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The impact of measures to reduce road dust, evaluated for a street canyon in Helsinki

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Abstract. We have evaluated numerically how effective a few selected measures would be for reducing road dust. 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 location 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} within the street canyon. The predicted concentrations were compared with the air quality measurements. Both models reproduced the seasonal variability of the PM_{10} concentrations but under-predicted the yearly 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 increment of PM_{10} from 10 to 22 %, depending on the model used and the year considered. The corresponding decrease after removal of sanding and salting would be from 4% and 20% and from 0.1% to 4%, respectively. The results can be used for finding optimal strategies for reducing the high springtime particulate matter concentrations originated from 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.

The non-exhaust emissions of respirable particles, PM_{10}, include particles formed due to the wear of pavement, brakes and tyres, and the suspension of particles that have been accumulated on the road surface. The latter category is commonly originated from (i) the wear of the road surface and the tires, (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; 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 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 surfaces during dry periods.

The wear of pavements associated with the use of studded 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 % (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. 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 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 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 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 site

The study was carried out for a selected segment of a major street called Hämeentie, located in central Helsinki. 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.

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 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

The traffic volume data and weekly and monthly variations of the traffic volume are based on the estimations made by the Helsinki City Planning Department. The yearly 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 average weekday traffic volume measured at Hämeentie in 2015 is used for year 2014. For the other considered years, we have used the measured traffic volumes at Pitkäsilta, scaled by the ratio of yearly average weekday traffic volumes at Hämeentie in 2015 and at Pitkäsilta in 2014.

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

The drivers are legally obliged to use winter tyres in Finland from December to February. 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 outside of this period, if required by the weather conditions. The maximum share of vehicles using studded tyres is 80 %. In 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 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. For year 2014, the transition to winter tyres is based on the weekly counting of the vehicles with studded tyres in Helsinki (REDUST, 2014).

2.1.3 Meteorological data

The meteorological data is obtained from two weather stations located at Kaisaniemi and Kumpula (Fig.1) 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 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 can be considered to be commonly occurring ones for this climate zone.

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 year during the study period is presented in Table 2. The approximate timing of these activities has been presented in Fig. 3. The data for the autumn months (October-December) was available only for one year.

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 done 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 is presented in the following. More detailed description of the models can be found from Denby et al. (2013a, 2013b) (NORTRIP) and Berkowicz (2000) (FORE).

The road dust emission model NORTRIP

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

The emission calculation is based on the total wear rates and the size distributions of the different wear sources. The total road wear for studded tyres is determined using the Swedish road wear model (Jacobson and Wågberg, 2007). Total brake and tyre wear and size distribution are based on the literature (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 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 (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. In this study, the amount of suspendable material in sand was set to 2%. Salt contributes directly to the dust loading and impacts predicted surface condition via surface vapour pressure which inhibits 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 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 emissions can be formed by the wear of road pavement 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.

The use of the model requires as input values various hourly meteorological variables, the roughness length, the share of studded tyres, and the dates of the street sanding. The model uses empirical reference emission factor which depends on the time of the year, the mass fraction of particles, and the traffic environment.

We have adopted the reference emission factors evaluated for Stockholm estimated by Omstedt et al. (2005). The climatic conditions, studded tyre shares and the procedures of using traction sand are fairly similar in Stockholm and Helsinki, but 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 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 reduced caused by the suspension of particles to the air and by runoff due to precipitation.

The mathematical treatment of the moisture on the road surface is based on modelling of precipitation, runoff, and evaporation. The roughness length of the surroundings of the street is needed for the evaluation of the evaporation. In the present case, the roughness length was determined by considering the average building heights in the vicinity of the study site. This analysis resulted in the roughness length value of 2.6 m.

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

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

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. For instance, assuming that 80%, 50%, 30% or 0% of the LDVs 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, 2015a). 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.

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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.

The OSPM model requires as input data information on vehicular traffic, the meteorological parameters, the street configuration and the urban background concentrations. The input information on the street configuration includes the geometry of the surroundings of the studied street segment. 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.

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

3. Results and discussion

Two models, NORTRIP and FORE, were applied to compute the vehicular non-exhaust PM_{10} emissions that were, together with the exhaust emissions, then implemented 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.

For the comparison with the measured concentrations we focus 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.

Results are presented as yearly and seasonal mean values. Seasons were defined here as follows: winter (1.1.-14.3.), spring (15.3.-31.5.), summer (1.6.-30.9.) and autumn (1.10-31.12.).

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

The kerbside air quality measurements at the station of Hämeentie were performed in 2009 and 2014. The time series of modelled and observed mean daily street increments are presented in Fig. 4. The mean yearly and seasonal 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. 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

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of April. The street cleaning measures started late in 2009, due to frequent night frosts. This contributed, together with the lack of precipitation, to the existence of a prolonged street 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, 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 mean values. The PM_{10} concentrations predicted by the FORE model are higher than the observed values in winter and lower in spring. The NORTRIP model systematically under-predicts the measured concentrations. However, it was found that the predicted daily mean concentrations of NORTRIP correlated reasonably well with the measured values (the coefficients of determination R^2 = 0.51 and 0.32 for 2009 and 2014). The corresponding correlations for the FORE model were slightly lower (R^2 = 0.24 and 0.20 for 2009 and 2014).

There are significant uncertainties with 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 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 of the models

In order to analyse the results in more detail, we have assessed sensitivity of the models to key parameters for the study site.

3.2.1 Sensitivity analyses of the NORTRIP model

There are numerous model input values and parameters used for the NORTRIP model computations. Denby et al. (2013b) studied sensitivity to these parameters and demonstrated ability of the NORTRIP model to predict the mean concentrations of PM_{10} within a range of ± 35 % of observations for a number of data sets. The results from this study fall outside of this range.

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 that the NORTRIP model does not generate enough dust during winter and spring months for Hämeentie.

The formation of wear particles by studded tyres that dominates in the road dust emissions depends on pavement characteristics (stone sizes and wear parameters). Hämeentie is paved with the stone matrix asphalt (SMA) but the detailed information about road surface parameters is missing which can be a source of a significant uncertainty in the used studded tyre wear rate. Doubling the wear rate would increase mean non-exhaust and street increment concentrations computed with the NORTRIP model by 61 and 33%, respectively, without significant impact on correlation.

The wear rate is assumed to be linearly dependent on vehicle speed (Denby et al., 2013a). In previous calculations using the NORTRIP model (Denby et al., 2013b) no roads with vehicle speeds less than 40 km h^{-1} were assessed and the linear assumption may not hold for the traffic speeds here (< 30 km h^{-1}). The NORTRIP model does not account for congested driving conditions where acceleration will likely lead to enhanced road wear.

3.2.2 Sensitivity analyses of the FORE model

Regarding the predictions of the FORE model, the key parameter is the reference emission factor which sets baseline value for suspension. In this study, we have used the reference emission factors estimated by Omstedt et al. (2005) for Hornsgatan in Stockholm. The average daily 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 notable differences between these two measurement campaigns (Hornsgatan, 2000 and this study). We have therefore estimated numerically, how changes of the reference emission values would affect the results predicted by the FORE model. We evaluated four additional cases with different sets of PM_{10} reference emission factors, and compared the 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 reference emission values is as large as was considered to be physically possible.

For the cases presented in Table 6, the yearly 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. The suspension emissions are modelled for the whole vehicle fleet, i.e., the details such as 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.

3.2.3 Sensitivity analyses of the OSPM model

We have also studied the influence of one key parameter in the OSPM model, the so-called roof parameter (fRoof). This parameter relates the measured or modelled wind speed at a meteorological mast with the wind speed at roof level. The value of the fRoof parameter depends on building and roughness situations around the meteorological station and should be adjusted based on the model-measurement comparisons for several different compounds.

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 suggested that a value of 0.6 could be more appropriate (OSPM FAQ, 28.03.2017).

The numerical computations showed that the yearly mean PM_{10} non-exhaust and $PM_{2.5}$ exhaust concentrations were approximately 26% lower with fRoof = 0.6, compared to those with fRoof = 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 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 traction control measures. The effects of these measures were evaluated for the non-exhaust street increments of PM_{10}. In the so-called reference case, we have assumed that the reported road maintenance activities have been done, and the 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 share of vehicles using studded tyres (80%) was numerically reduced to 50% (st50), 30% (st30) and 0% (st0). We also assumed that all recorded sanding events would not have been done (noSand). The impact of not including traction salt was studied using the NORTRIP model (noSalt).

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

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According to these computations, the largest reductions of concentrations can be achieved by reducing the use of studded tyres. For the theoretical case with no studded tyres in traffic, the predicted mean PM_{10} reductions were 39% and 40% for the NORTRIP and FORE models, respectively. A 50 % percent decrease in the share of vehicles using studded tyres would result in an average decrease in non-exhaust increment of PM_{10} of 16% (NORTRIP) or 17% (FORE).

The yearly PM_{10} concentrations are strongly influenced by meteorology. The meteorological input data influences the modelled road surface conditions, which control the suspension emissions and the dust and salt removal processes. Clearly, the type and number of the road maintenance operations is also directly associated with the meteorological conditions. Modelled changes in the PM_{10} concentrations represent the combined impacts of selected measures and meteorology.

The number of reported sanding events in Hämeentie was 9 for year 2007 and 18 for years 2009 and 2014. In year 2008 all traction control was done by salting. All sanding events occurred during January and February. Both models predict similar changes in modelled non-exhaust PM_{10} concentrations after removal of sanding; however, with different seasonal variation. The modelled reduction ranges from 4 to 20%, depending on the year and the model. 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 owing to model's concept regarding 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 yearly non-exhaust 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.

4 Conclusions

We have conducted numerical computations regarding the effectiveness of selected measures to reduce road dust. The evaluated mitigation measures contained the reduction of the use of studded tyres and phasing-out of the application of traction sand or salt. The effects of these measures were analyzed 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 predictions of the modelling system were also compared with the available street canyon measurements for a period of two years.

Both models reproduced the seasonal variability of the concentrations of PM_{10} fairly well, but the models under-predicted the yearly mean values. The PM_{10} concentrations predicted by the FORE model were higher than the observed values in winter and lower than the measured concentrations in spring, whereas the NORTRIP model systematically under-predicted the measured concentrations. The predicted daily mean concentrations of NORTRIP correlated reasonably well with the measured values; the correlation was better that the corresponding one for the FORE model.

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 in the prediction capacity of these models for analyzing the influence of various measures.

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 share of vehicles using studded tyres would result in an average decrease of the non-exhaust increment of PM_{10} from 16% to 34%, depending on the model used and the year considered. The corresponding values for the total removal of sanding or salting would range from 4% to 20%, and from 1% to 4%, respectively.

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 can be used as one aspect in finding optimal strategies for reducing the high springtime particulate matter concentrations.

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

Year	AADT (vehicles day^{-1})	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 numbers of the road maintenance measures for Hämeentie for each year, in 2007 – 2009 and in 2014.

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

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}. 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 emission factors of $PM_{2.5}$ (g km^{-1} veh^{-1}) in Helsinki for the target years, based on the 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 yearly and seasonal observed and modelled street increments of PM_{10} ($\mu g\ m^{-3}$) in 2009 and 2014.

Year		Winter	Spring	Summer	Autumn	Yearly mean
2009	Observed	7.8	20.1	6.9	6.4	10.1
	FORE	13.4	12.4	5.6	6.0	8.5
	NORTRIP	5.3	9.4	4.5	3.9	5.7
2014	Observed	8.2	15.7	7.7	9.0	10.2
	FORE	9.2	11.2	5.3	3.7	8.0
	NORTRIP	2.3	7.2	4.5	2.3	4.2

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

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. Summary of the selected numerical cases with reduced shares of light duty vehicles using studded tyres, and with applied road maintenance measures. The symbol + refers to 'included' and – to 'not included'.

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

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%	-

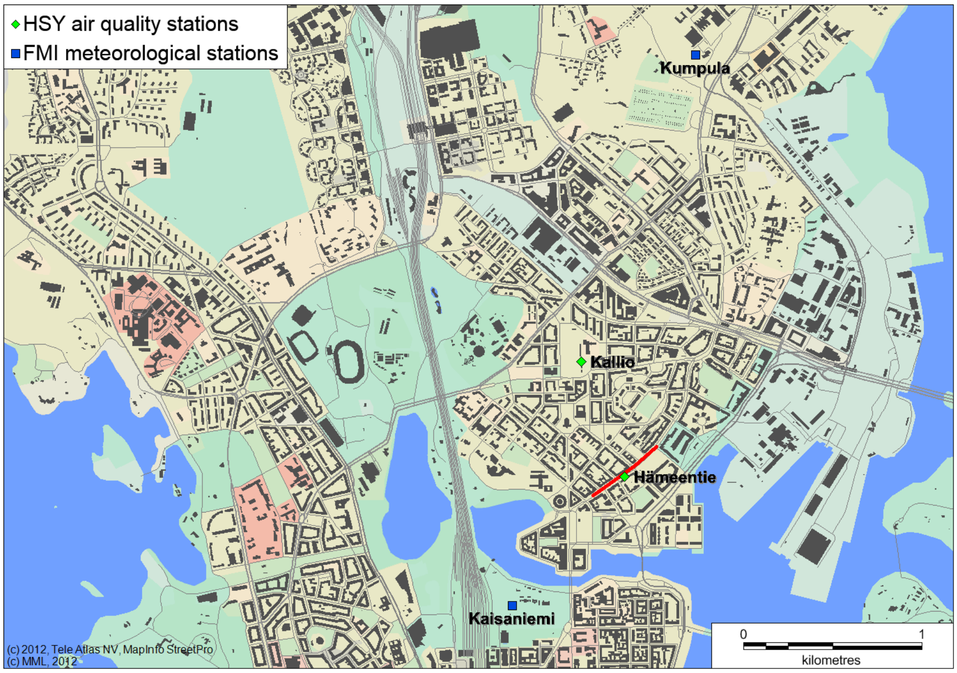

Figure 1. The locations of studied street segment (red line) at Hämeentie, air quality stations (green diamond) and weather stations (blue square) in central Helsinki. Buildings have been marked with black colour. The parks have been presented in green, the urban and industrials areas in light brown and grey, and special sites, such as hospitals, in red.

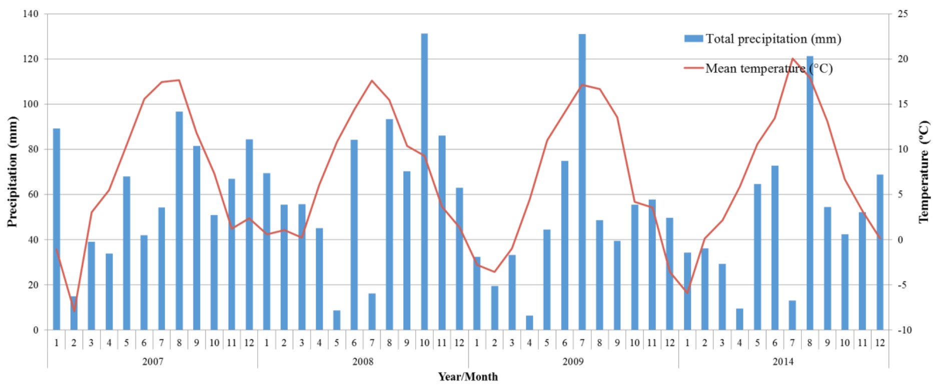

Figure 2. Monthly mean temperature (°C) and total precipitation (mm) during the study period (2007 – 2009 and 2014), as measured at the meteorological station of Kaisaniemi.

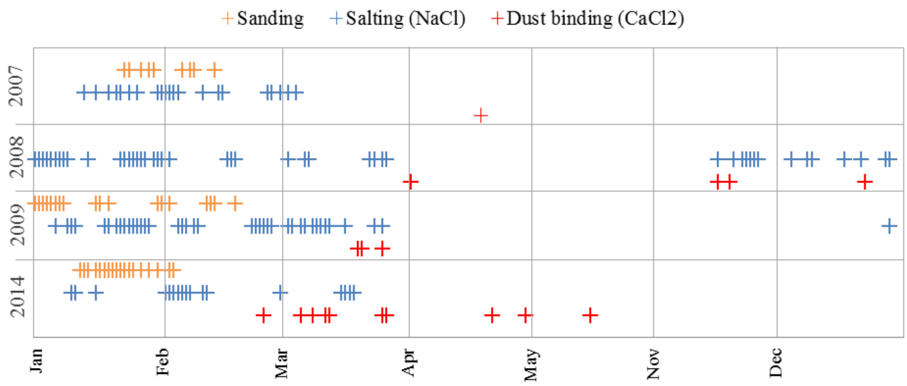

Figure 3. The approximate timing of the road maintenance measures at Hämeentie in 2007-2009 and 2014. The relevant information for the latter part of the year (from October to December) was available only for 2008.

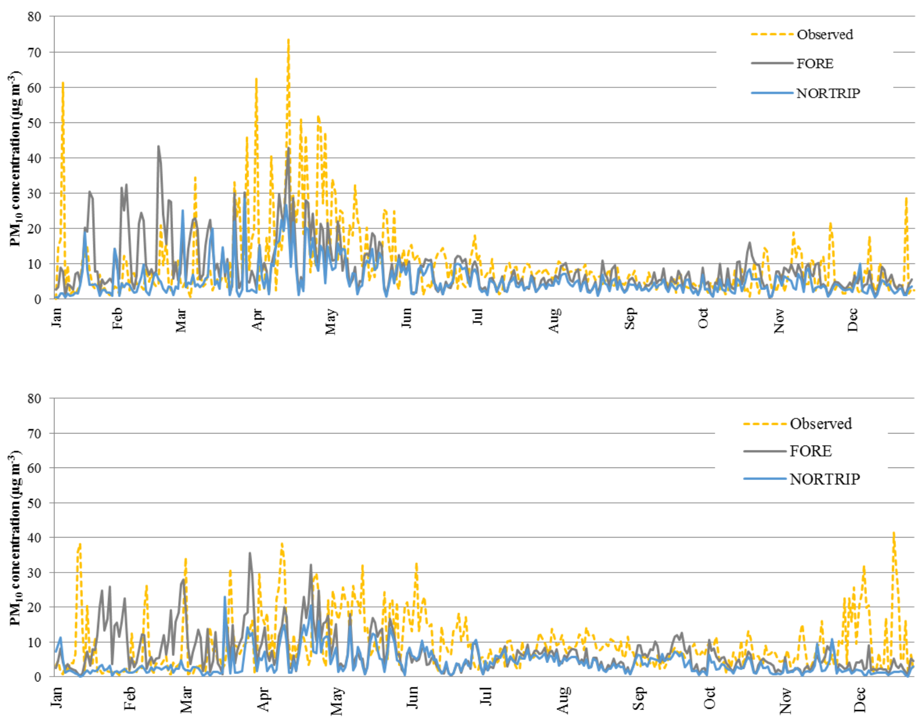

Figure 4. Time series of daily mean modelled and observed street increments of PM_{10} at Hämeentie in 2009 (upper panel) and 2014 (lower panel).

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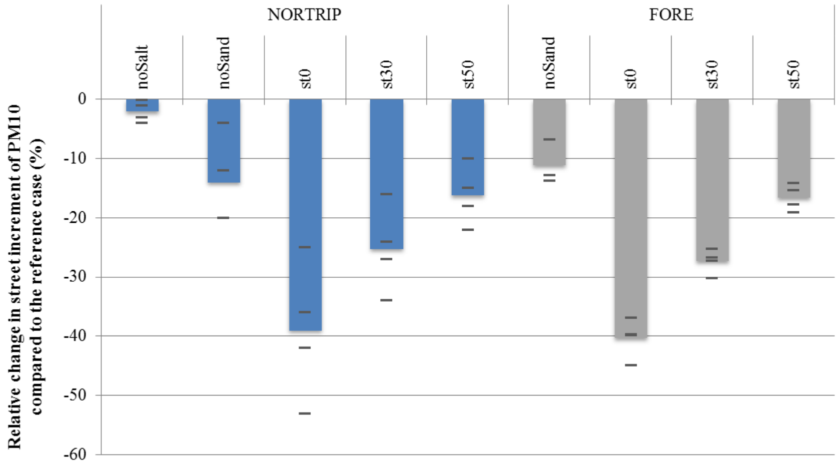

Figure 5. Changes in modelled non-exhaust PM_{10} concentration due to the reduction in the share of light-duty vehicles using studded tyres and with excluding the reported sanding and salting events. The results were computed by the two road dust emission models. Impact of traction salting is estimated using the NORTRIP model. Relative changes compared to the reference case are presented as four-year average values with line markers showing values for the individual years.