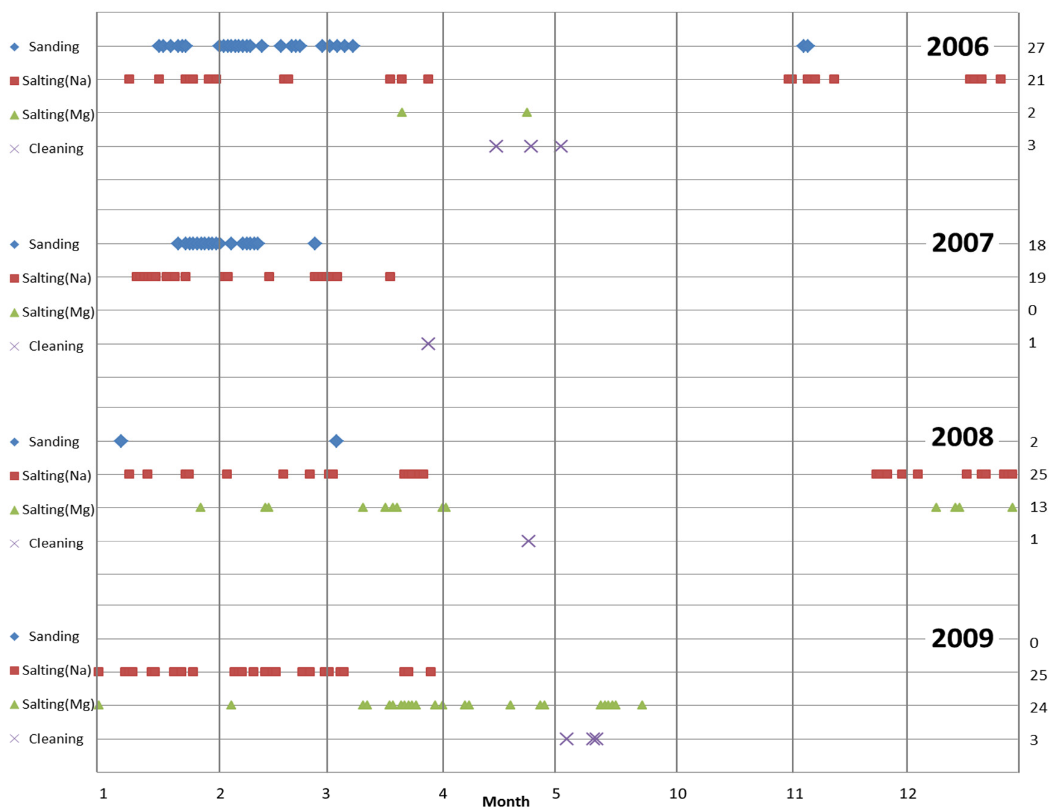

Figure 15. Mannerheimintie road maintenance activities used in the “current state” model input. Salting(Na) refers to winter-salting with NaCl and salting(Mg) refers to dust binding.

4.1 Impact of road maintenance activities

Sensitivity of modelled mean PM_{10} concentrations to different road maintenance practices was investigated by applying model for two traction control and four dust control cases:

Traction control cases:

1. All recorded traction control done by sanding (allSand)
2. All recorded traction control done by salting (allSalt)

Dust control cases:

3. No cleaning (noCleaning)
4. No dust binding (noDB)
5. No cleaning and no dust binding (noCleaningNoDB)
6. Maximal potential number of dust binding events (maxDB)

4.1.1 Traction control measures

Figure 16 shows the mean annual and spring period modelled non-exhaust PM_{10} concentrations and relative change in mean concentrations compared to the “current state” for the tested traction control cases. Source contributions are presented in Figure 17.

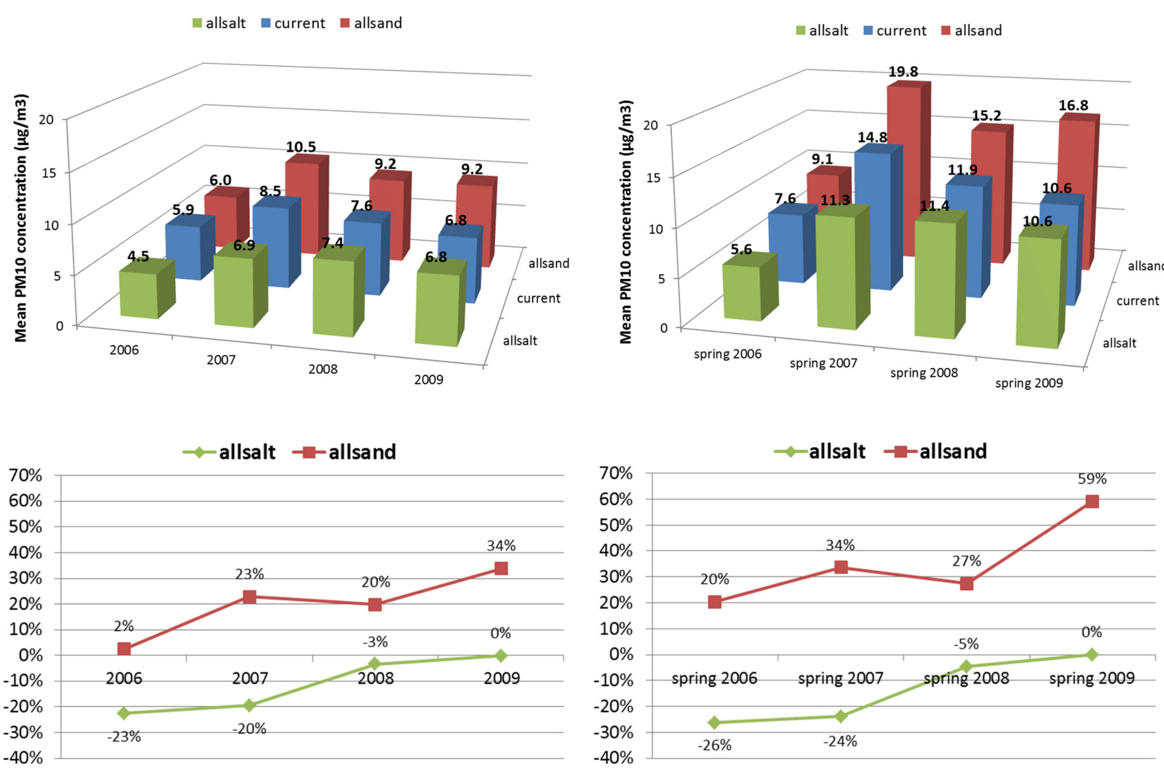

Figure 16. Mean annual (top left) and spring (top right) modelled non-exhaust PM_{10} concentrations for the tested traction control cases and relative changes of the mean annual (bottom left) and spring (bottom right) concentrations compared to the “current state“. Modelled non-exhaust concentrations don’t include PM_{10} background concentration.

The model indicates that using sand as a single traction control measure increases mean annual PM_{10} concentrations on average by 20% for the observed period. The impact of sanding is more pronounced during spring period with the change in mean concentrations between 20 to 59% for individual years. This will depend on the additional number of sanding events compared to the “current state”, timing of sanding, meteorological conditions and accompanying road maintenance activities. Impact on number of exceedance days varies from no changes in 2006 to 16 additional exceedances in 2009.

For years 2006 and 2007 with the extensive use of sanding, application of salt instead resulted in average reduction of mean PM_{10} concentration by 22% on annual level and 25% during spring. The number of exceedance days was reduced by 5 days in 2006 but remained unchanged in 2007. In 2007 PM_{10} peaks were lowered but not below the limit value. In 2008 substituting sand for salt on 2 recorded sanding days leads to reduction of mean annual PM_{10} concentration by 3% and 1 less exceedance day. There were no recorded sanding events in 2009 and therefore no change compared to the “current state”. It is important to note, that in reality all sanding events cannot be replaced completely with salting during very cold winter periods.

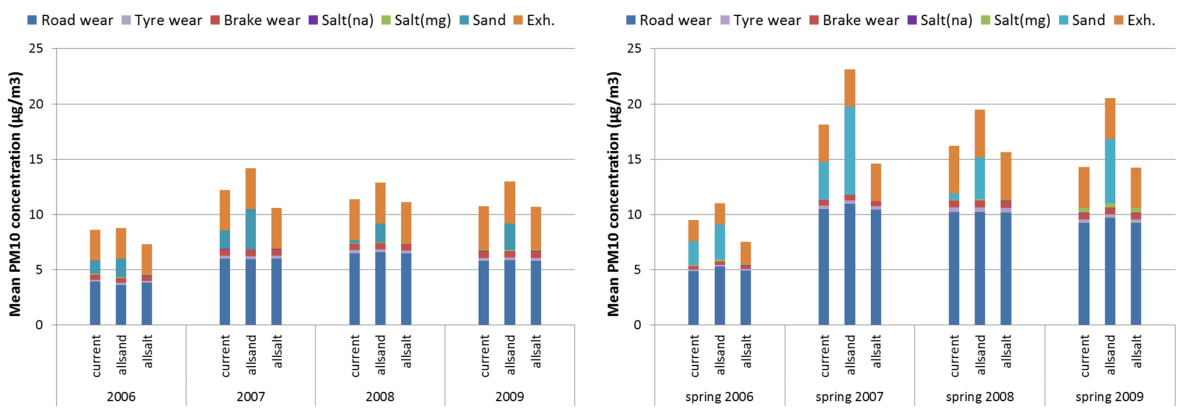

Figure 17. Source contributions of non-exhaust and exhaust PM_{10} particles for the tested traction control cases and “current state” in Mannerheimintie for the period 2006-2009. Modelled non-exhaust concentrations don’t include PM_{10} background concentration. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

4.1.2 Dust control measures (dust binding and street cleaning)

Figures 18 and 19 show results for the tested dust control measures. The results indicate air quality benefits of used dust binding and street cleaning practice. The reduction of mean PM_{10} concentration by cleaning alone ranged from 9% to 40% on annual level with 1-2 less exceedance days. Effect of cleaning will depend on timing and number of cleaning events but also on the predefined cleaning efficiency which is in this case chosen to be 30%. In reality, the cleaning efficiency is dependent on different cleaning technology types and might be clearly lower than 30%.

Impact of dust binding was tested by removing all dust binding events and by increasing number of dust binding events to a maximal potential number using selected criteria. Additional dust binding events took place on a dry day with average daily temperature >-7ºC one day before the observed exceedance day. Furthermore, two subsequent additional dust binding events have to be one day apart. Approximate timing and maximal potential number of dust binding events is shown in Figure D.1.

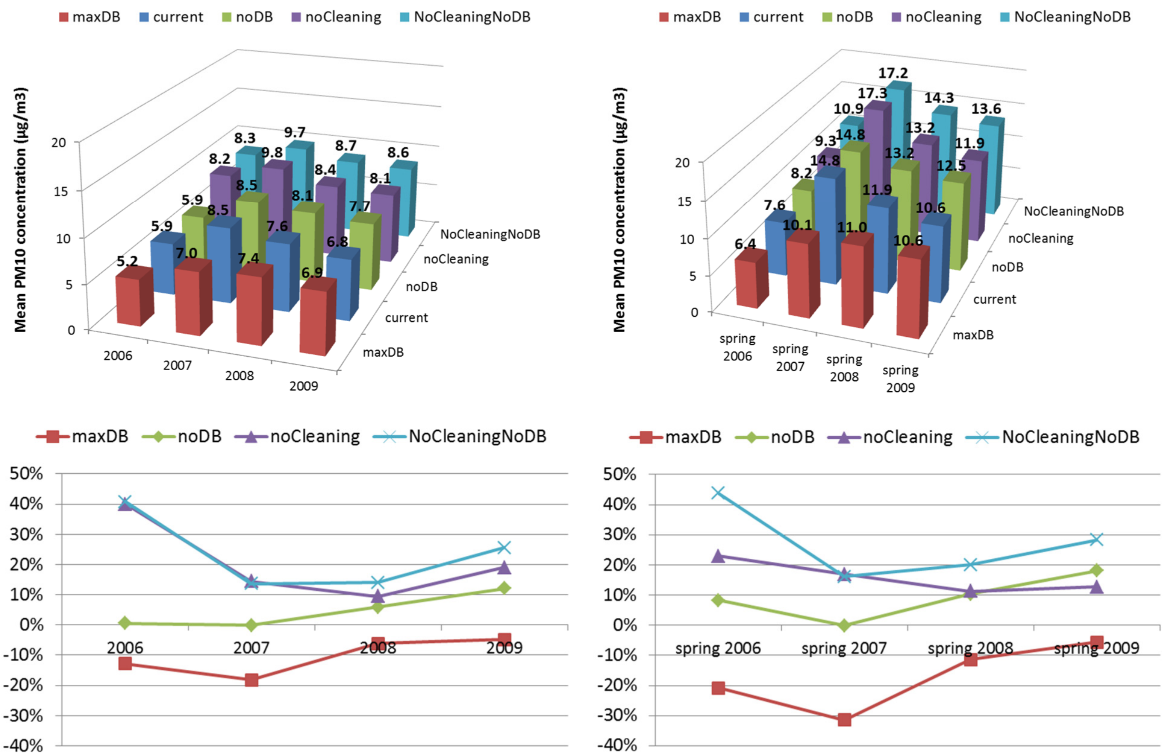

Figure 18. Mean annual (top left) and spring (top right) modelled non-exhaust PM_{10} concentrations for the tested dust control cases and relative changes of the mean annual (bottom left) and spring (bottom right) concentrations compared to the "current state" in Mannerheimintie for the period 2006-2009. Modelled non-exhaust concentrations don't include PM_{10} background concentration.

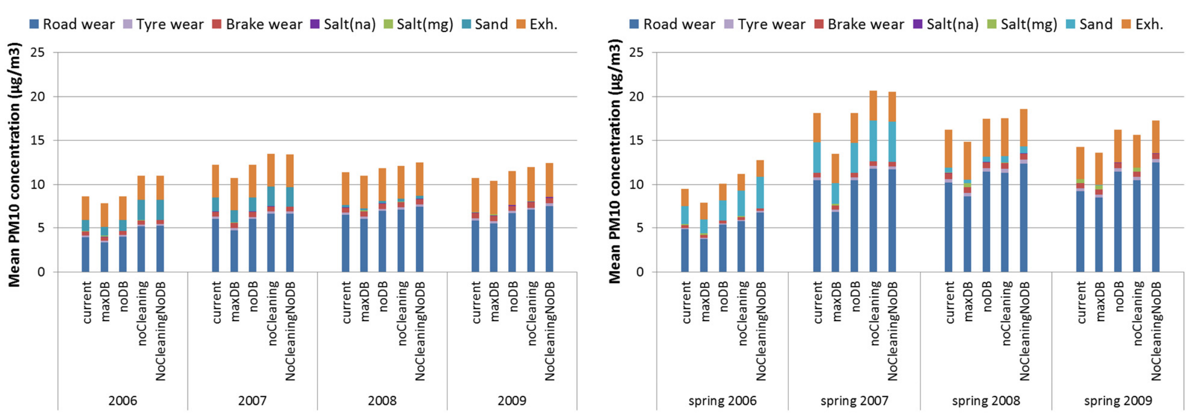

Figure 19. Source contributions of non-exhaust and exhaust PM_{10} particles for the tested dust control cases and the "current state" in Mannerheimintie for the period 2006-2009. Modelled non-exhaust concentrations don't include PM_{10} background concentration. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

For years 2008 and 2009 the achieved reduction of mean annual PM_{10} with the "current state" dust binding practice was 6% and 12%, respectively with 3-4 avoided exceedance days. Impact of dust binding was more significant in the spring period, also for year 2006 with only two dust binding events.

Additional number of dust binding events significantly reduces mean PM_{10} concentrations in 2006 and 2007 when "current state" case had 2 and 0 dust binding occasions, respectively. Additional 22 dust bindings in 2006 and 21 in 2007 reduce mean annual concentrations by on average 15% for the two-year period with around 30% less exceedances. In 2008 and 2009 with already extensive dust binding use, additional dust binding days reduce PM_{10} concentrations by 6% in 2008 and 5% in 2009 and exceedance days by 9 in 2008 and 2 in 2009. Effect of additional dust binding on mean PM_{10} is more pronounced for the spring period.

4.2 Impact of studded tyre share

Impact of studded tyres on PM_{10} was assessed by reducing the maximum share of light duty vehicles using studded tyres to 70, 50 and 30%. The results are shown in Figure 20 as mean annual and spring period PM_{10} concentrations and relative change in mean concentrations compared to the "current state" where maximum studded tyre share was 80%. Source contributions for the tested cases are presented in Figure 21.

Sensitivity test shows that 10% change in studded tyre share lead to average decrease in mean annual PM_{10} concentration of 7% and on average 2 exceedance days less for the observed four-year period. Number of exceedance days avoided by 10% reduction in studded tyre share range from 1 to 6 for the individual years and cases studied, and is highly dependent on meteorological conditions and background concentrations.

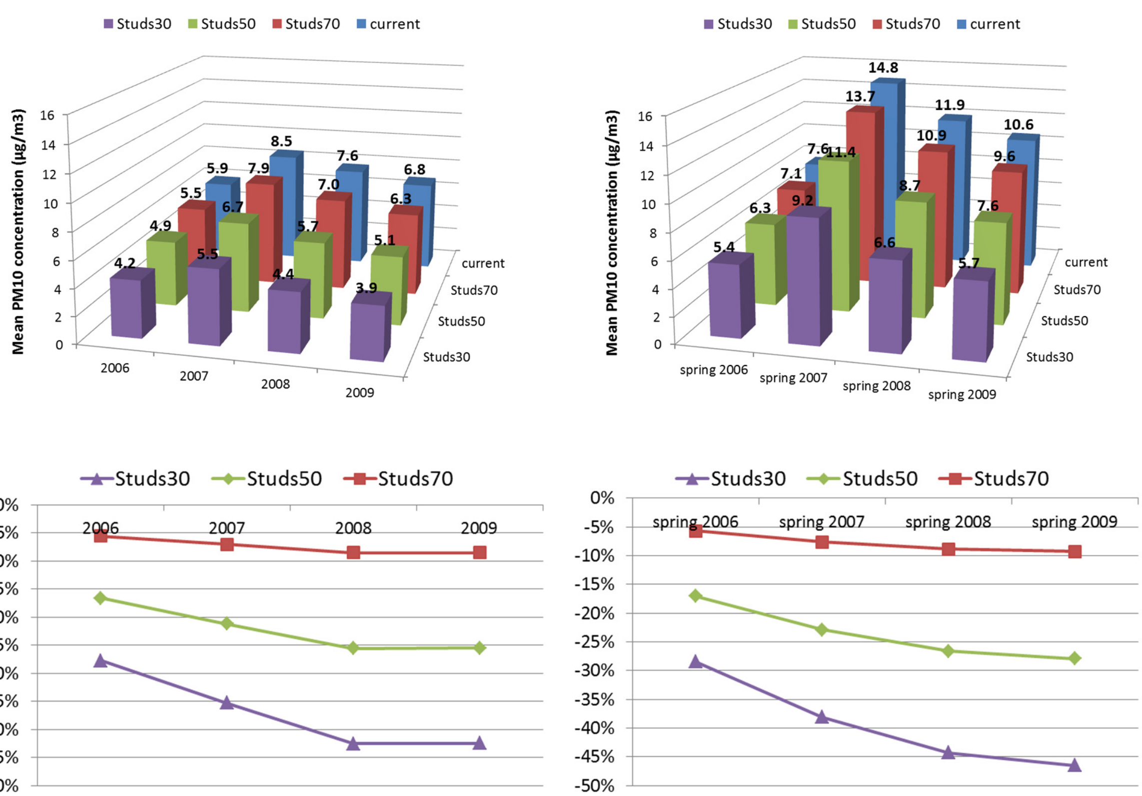

Figure 20. Mean annual (top left) and spring (top right) modelled non-exhaust PM_{10} concentrations for the reduced studded tyre cases and relative changes of the mean annual (bottom left) and spring (bottom right) concentrations compared to the "current state" in Mannerheimintie for the period 2006-2009. Modelled non-exhaust concentrations don't include PM_{10} background concentration.

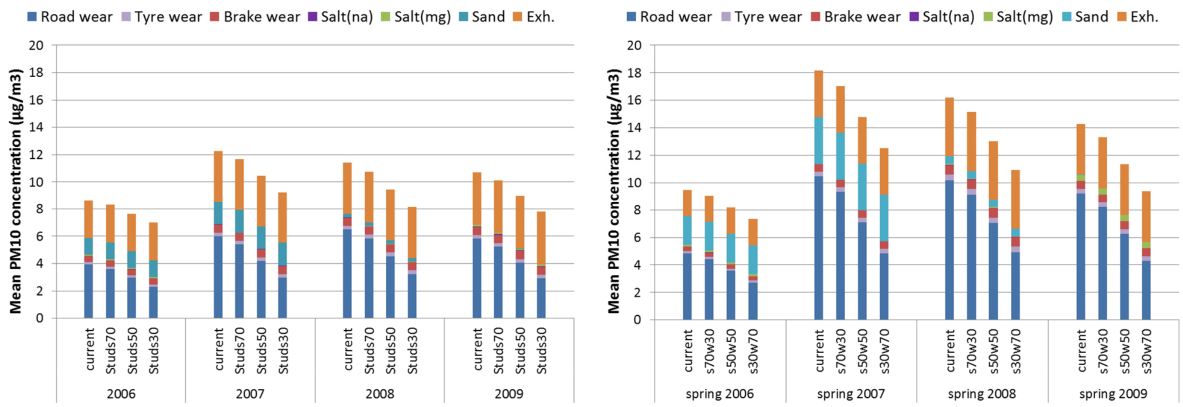

Figure 21. Source contributions of non-exhaust and exhaust PM_{10} particles for the reduced studded tyre cases and the "current state" in Mannerheimintie for the period 2006-2009. Modelled non-exhaust concentrations don't include PM_{10} background concentration. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

4.3 Impact of traffic parameters

Impact of traffic parameter changes on mean PM_{10} concentrations was investigated using following cases:

Traffic speed cases:

1. Speed limit of 50 km/h (mean hourly driving speed 41 km/h)
2. Speed limit of 80 km/h (mean hourly driving speed 71 km/h)

Traffic volume cases:

3. No HDV (HDVx0)
4. Double HDV number (HDVx2)
5. Half of LDV number (LDVx0.5)
6. Double LDV number (LDVx2)
7. Double LDV and HDV number (LDV&HDVx2)

4.3.1 Traffic speed

Traffic speed is an important factor affecting PM_{10} concentrations through increased road wear and road dust suspension which are in the model set to be linearly dependent on speed. Mean annual and spring period PM_{10} concentrations and relative change in mean concentrations compared to the "current state" for the tested traffic speed cases are presented in Figure 22.

Change in speed limit from the current state 30 km/h (i.e. mean hourly driving speed 25 km/h) to 50 km/h (mean hourly driving speed 41 km/h) leads to on average by factor 1.8 higher mean annual concentrations. Setting the speed limit to 80 km/h (mean hourly driving speed 71 km/h) results in on average 3.7 times higher mean annual PM_{10} concentrations. Accordingly, number of exceedance days is on average 1.6 and 3.2 times higher for the speed limit of 50 and 80 km/h, respectively. However, the comparison of modelled and measured results from main roads (Ring I and Ring III; Section 3.2.2) indicates that the current parametrisation of NORTRIP model might lead to the overestimation of PM_{10} emissions in high driving speeds.

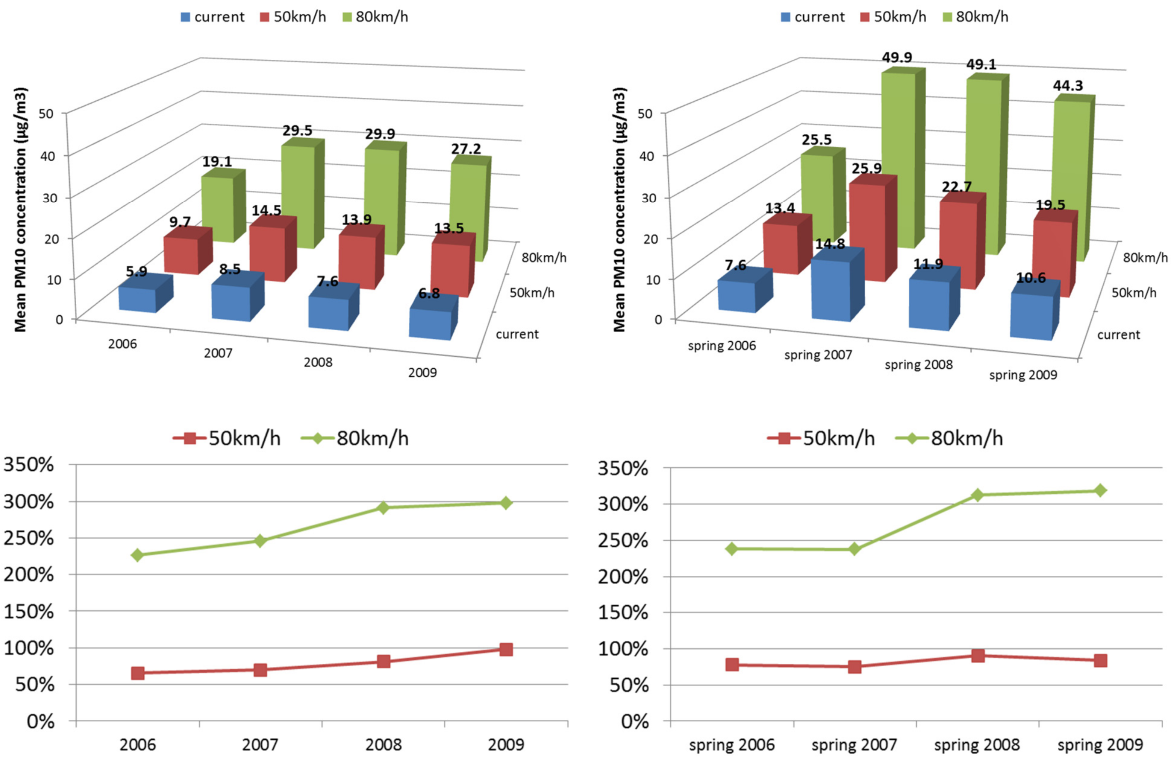

Figure 22. Mean annual (top left) and spring (top right) modelled non-exhaust PM_{10} concentrations for the increased speed cases and relative changes of the mean annual (bottom left) and spring (bottom right) concentrations compared to the "current state" in Mannerheimintie for the period 2006-2009. Modelled non-exhaust concentrations don't include PM_{10} background concentration.

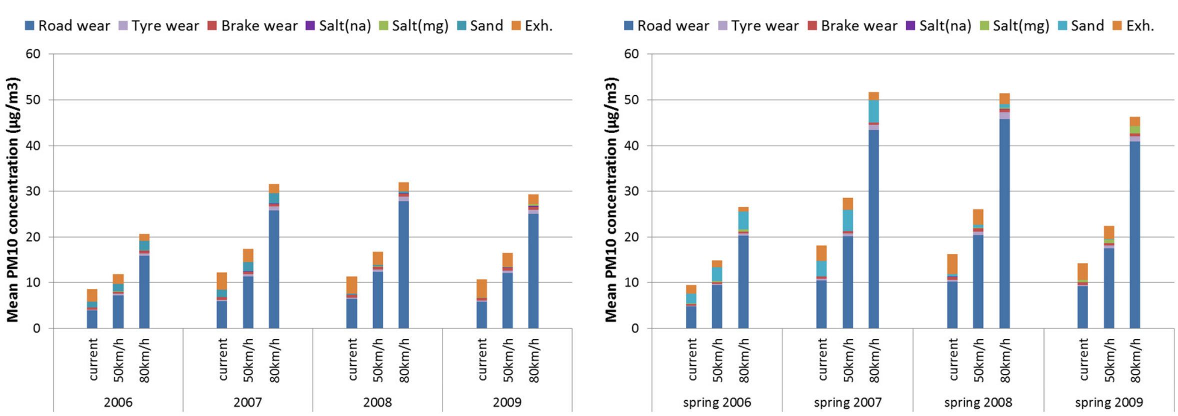

Figure 23. Source contributions of non-exhaust and exhaust PM_{10} particles for the increased speed cases and the "current state" in Mannerheimintie for the period 2006-2009. Modelled non-exhaust concentrations don't include PM_{10} background concentration. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

4.3.2 Traffic volume

The model was applied to assess impact of reduced (HDVx0 and LDVx0.5) and increased (HDVx2, LDVx2 and LDV&HDVx2) traffic volume cases. Heavy duty vehicles make 5.9% of the total traffic in Mannerheimintie in 2006 and 5% for years 2007-2009. Impact of heavy duty vehicles is described through 5 times higher wear, 10 times higher suspension and 6 times higher vehicles spray compared to the light duty vehicles. Traffic volume changes influence PM_{10} through changes in road wear, dust suspension, exhaust and change in road surface conditions.

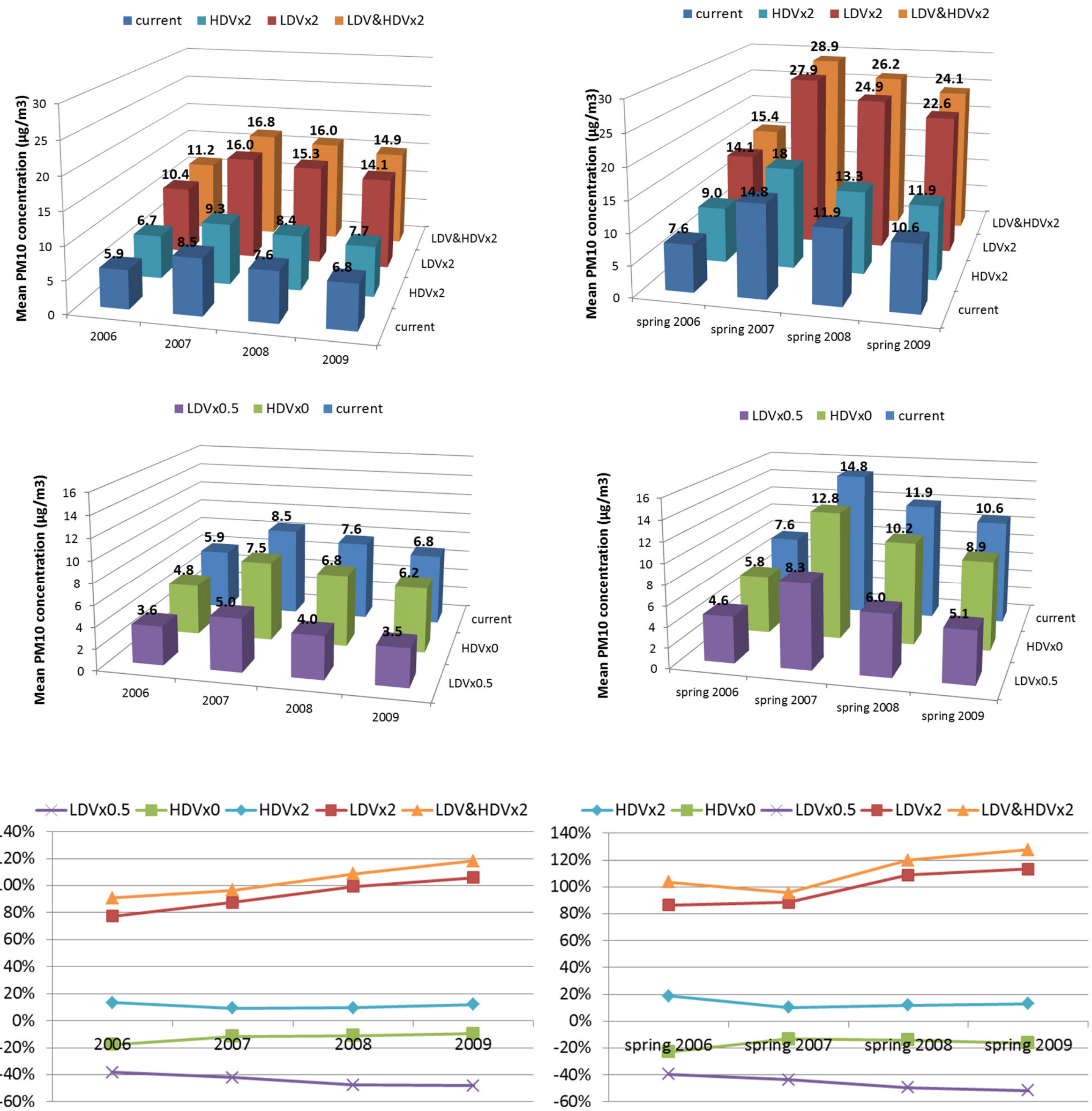

Figure 24. Mean annual (top left) and spring (top right) modelled non-exhaust PM_{10} concentrations for the increased traffic volume cases. Mean annual (mid left) and spring (mid right) non-exhaust PM_{10} concentrations for the reduced traffic volume cases. Relative changes of the mean annual (bottom left) and spring (bottom right) concentrations compared to the "current state" in Mannerheimintie for the period 2006-2009. Modelled non-exhaust concentrations don't include PM_{10} background concentration.

All traffic volume changes lead to significant changes in predicted PM_{10} concentrations. Doubling the HDV number leads to around 11% increase in mean PM_{10} concentrations and 0 to 5 additional exceedance days. The same change in LDV results in on average 1.9 times higher PM_{10} concentrations and 20 to 45 additional exceedances. Effects of double HVD and LDV add up in case when both changes are applied.

Average decrease in PM_{10} concentrations for the two reduced traffic volume cases are 46% for the LDV reduced by half and 13% for complete removal of HDV. Reduction in number of exceedance days would be 7 to 19 for reduced LDV number and 0 to 5 for case with no HDV.

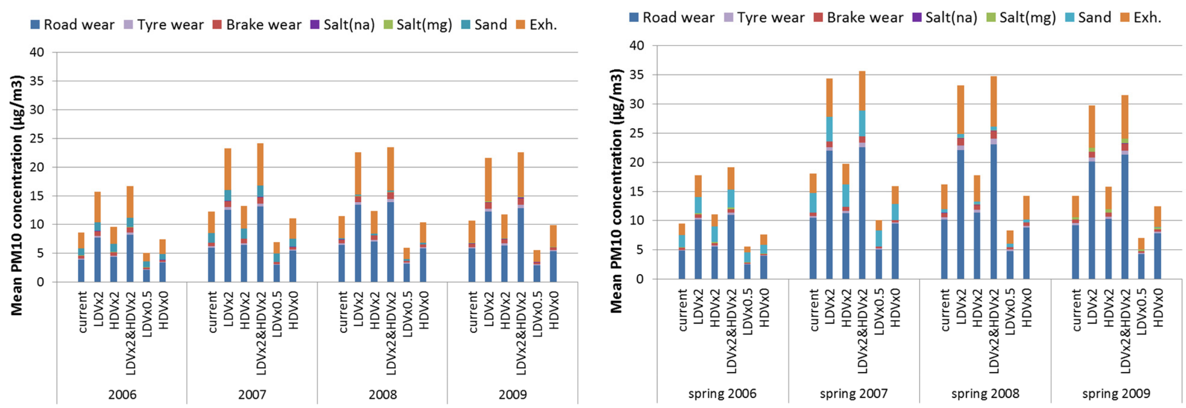

Figure 25. Source contributions of non-exhaust and exhaust PM_{10} particles for all tested traffic volume changes and the "current state" in Mannerheimintie for the period 2006-2009. Modelled non-exhaust concentrations don't include PM_{10} background concentration. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

4.4 Summary of the sensitivity analyses results

The NORTRIP model was applied to four years of data at Mannerheimintie in order to investigate sensitivity of the model predictions to changes in road maintenance activities including traction control (sanding and salting) and dust control (dust binding and street cleaning) activities, studded tyre share and traffic parameters. Modelling results for all tested cases were compared to the modelling results with the "current state" road maintenance practice. Summary of the sensitivity analysis results is presented in Table 4 as relative and absolute change of the modelled non-exhaust annual mean concentrations for different cases compared to the "current state" case. Since the model is still under development, the results of this analysis should be considered as indicative.

The model indicates that using sand as a single traction control measure increases mean annual PM_{10} concentrations on average by 20% for the observed period. Impact of sanding was more pronounced for the spring period. Number of additional exceedance days was 0 (2006), 3 (2007), 6 (2008) and 16 (2009).

For years 2006 and 2007 with the extensive use of sanding, application of salt instead leads to reduction of mean PM_{10} concentration on average by 22% on annual level and 25% during spring. In 2008 replacing sand with salt on 2 recorded sanding days leads to reduction of mean annual PM_{10} concentration by 3%. The impact on exceedance days varies from year to year with 0 to 6 less exceedance days. In reality, sanding cannot be replaced completely with salting during the coldest winter periods.

The model results indicate that “current” dust control measures bring improvements to air quality although the cleaning impact is very uncertain because it depends on predefined efficiency (30% for all studied cases) which may be overstated. For years 2008 and 2009 with more frequent use of dust binding compared to the first two years of the observed period, achieved reduction of mean annual PM_{10} with the “current state” dust binding practice was 6% and 12%, respectively with 3-4 avoided exceedance days. Impact of the dust binding was more pronounced for the spring period.

Impact of the more extensive use of dust binding was tested by creating additional dust binding events using the selected criteria. Additional number of dust binding events significantly reduces mean PM_{10} concentrations in 2006 and 2007 when “current state” case had 2 (2006) and 0 (2007) dust binding occasions. Achieved reduction in mean PM_{10} concentrations was 11% in 2006 and 18% in 2007 with 6 and 11 avoided exceedance days in 2006 and 2007, respectively

Table 4. Results of the sensitivity analysis presented as relative (%) and absolute change (μg/m³) *(value in brackets) of the modelled non-exhaust annual mean concentrations for different cases compared to the “current state” case.*

	2006	2007	2008	2009
AllSand	2% (0.1)	23% (1.9)	20% (1.5)	34% (2.3)
AllSalt	-23% (-1.3)	-20% (-1.7)	-3% (-0.3)	0% (0)
NoDB	1% (0.03)	0% (-0.02)	6% (0.45)	12% (0.82)
noCleaning	40% (2.4)	14% (1.2)	9% (0.7)	19% (1.3)
Speed50	66% (3.8)	70% (5.9)	81% (6.2)	98% (6.7)
Speed80	226% (13.3)	246% (20.9)	291% (22.3)	297% (20.3)
10%studded	-6% (-0.3)	-7% (-0.6)	-9% (-0.7)	-8% (-0.6)
LDVx2	77% (4.5)	88% (7.5)	99% (7.6)	106% (7.2)
HDVx2	14% (0.8)	9% (0.8)	9% (0.7)	12% (0.8)
LDVx0.5	-38% (-2.2)	-42% (-3.6)	-48% (-3.6)	-48% (-3.3)
HDVx0	-18% (-1)	-12% (-0.9)	-11% (-0.9)	-10% (-0.7)

Sensitivity test shows that 10% change in studded tyre share leads to average decrease in mean annual PM_{10} concentration of 7% and on average 2 exceedance days less for the observed four-year period.

The results show that changes in traffic properties (speed and traffic volume) can have a significant impact on PM_{10} concentrations. Mean annual PM_{10} concentrations are increased by a factor of 1.8 and 3.7 for the increased speed limit of 30 km/h to 50 km/h and 80 km/h (i.e. mean hourly driving speed of 25 km/h to 41 km/h and 71 km/h), respectively. However, the current parametrisation of the NORTRIP model might lead to the overestimation of PM_{10} emissions in high driving speeds. Doubling the LDV number leads to around 90% increase in mean PM_{10} concentrations and 20 to 45 additional exceedances. An average decrease in PM_{10} concentrations for the reduced number of LDV’s by half is 46% with 7-19 less exceedance days. Doubling the HDV number leads to around 11% increase in mean PM_{10} concentrations and 0 to 5 additional exceedance days. Average reduction of mean annual PM_{10} concentrations for the complete removal of HDV is 13%.

5 Scenarios for reducing PM_{10} dust in busy and wide street canyons

The combined impact of different maintenance measures and traffic properties to reduce PM_{10} concentrations were estimated for busy and wide street canyon environments. Mannerheimintie street canyon configuration (6-storey height and 47 m width) was selected to represent a wide street canyon. The NORTRIP model was applied over a four-year period (2006-2009) in Mannerheimintie to test following scenarios:

1. Minimal emission scenario for Mannerheimintie (Scen1):

- "Current state" traffic volume and speed in Mannerheimintie: 20 500 vehicles/day, 5% HDV, 30 km/h signed speed limit and 22 km/h mean driving speed, 80% of LDVs uses studded tyres in winter
- Share of studded tyres reduced to 30% for LDVs
- Only half the amount of sand used compared to the "current state"
- Maximum potential number of dust binding events
- Double cleaning removal efficiency for suspendable dust compared to the "current state"

2. Minimal emission scenario for doubled traffic volume and speed (Scen2):

- As in Scen1 with total daily traffic of 40000 vehicles/day, 10% HDV and 50km/h signed speed limit and 40 km/h mean driving speed.

3. 80% studded tyre scenario for doubled traffic volume and speed (Scen3):

- As in Scen2 with 80% share of studded tyres

Results are presented in figures 26 and 27 similar as for the sensitivity analysis. Minimal emission scenario for Mannerheimintie (Scenario 1) indicates that even 50% of non-exhaust PM_{10} concentrations could be reduced if all potential mitigations measures were applied. The result demonstrates that large-scale replacing of studded tyres (30%) with friction tyres (70%) together with very intensive street maintenance could significantly improve air quality in the street canyons of Helsinki. However, it would be necessary to model different street environments and perform sensitivity analyses to get more reliable and comprehensive view on optimal combination of mitigation measures.

Scenario 2 represents a street canyon with high traffic volume and speed, but low share of studded tyres (30%) and very intensive street maintenance. Annual and spring-time non-exhaust PM_{10} concentrations could be about 50-100% higher than those in "current state" Mannerheimintie. PM_{10} concentrations are high since traffic volume and speed is about double compared to the "current state" Mannerheimintie. Based on the sensitivity test (see Table 4), the modelled PM_{10} concentrations rise strongly if speed or traffic volume is increased. For instance, the change from "current state" driving speed 22 km/h to 50 km/h causes 66-98% increase in annual non-exhaust PM_{10} concentration (Table 4).

Scenario 3 also represents a street canyon with high traffic volume and speed as well as very intensive street maintenance, but the share of studded tyres (80%) is assumed to stay as high as in the "current state" Mannerheimintie. In that scenario, non-exhaust PM_{10} concentrations might increase very strongly (150-300%) compared to the "current state" Mannerheimintie. Scenario 3 demonstrates that high traffic volumes and speeds together with high share of studded tyres may lead to very high PM_{10} dust concentrations, which might be difficult to mitigate by only using intensive street maintenance measures. In the future modelling studies, it might be possible to obtain more reliable non-exhaust PM_{10} concentration estimates for wide and busy street canyons by modelling existing wide street canyons with very high traffic volume and driving speed (e.g. Mäkelänkatu or Töölöntulli sites).

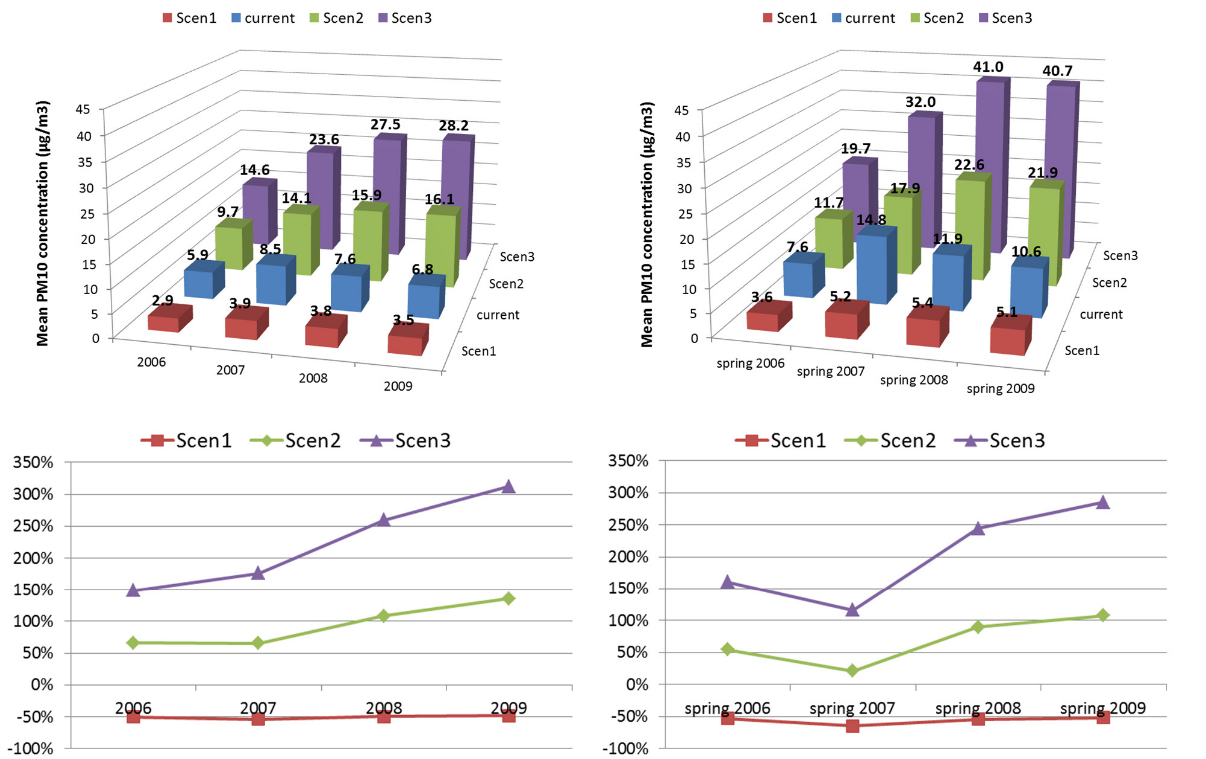

Figure 26. Mean annual (top left) and spring (top right) non-exhaust PM_{10} concentrations and relative changes of the mean annual (bottom left) and spring (bottom right) concentrations compared to the "current state".

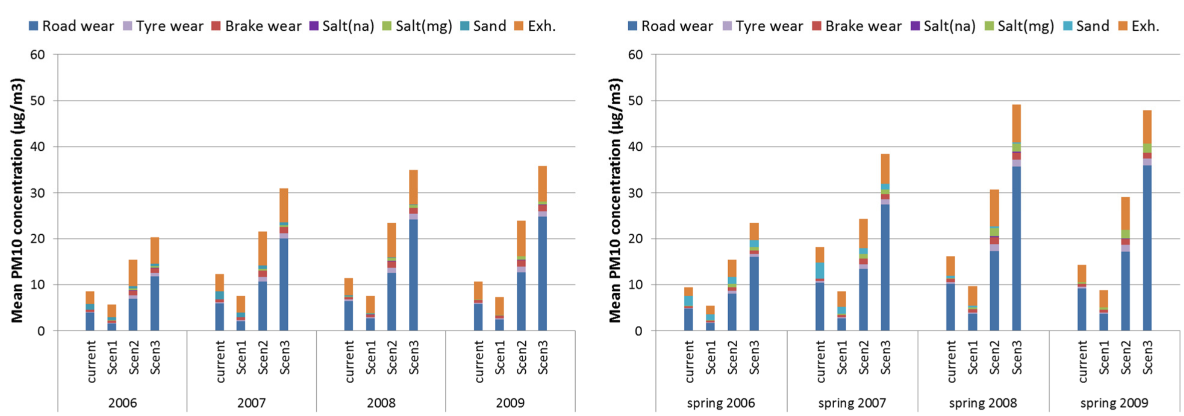

Figure 27. Source contributions of non-exhaust and exhaust PM_{10} particles for the tested scenarios and the "current state". Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

6 Conclusions

In this study the NOTRIP model was applied for several street and road environments in the Helsinki metropolitan area during multiple years between 2006 and 2013. The model results have been compared with available local air quality and emission measurements and the results of the source apportionment studies. The sensitivity analyses were conducted to study the impact of measures that can be used to reduce non-exhaust emissions on the modelled PM_{10} concentrations.

The NORTRIP model requires a range of input data and information on number of parameters in order to calculate non-exhaust emissions of the traffic. These include road maintenance activities (traction sanding and salting, dust binding, cleaning and ploughing), traffic properties (traffic volume and speed together with estimated NOx and exhaust particles emissions), road pavement properties and representative meteorological data. Reliable and complete data with suitable technical and temporal detail will contribute to the better model performance.

The main challenge concerning datasets used in this study was related to the road maintenance activity data. The exact timing of actions was missing as well as amounts of materials used (sand as well as traction and dust binding salts). In the light of the recent findings amounts of the traction and dust binding salt used in practice may be even half of those used in this study. This issue will be further reviewed and possible updates to the model input will be done in future work. All the results presented in this study, apart from Suurmetsäntie results, are based on use of modelled surface moisture which has an influence on variation and timing of modelled road dust emissions particularly during winter and spring months.

The results of the model performance evaluation indicated issues that need to be addressed in the future model development work. Further work will be needed to explain factors leading to the overestimation of PM_{10} concentrations in the ring road environment during winter and spring months. In order to better assess the impact of sand on the PM_{10} concentrations, parameters and processes related to the sand need more attention.

The other local PM_{10} emission sources, for example tram lines or construction sites, that are not included in the model, can have an influence on the PM_{10} concentrations. Knowledge about the presence and essence of such other PM_{10} emission sources helps the evaluation of the model performance.

The NORTRIP model was applied to study sensitivity of PM_{10} concentrations and number of exceedance days to measures that can be used to reduce non-exhaust emissions. The results demonstrate that choice of the different traction control (sanding and salting) and dust control measures (dust binding and cleaning) can have a significant impact on air quality. However, the effect on air quality is eventually dependent on the meteorological conditions, number and timing of the measures. The PM_{10} concentrations and number of exceedance days was particularly sensitive to changes in the traffic properties (volume, speed) and share of studded tyres.

The NORTRIP model is currently the most comprehensive process based non-exhaust emission model that can be used for better understanding and controlling of the PM_{10} emissions. Although a number of model parameters still need to be refined the possibility to separately study influence of different processes and factors governing the PM_{10} emissions makes it a useful tool in air quality management.

7 References

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8 Appendix A- Graphical summary of the modelling results

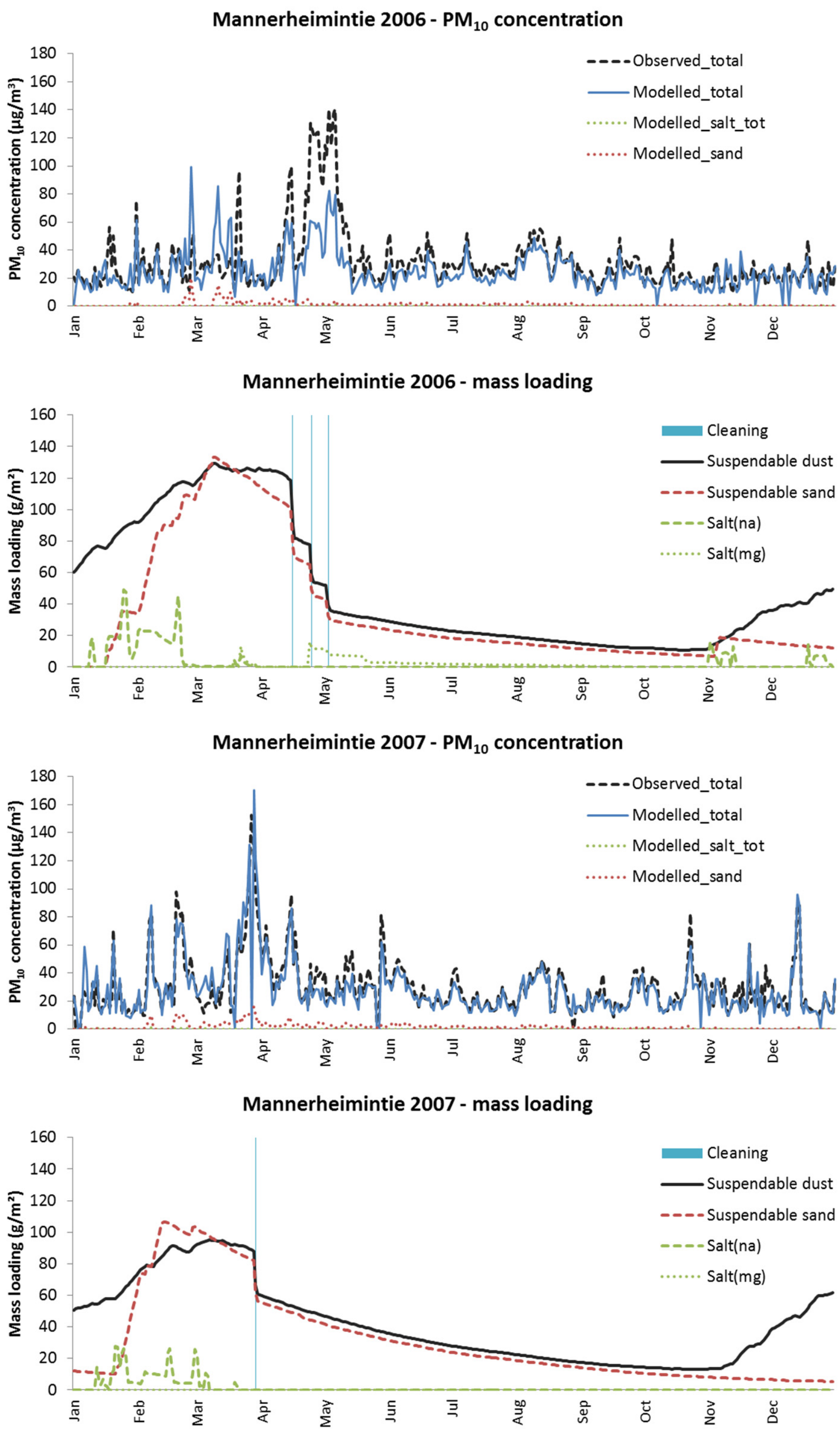

Figure A.1. Modelled and observed total daily mean PM_{10} concentrations and mass loading of suspendable dust (size fraction < 200 µm) at Mannerheimintie for years 2006 and 2007. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

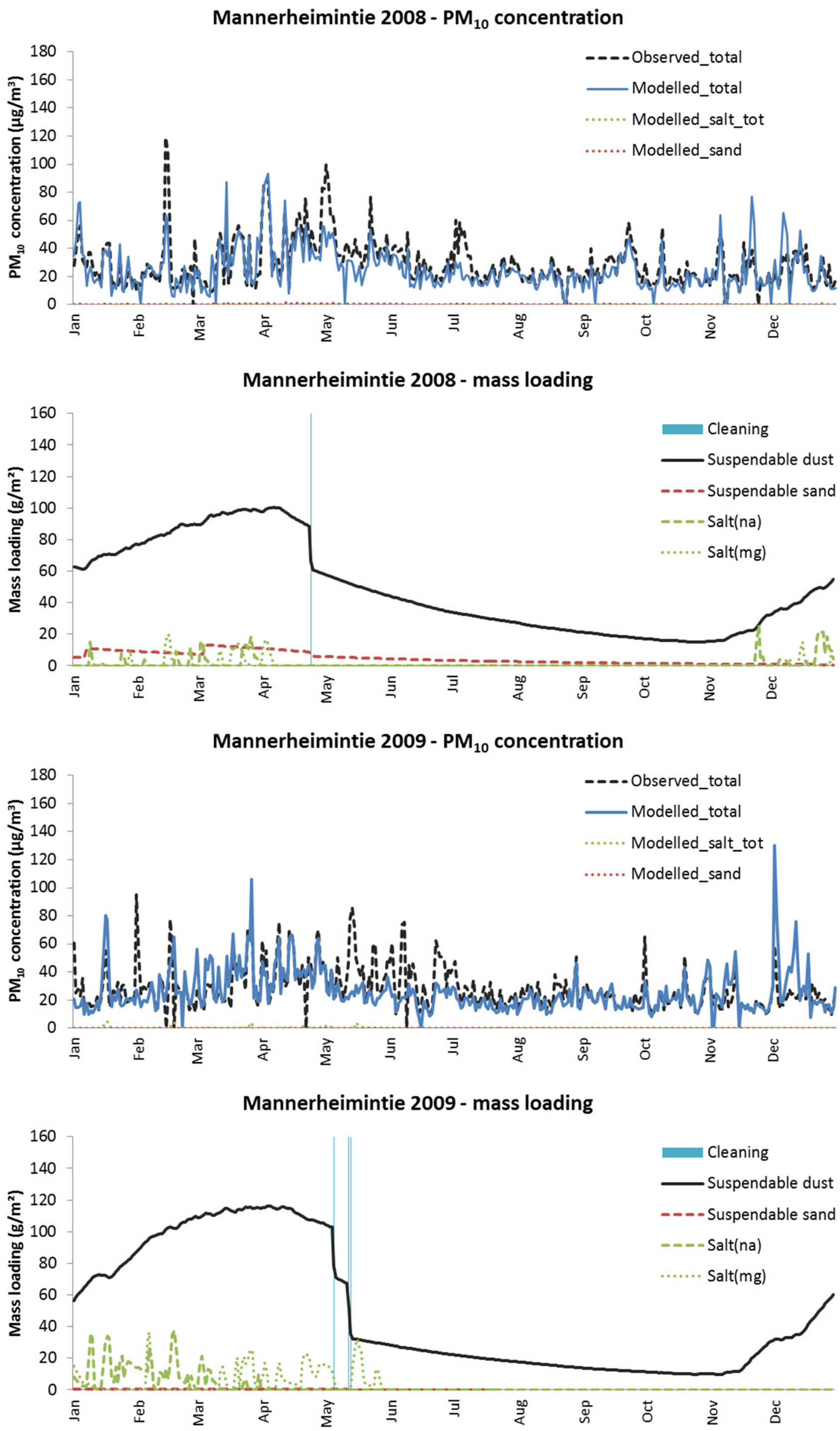

Figure A.2. Modelled and observed total daily mean PM_{10} concentrations and mass loading of suspendable dust (size fraction < 200 µm) at Mannerheimintie for years 2008 and 2009. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

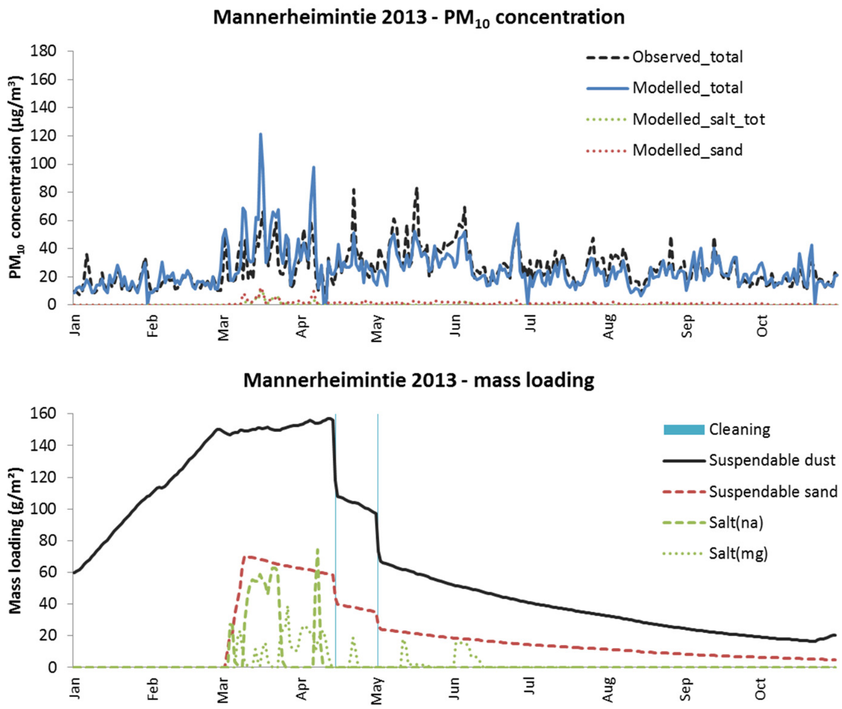

Figure A.3. Modelled and observed total daily mean PM$_{10}$ concentrations and mass loading of suspendable dust (size fraction < 200 µm) at Mannerheimintie for year 2013. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

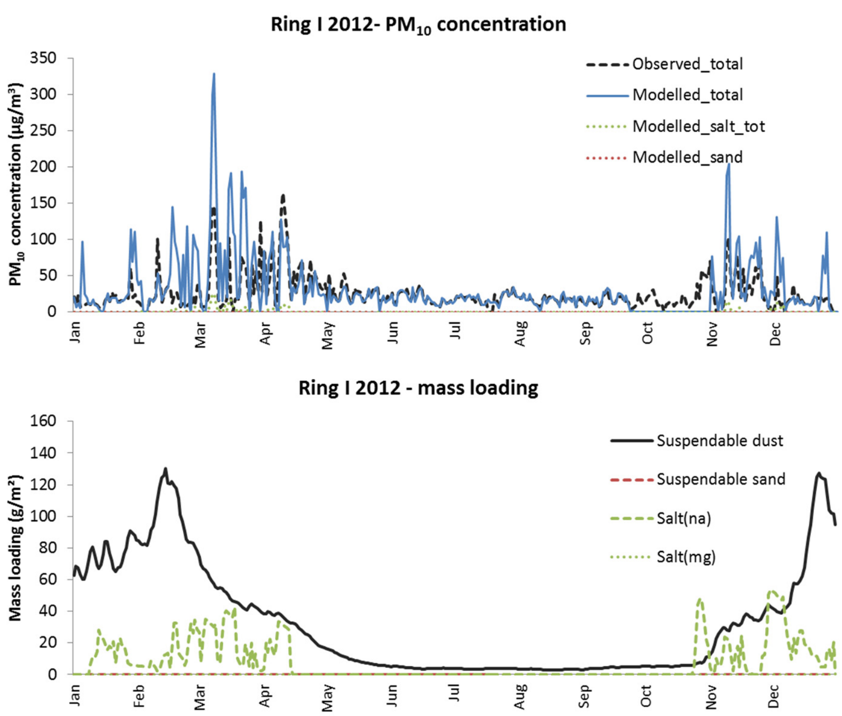

Figure A.4. Modelled and observed total daily mean PM$_{10}$ concentrations and mass loading of suspendable dust (size fraction < 200 µm) at Ring I for the year 2012. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

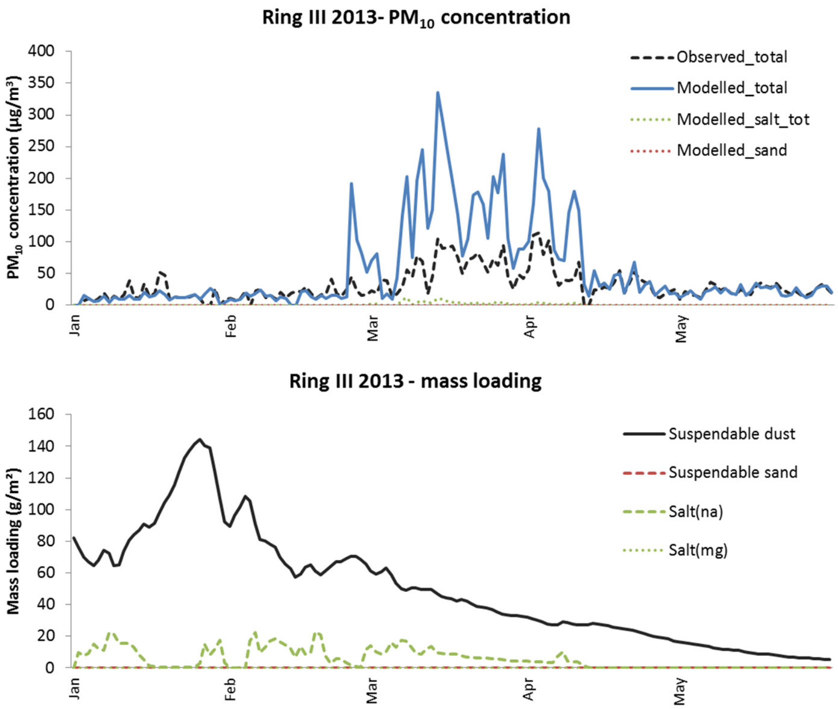

Figure A.5. Modelled and observed total daily mean PM_{10} concentrations and mass loading of suspendable dust (size fraction < 200 µm) at Ring III for the period 1.1.-31.5.2013. Salt(na) refers to winter-salting with NaCl and salt(mg) refers to dust binding.

9 Appendix B - Statistical summary of the modelling results

Fractional bias (FB%) is a measure of the difference between the calculated average and the observed average concentration. FB=0 indicates no difference, FB>0 indicate an overestimate in predicted concentrations and FB<0 indicate an underestimate. Fractional bias value range is between -200% (extreme under prediction) to +200% (extreme over prediction).

$$\mathrm{FB} = \frac{\overline{Cp} - \overline{\mathrm{Co}}}{0.5 * (\overline{Cp} + \overline{\mathrm{Co}})} * 100$$

Root mean square error (RMSE) gives the standard deviation of the model prediction error. It has the same units as the quantity being estimated. A smaller value indicates better model performance.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Co - Cp)^2}$$

Table B.1. Statistical summary for the total modelled PM_{10} concentrations for Mannerheimintie calculated on annual level and for the spring period.

	Observed mean (µg/m^3)	Modelled mean (µg/m^3)	Observed 90'th percentile	Modelled 90'th percentile	Observed days >50 (µg/m^3)	Modelled days >50 (µg/m^3)	RMSE (µg/m^3)	Correlation (R^2)	FB%
2006	31.3	25.2	51.6	40.7	37	21	16.2	0.57	-21%
2007	30.6	28.9	51.6	47.9	39	35	8.0	0.84	-6%
2008	29.8	25.9	50.8	46.7	37	27	10.9	0.64	-14%
2009	28.9	26.1	50.4	44.8	35	25	14.0	0.34	-10%
2013	25.5	25.3	42.8	41.9	18	21	10.2	0.55	-1%
Spring 2006	50.1	32.3	117.2	61.0	27	15	30.4	0.73	-43%
Spring 2007	45.2	42.8	74.0	79.4	24	21	11.5	0.87	-6%
Spring 2008	44.5	37.9	75.7	55.6	25	16	13.4	0.67	-16%
Spring 2009	41.7	36.2	68.9	61.3	18	13	15.8	0.36	-14%
Spring 2013	36.5	37.2	56.2	58.5	11	11	15.6	0.35	2%

Table B.2. Statistical summary for the total modelled PM_{10} concentrations for Ring I calculated on annual level and for the spring period.

	Observed mean (µg/m³)	Modelled mean (µg/m³)	Observed 90'th percentile	Modelled 90'th percentile	Observed days >50 (µg/m³)	Modelled days >50 (µg/m³)	RMSE (µg/m³)	Correlation (R2)	FB%
2012	27.1	37.7	54.5	92.5	34	61	33.6	0.48	33%
Spring 2012	42.1	48.3	75.4	105.0	21	21	36.6	0.36	14%

Table B.3. Statistical summary for the total modelled PM_{10} concentrations for Ring III calculated on annual level and for the spring period.

	Observed mean (µg/m³)	Modelled mean (µg/m³)	Observed 90'th percentile	Modelled 90'th percentile	Observed days >50 (µg/m³)	Modelled days >50 (µg/m3)	RMSE (µg/m³)	Correlation (R2)	FB%
1.-5.2013	32.8	58.6	71.3	178.2	26	44	57.4	0.74	56%
Spring 2013	40.7	72.4	81.2	179.7	21	30	59.0	0.83	56%

Table B.4. Number of exceedance days for the sensitivity analyses cases and for the "current state".

	Current state	allSand	allSalt	noCleaning	noDB	NoCleaningNoDB	maxDB	s70w30	s50w50	s30w70	LDVx2	HDVx2	LDVx2&HDVx2	LDVx0.5	HDVx0	50km/h	80km/h
2006	21	21	16	23	21	23	15	21	19	16	41	24	46	14	19	34	70
2007	35	38	35	36	35	36	24	35	32	26	69	35	71	20	35	53	86
2008	27	33	26	28	30	32	18	24	15	11	72	30	75	8	22	51	98
2009	25	41	25	27	29	30	23	19	15	13	70	30	75	10	20	59	82
spring 2006	15	16	14	15	15	15	12	15	15	14	22	16	23	12	15	21	31
spring 2007	21	22	21	22	21	22	15	21	20	16	30	21	30	14	21	26	34
spring 2008	16	21	15	17	16	18	10	14	8	7	38	18	39	5	11	31	45
spring 2009	13	21	13	13	17	17	12	10	9	8	33	13	35	6	10	25	41

10 Appendix C - PM_{10} source apportionment studies for Mannerheimintie

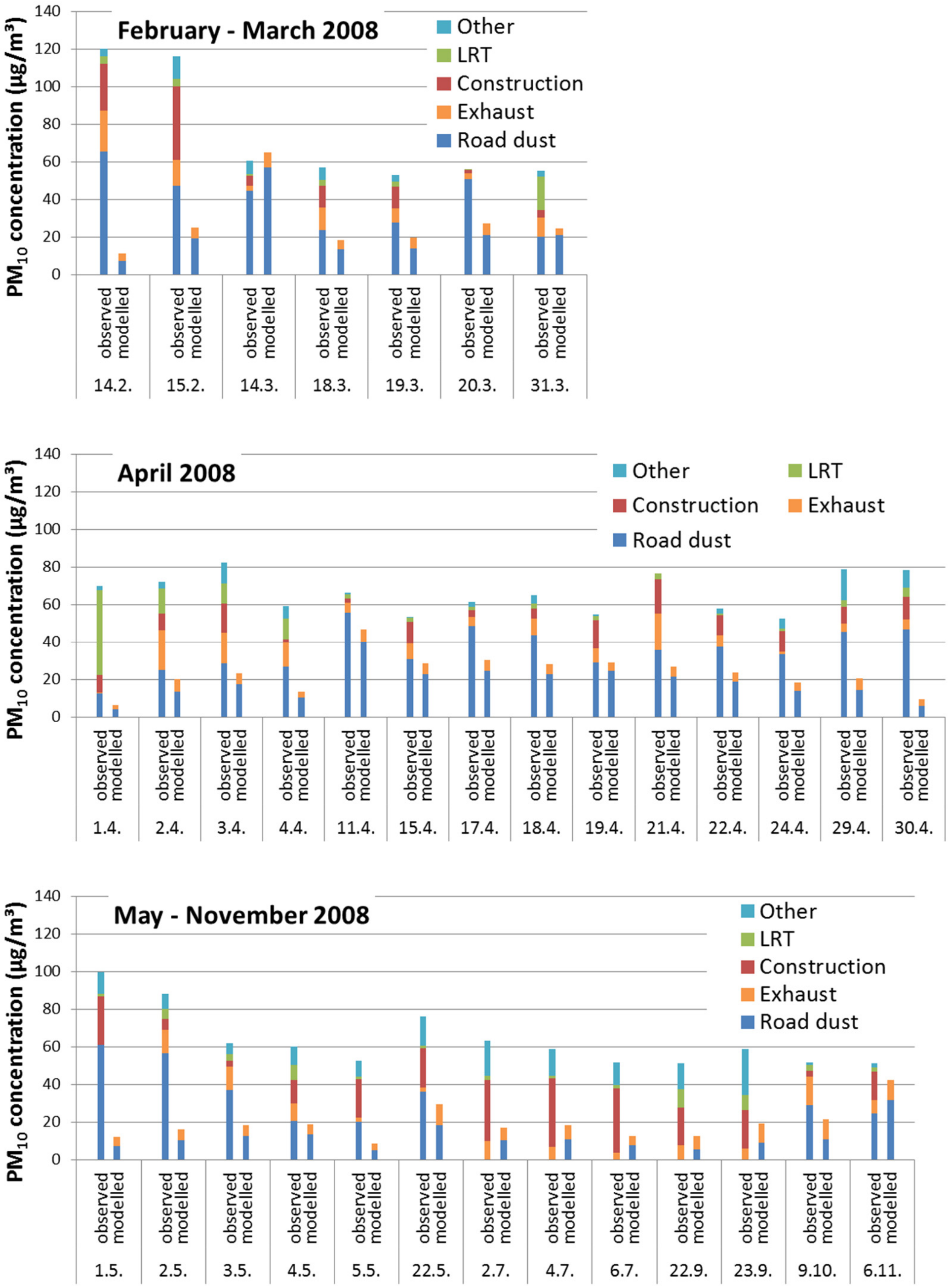

Figure C.1. Measured and modelled PM_{10} source contributions on exceedance days in Mannerheimintie 2008. "Measured" refers to the results from the source apportionment studies. LRT refers to regionally and long-range transported particle mass.

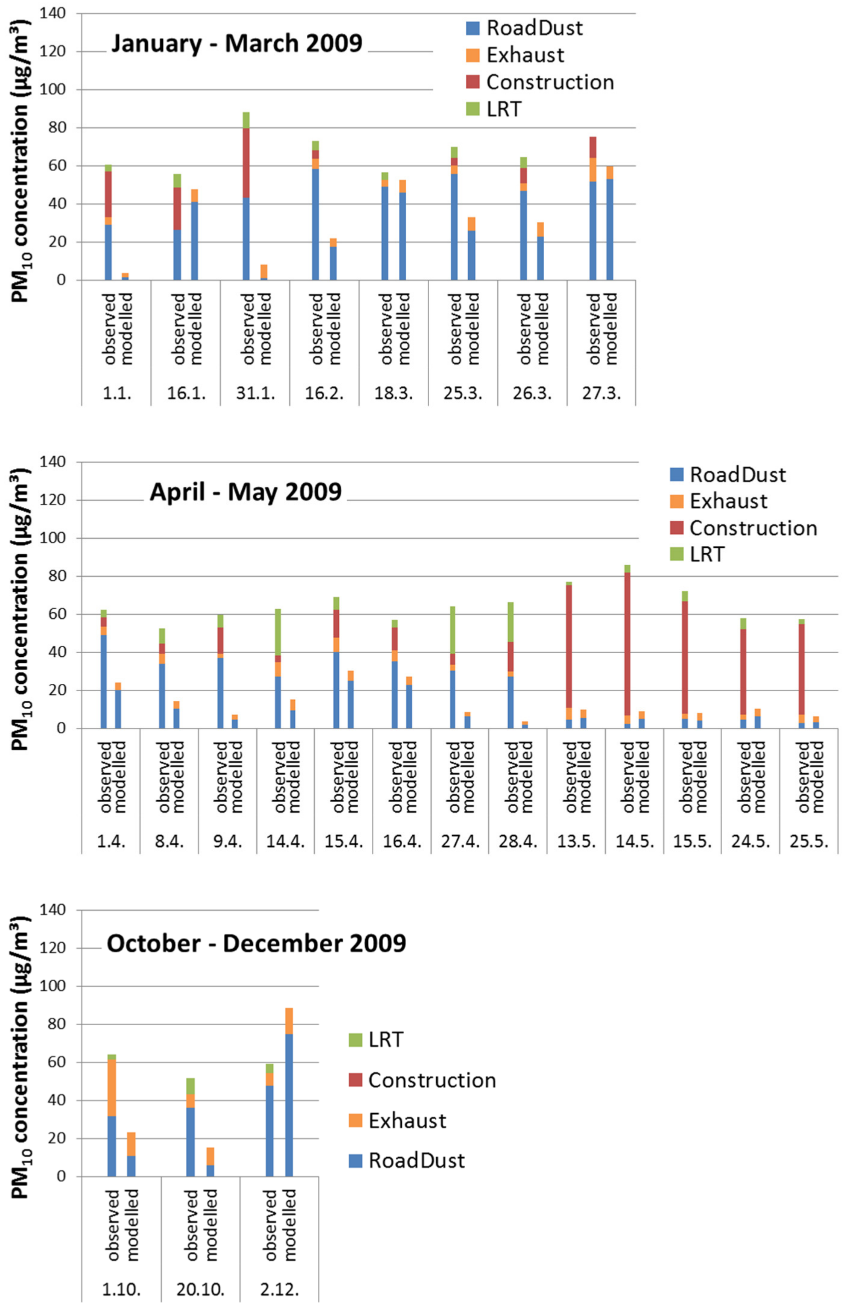

Figure C.2. Measured and modelled PM_{10} source contributions on exceedance days in Mannerheimintie 2009. "Measured" refers to the results from the source apportionment studies. LRT refers to regionally and long-range transported particle mass.

11 Appendix D - Maximal number of dust binding events used for the sensitivity analysis

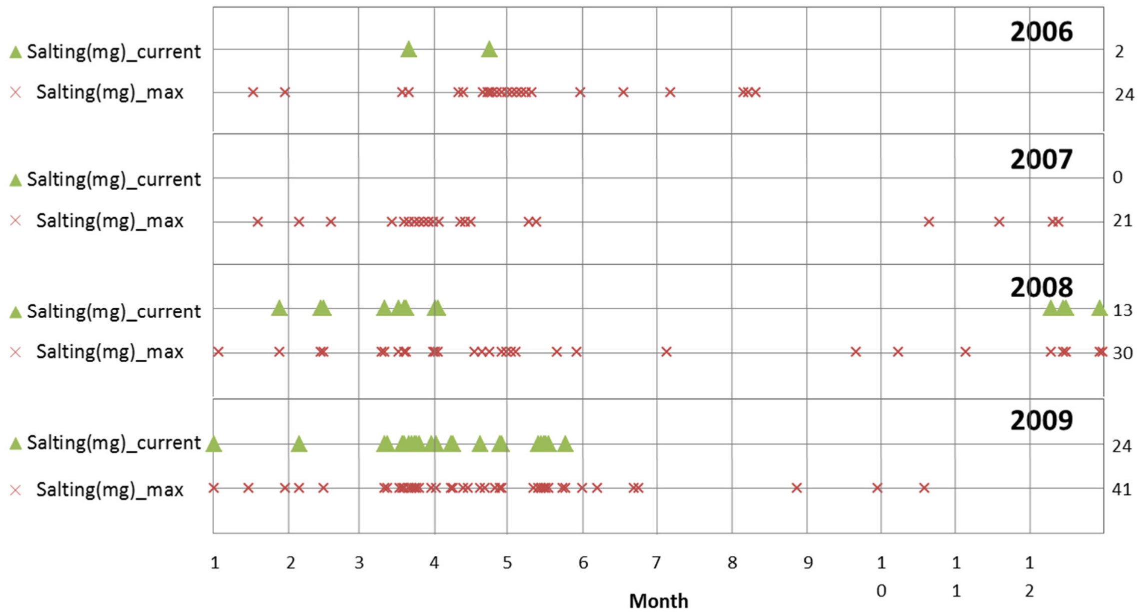

Figure D.1. Maximal number of dust binding events produced using the selected criteria.

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