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Modelling road dust emission abatement measures using the NORTRIP model: Vehicle speed and studded tyre reduction

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HIGHLIGHTS

- The NORTRIP road dust emission model is applied to assess the impact of traffic measures.
- The model reproduces the impacts of both traffic and meteorological conditions.
- Road surface conditions have as significant an impact on road dust emissions as traffic abatement measures.
- The model can be usefully applied to assess these measures in future air quality planning.

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ABSTRACT

Road dust emissions in Nordic countries still remain a significant contributor to PM_{10} concentrations mainly due to the use of studded tyres. A number of measures have been introduced in these countries in order to reduce road dust emissions. These include speed reductions, reductions in studded tyre use, dust binding and road cleaning. Implementation of such measures can be costly and some confidence in the impact of the measures is required to weigh the costs against the benefits. Modelling tools are thus required that can predict the impact of these measures. In this paper the NORTRIP road dust emission model is used to simulate real world abatement measures that have been carried out in Oslo and Stockholm. In Oslo both vehicle speed and studded tyre share reductions occurred over a period from 2004 to 2006 on a major arterial road, RV4. In Stockholm a studded tyre ban on Hornsgatan in 2010 saw a significant reduction in studded tyre share together with a reduction in traffic volume. The model is found to correctly simulate the impact of these measures on the PM_{10} concentrations when compared to available kerbside measurement data. Importantly meteorology can have a significant impact on the concentrations through both surface and dispersion conditions. The first year after the implementation of the speed reduction on RV4 was much drier than the previous year, resulting in higher mean concentrations than expected. The following year was much wetter with significant rain and snow fall leading to wet or frozen road surfaces for 83% of the four month study period. This significantly reduced the net PM_{10} concentrations, by 58%, compared to the expected values if meteorological conditions had been similar to the previous years. In the years following the studded tyre ban on Hornsgatan road wear production through studded tyres decreased by 72%, due to a combination of reduced traffic volume and reduced studded tyre share. However, after accounting for exhaust contributions and the impact of meteorological conditions in the model calculations then the net mean reduction in PM_{10} concentrations was only ~50%, in agreement with observations. The NORTRIP model is shown to be able to reproduce the impacts of both traffic measures and meteorology on traffic induced PM_{10} concentrations, making it a unique and valuable tool for predicting the impact of measures for air quality management applications.

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1. Introduction

Non-exhaust traffic induced particle emissions are known to contribute significantly to the total concentrations of inhalable airborne particulate matter in the size range <10 µm (PM_{10}), e.g. Amato et al. (2014), Mathissen et al. (2012), Bukowiecki et al. (2010), Gustafsson et al. (2008), Norman and Johansson (2006) and Boulter (2005). Non-exhaust PM_{10} emissions are composed of a number of wear sources (road, tyre and brake) and may also contain emissions from traction sanding, from road salt, from deposited material from construction work, from road side soil sources or from deposition of atmospheric PM. The problem in Nordic countries is mostly related to studded tyre wear, the build-up of road dust during the wet winter period and the subsequent suspension of this dust during the dry spring period.

A number of abatement measures have been introduced to reduce road dust emissions in the Nordic countries. These include reductions in the number of vehicles with studded tyres, speed reduction, dust binding, flushing and cleaning of the road surface. Though such measures are regularly implemented their impact has not been properly quantified, even though there can be significant costs connected to their implementation. In most cases the use of observations to assess the impact of measures is difficult because other changes, such as meteorological conditions, also affect the observed concentrations. Quantification of the impact of measures prior to implementation is desirable but doing so requires the use of appropriate and reliable modelling tools. Such modelling tools cannot be based on empirical emission factors as these do not take into account the various processes that would be affected by the measures being implemented.

The NORTRIP road dust emission model (Denby et al., 2013a, 2013b) is a model capable of assessing these measures. It is a coupled road dust and surface moisture model that describes a range of processes related to the generation and removal of dust, sand and salt on the road surface as well as their subsequent suspension and emission. Wear from road, brake and tyres generate direct emissions under dry conditions but accumulate on the surface when it is wet, being suspended when the surface dries out. This process is described in the model using a mass balance approach. The suspension and retention of dust and salt is governed by the road surface moisture and this is also described using a mass and energy balance approach. Surface moisture accumulates through precipitation, condensation and wetting (by road maintenance activities) and is removed through evaporation, drainage and vehicle spray processes. With these wet removal processes both dust and salt can be removed. This model has already been applied at a number of sites, including the sites addressed in this paper, and has been shown to reproduce well emissions of road dust under a range of meteorological conditions (Denby et al., 2013a, 2013b).

In this paper we further apply the NORTRIP model to analyse real world abatement measures carried out in Oslo and Stockholm and to assess the models suitability for predicting and quantifying the impact of these measures. Two of the abatement measures

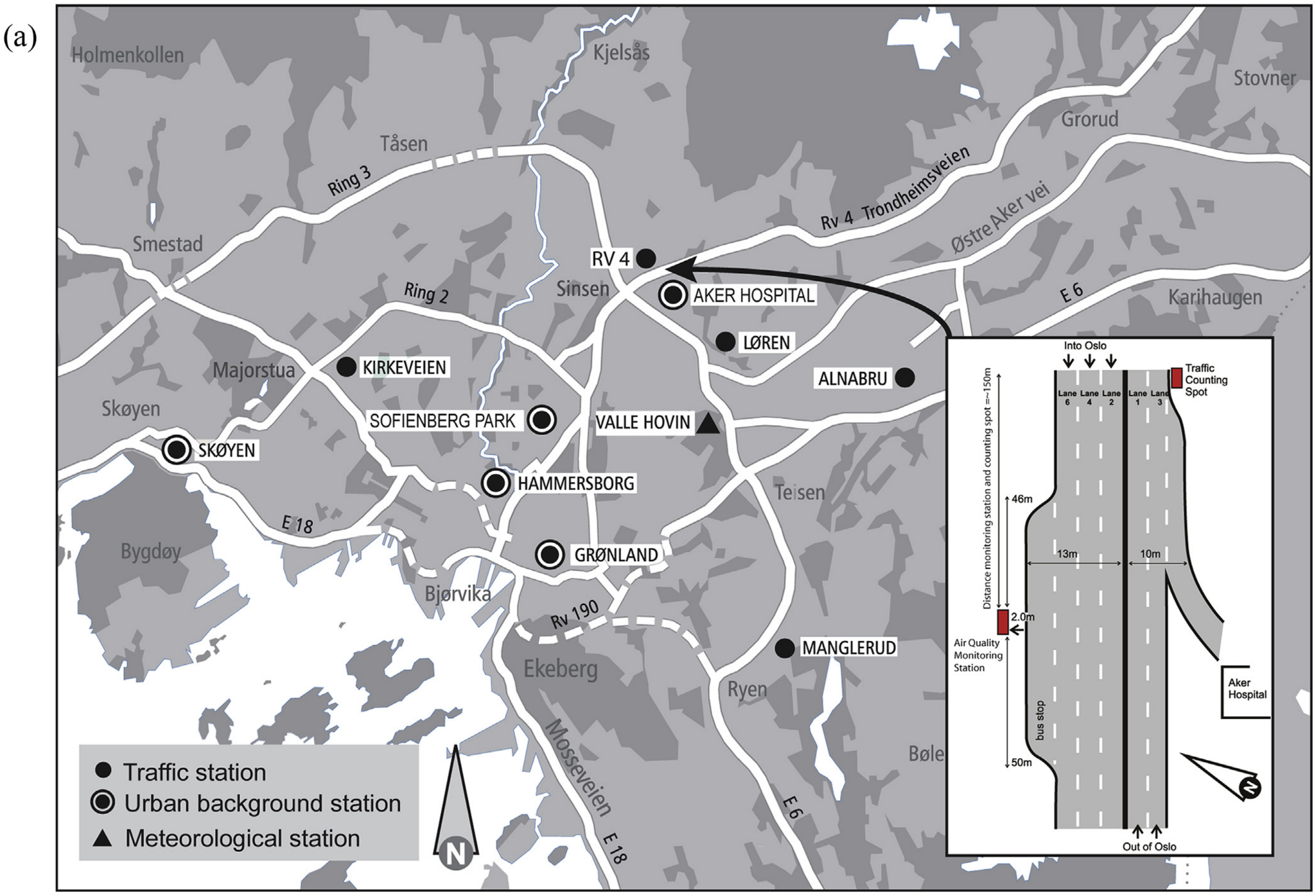

Fig. 1. a) Map of Oslo showing the position of the air quality kerbside site (RV4), the urban background site (Aker hospital), the meteorological site (Valle Hovin) and a number of other air quality sites in operation in 2004–2006 in Oslo. Road salting data has been taken from the road labelled ‘Ring 2’. b) Map of Stockholm showing the position of the kerbside air quality site (Hornsgatan) and the urban background and meteorological site (Torkel Knutssonsgatan).

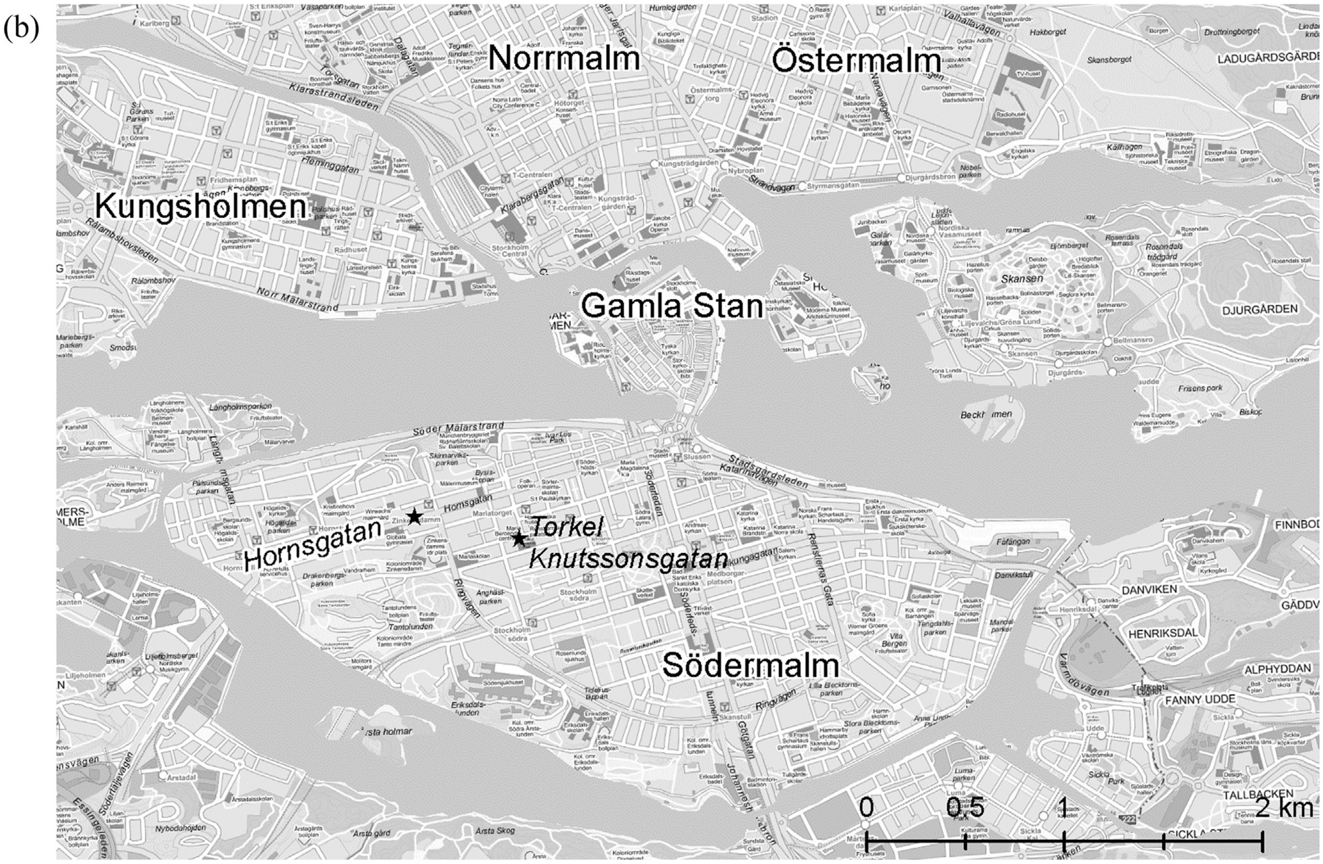

Fig. 1. (Continued)

described above, studded tyre reduction and vehicle speed reduction, have been implemented in these two cities. In Oslo speed signage was used between 2006 and 2012 to reduce traffic speed on major arterial and ring roads with the explicit intention of reducing traffic induced PM_{10} emissions. The use of speed signage was first tested in 2004–2006 on a single road in Oslo, RV4, and it is this test period that is addressed here. In addition a studded tyre fee was introduced in Oslo in November 2004 and this also lead to a decline in the use of studded tyres during this period. In Stockholm a studded tyre ban was introduced on Hornsgatan in 2010 to reduce studded tyre use with the additional impact of a reduction in traffic volume on this road. The analysis for Hornsgatan is carried out in the period from 2006 to 2014 in order to further address the impact of meteorological conditions on the road dust emissions.

In this paper we first describe the sites, the relevant input data and the abatement measures that have been implemented (Section 2). We then summarize the NORTRIP model with a short overview of the model process descriptions relevant for the current application (Section 3). Model calculations for the two sites are then presented as daily mean time series and statistically assessed to determine means, percentiles, R^2 and root mean square errors (Section 4). The results are then further analysed in order to quantify the changes related to each of the measures as well as the impact of meteorology on the PM_{10} concentrations (Section 5). We finish with a discussion and conclusion (Section 6).

2. Site descriptions, data and implemented measures

Two measurement sites, one in Oslo (RV4) and one in Stockholm (Hornsgatan), are used in this study (Fig. 1). For RV4 the data spans three winter seasons (2004–2006) whilst for Hornsgatan complete data is available from 2006 to 2014, covering eight winter seasons. At both these sites hourly mean measurements of PM_{10} and NO_X concentrations are available at a kerbside traffic site and at a nearby urban background site (NO_X is used as a tracer to determine dispersion, see Section 3). Meteorological data required for the model calculations is also available from nearby sites. For Hornsgatan measurements of temperature and humidity are available in the street canyon. Measurements of road surface temperature and road surface moisture are also available for Hornsgatan using in situ thermistor and conductivity measurements at three positions on the road surface (Denby et al., 2013b).

Winter road maintenance activity data, required by the model, is only partially available at these sites. At Hornsgatan good salting data is available from 2010 to 2011 onwards. Prior to this the salting rule model is used to generate salting for the road (Section 2.10, Denby et al., 2013b). No direct salting data is available for RV4 during the analysis period, but concise data is available from another area of Oslo not far from RV4 (Ring 2, see Fig. 1). It is assumed that similar salting activities were undertaken in both areas.

2.1. RV4 measures and data

RV4 is a major arterial road into Oslo (Fig. 1) with an average daily traffic (ADT) of over 40,000 veh/day. The signed speed for this road in 2004 was 80 km/h. As part of an experiment for The Norwegian Public Roads Administration, speed signage was changed prior to the winter of 2005 from 80 to 60 km/h which resulted in an

Table 1
Traffic and road maintenance summary data for the three years of data from RV4. The period modelled is from November to April (inclusive) but only results from January to April, corresponding to available observations, are used.* indicates values calculated by the model.

Year	Number of days used	ADT	Heavy duty vehicle fraction (%)	Mean speed (km/hr)	Mean studded (% LDV)	Max studded (% LDV)	Total salt (ton/km)	Salting events (NaCl)	Sanding events	Cleaning events	Ploughing events*
2004	121	42,581	4.9	74.7	26	27	39	113	0	0	9
2005	120	40,927	6.4	64.1	20	24	12	43	0	0	0
2006	120	41,278	4.2	63.7	20	20	51	114	0	5	10

observed change of average speed from 75 to 65 km/h, as well as a slight reduction in traffic volume (4%). Between these two seasons the maximum share of vehicles with studded tyres also fell from 27% to 24%, assumed to be related to the introduction of a studded tyre fee in 2004.

In 2004–2005 a measurement campaign for both traffic and air quality took place in order to assess the impact of this speed change on PM_{10} concentrations (Hagen et al., 2005). These measurements were also in place in 2006 though there was little change in traffic characteristics between 2005 and 2006. Based on the observational data Hagen et al. (2005) determined that the net relative reduction in PM_{10} concentrations (36%) was significantly larger than the relative reduction in speed (12%) and concluded that speed reduction was an effective means of reducing PM_{10} road dust emissions. These results were further used to support the implementation in Oslo of an environmental speed limit in 2006, where the speed limit on the ring road system and two other major arterial roads was reduced from 80 to 60 km/h in the winter season. Due to legal reasons this speed limit has, since 2012, been changed to 70 km/h all year round.

In Table 1 a summary of traffic and winter road maintenance data for RV4 is given and in Table 2 a summary of meteorological data is provided for the assessment periods. The period modelled is from November to April (inclusive) but only results from January to April, corresponding to the available observations, are used.

2.2. Hornsgatan measures and data

Hornsgatan is a street canyon in Stockholm (Fig 1.) with an ADT of 29,000 veh/day in 2007, but reduced to 20,000 veh/day by 2014. The signed speed for this road is 50 km/h but the average speed is around 43 km/h. For the winter season 2009–2010 the Stockholm city council introduced a studded tyre ban on Hornsgatan. The maximum number of vehicles using studded tyres on this road was reduced from 70% in 2008–2009 to 50% in 2009–2010 and further down to 36% in 2010–2011 and 31% in 2013–2014. At the same time traffic volume dropped significantly on Hornsgatan, from 27,200 veh/day in 2008–2009 to 23,700 veh/day in 2009–2010 and further down to 21,800 veh/day in 2010–2011. This is mostly a result of vehicles with studded tyres avoiding the use of Hornsgatan, but decreased traffic is also observed during the summer period when no studded tyres are used. Hourly traffic counts were made using induction loop measurements in the road surface. Detailed fleet make up was observed during three months in 2009. The heavy duty share was 3% (1.8% busses and 1.2% heavy truck) and was used for all modelled years. Studded tyre share is based on weekly manual counting during the studded tyre season using the difference in sound between studded and non-studded tyres.

Air quality measurements, in place on Hornsgatan since 2000, show a corresponding reduction in both annual mean net PM_{10} concentrations and the number of exceedance days on Hornsgatan during and after the implementation of the ban (Gustafsson et al., 2013, 2014; 2015). In the last three years, since the 2011–2012 winter period, other measures in regard to cleaning and dust binding have also been implemented. Whilst cleaning did not show a measureable impact on concentrations, dust binding did show some impact on the days on which it was applied. Though these processes are included in the model, as described in Denby et al. (2013b), they will not be discussed further here as they will be the subject of a later paper.

In Table 3 a summary of traffic and winter road maintenance data for Hornsgatan is given and in Table 4 a summary of meteorological data is provided for the assessment periods. The periods modelled are from July to May (inclusive) but only results from the eight month period from October to May are used in the comparison with observations.

3. Modelling

The NORTRIP model is a coupled road dust/salt and road surface moisture model. It is based on the physical processes that govern the mass balance of water/ice/snow and of dust/salt on the road surface. Included in the model are process descriptions for the energy balance of the road surface, the surface temperature, the impact of salt on vapour pressure and melting as well as processes governing the emission and build-up of dust and salt on the road surface. The impact of dust binding is included through its effect on the surface vapour pressure.

Road dust emissions and loading are the result of road wear by studded tyres as well as contributions from tyre and brake wear. These wear sources are each specified with their own size distribution in the model. Friction sanding may also contribute with its own size distribution. Emissions are described as ‘direct emissions’, the result of wear during dry conditions that are directly emitted or are quickly suspended to the air, and ‘suspended emissions’, resulting from the build-up of road dust on the surface during wet periods and the subsequent suspension of this dust loading during dry periods. It is the interaction between road surface conditions, dust loading and suspension that makes such a coupled model necessary.

Table 2
Meteorological summary data for the three years in the period from January to April (inclusive) for RV4.* indicates values calculated by the model.

Year	Mean temperature (C)	Mean RH (%)	Mean global radiation (W/m^2)	Mean cloud cover (%)*	Precipitation (mm)	Frequency precipitation (%)	Frequency wet road (%)*	Mean dispersion factor (($\mu g/m^3$)/(g/km))	Mean wind speed at 10 m (m/s)
2004	1.0	76	65	59	178	13	48	0.056	2.5
2005	1.7	70	56	69	78	6	31	0.043	3.1
2006	−1.0	78	69	53	118	13	83	0.051	2.7

Table 3
Traffic and road maintenance summary data for the eight years of data from Hornsgatan. The period modelled is from July to May (inclusive) but only results from October to May are used.* indicates values calculated by the model.

Year	Number of days used	ADT	Heavy duty vehicle fraction, estimated (%)	Mean speed (km/hr)	Mean studded (%LDV)	Max studded (%LDV)	Total salt (ton/km)	Salting events (NaCl)	Sanding events	Cleaning events	Ploughing events*
2006–2007	243	29,064	3	43	46.7	75	6.3*	45*	0	0	2
2007–2008	244	28,050	3	44	45.3	71	7.1*	51*	0	0	1
2008–2009	243	27,237	3	44	44.8	70	9.9*	71*	0	0	4
2009–2010	243	23,763	3	44	27.9	50	12.8*	92*	0	0	24
2010–2011	243	21,849	3	44	19.5	36	14.4	88	29	0	20
2011–2012	244	21,871	3	44	16.7	34	11.1	56	6	25	0
2012–2013	243	21,745	3	42	17.4	31	7.9	47	0	51	9
2013–2014	243	20,643	3	43	17.0	31	5.7	20	0	70	8

Table 4
Meteorological summary data for the eight years in the period from October to May (inclusive) for Hornsgatan. Also included are the observed frequency of wet roads as well as the fraction of correctly modelled road surface conditions.* indicates values calculated by the model.

Year	Mean Temperature (C)	Mean RH (%)	Mean global radiation (W/m^2)	Mean cloud cover (%)*	Precipitation (mm)	Frequency precipitation (%)	Frequency wet road modelled (%)*	Frequency wet road observed (%)	Road moisture hits (%)*	Mean dispersion factor ((μg/m^3)/(g/km))	Mean wind speed at roof top (m/s)
2006–2007	5.8	75	75	57	197	5.8	43	49	83	0.119	4.0
2007–2008	5.1	75	80	56	158	5.3	46	48	80	0.126	3.6
2008–2009	4.4	76	79	55	148	4.8	50	52	81	0.135	3.5
2009–2010	2.4	78	77	57	207	8.3	60	58	86	0.158	3.4
2010–2011	2.5	75	88	47	167	6.4	58	62	92	0.157	4.0
2011–2012	4.7	75	84	50	174	5.1	52	51	79	0.160	3.9
2012–2013	2.8	78	84	52	152	6.7	61	59	88	0.187	3.7
2013–2014	5.3	77	76	57	187	5.4	58	54	79	0.161	3.9

Input data required by the model includes hourly traffic and meteorological data as well as road maintenance activity data for salting, dust binding, cleaning and snow ploughing. Emission factors for exhaust are also included in order to determine the total PM_{10} emissions due to traffic. Conversion of emission data to concentrations, for comparison with measurements, is carried out using NO_X as a tracer. With knowledge of NO_X emission factors and measured NO_X concentrations then a dispersion factor (Tables 2 and 4) relating emissions to concentrations can be defined and the conversion from PM_{10} emissions to PM_{10} concentrations is made on an hourly basis. NO_x and PM-exhaust emission factors for Hornsgatan are based on the observed fleet composition, driving speed and driving conditions and have been estimated using the HBEFA 3.1 emission model (HBEFA, 2015). Both the NO_x and PM-exhaust emission factors have decreased during the modelling period due to the fleet turnover to cleaner vehicles (newer Euro classes). NO_x emission factors have decreased from 0.81 g/veh/km in 2007 to 0.70 g/veh/km in 2014. For RV4 these emission factors are based on a report from Hagman et al. (2011).

The model has been extensively described and assessed in Denby et al. (2013a, 2013b) and the reader is referred to these papers for more information. For the application here, the assessment of measures related to traffic volume, vehicle speed and studded tyre share, we provide an overview of the relevant model processes. A mathematical description of the processes can be found in Denby et al. (2013a, 2013b).

3.1. Traffic volume

Traffic volume impacts linearly on the production of wear, on the spray removal of water and dust/salt from the surface and on the dry suspension of dust/salt. Traffic volume also impacts, to a small degree, on the energy balance of the road as traffic related fluxes can contribute to the road surface temperature and to the turbulent exchange through traffic induced turbulence.

3.2. Vehicle speed

Vehicle speed impacts linearly on road and tyre wear. The road wear rates are based on the Swedish road wear model (Jacobson and Wågberg, 2007). The fraction of total wear <10 μm is taken to be 28% at speeds of 50 km/h and this is slightly dependent on vehicle speed, as described in Section 3.8 of Denby et al. (2013a). This fraction and the speed dependence is based on laboratory measurements described in Paper V of Snilsberg et al. (2008). Vehicle spray of surface water, dust and salt is also dependent on speed and can be a major source of dust removal for higher speed roads. The formulation described in Section 2.5, Denby et al. (2013b) for spray is specified as a quadratic dependence on speed. This has now been slightly updated to include a lower cut off speed of 20 km/h, below which no mass is removed from the road. The new formulation retains the same spray rate at the reference speed of 70 km/h. The spray part of the model remains uncertain and requires further refinement but the current spray parameters have been successfully tested on a number of roads.

3.3. Studded tyre share

Studded tyres are the major source of dust generation. The wear rate caused by studded tyres is specified using the Swedish road wear model (Jacobson and Wågberg, 2007) and is linear with studded tyre share. Road wear by studded tyres is also dependent on the pavement characteristics, stone sizes and stone wear parameters. For RV4 the stone sizes are smaller than for Hornsgatan and the road wear, according to the Swedish road wear model, is 1.6 times higher. This is uncertain since direct measurements of pavement characteristics have only been carried out for pavements and stones similar to Hornsgatan (Gustafsson and Johansson, 2012).

Table 5

Default total wear rates (Hornsgatan), road dust suspension rates and PM_{10} fraction of wear and suspension for light duty vehicles used in the NORTRIP model. Wear and suspension rates for heavy duty vehicles are considered to be 5 and 10 times larger respectively than for light duty vehicles. The reference speeds for the wear parameters and the PM_{10} fraction are 70 and 50 km/h respectively. The adjusted wear rate for RV4 is 1.6 higher due to the stone size characteristics. A complete list of model parameters can be found in Denby et al. (2013a; 2013b).

Parameter	Studded tyres	Non-studded tyres	PM_{10} fraction of wear (%)
Road wear (g km^{-1} veh^{-1})	2.88	0.14	28
Tyre wear (g km^{-1} veh^{-1})	0.10	0.10	10
Brake wear (g km^{-1} veh^{-1})	0.01	0.01	80
Road dust suspension rate (veh^{-1})	2.5×10^{-6}	2.5×10^{-6}	–

Non-studded tyres are taken to have a wear rate 1/20'th of studded tyre wear (Snilsberg et al., 2008) and so contribute significantly less to the total road wear when high shares of studded tyres are in use. However, for low studded tyre shares their relative contribution can be significant. Important model parameters for wear and suspension are summarized in Table 5.

4. Comparison of modelled and observed concentrations

For both sites the model is applied using the available hourly input data for traffic, meteorology and winter road maintenance. The results are presented here as time series of modelled and observed daily mean net PM_{10} concentrations as well as a statistical analysis of the results. Three winter seasons at RV4 and eight winter seasons at Hornsgatan are presented. For inter-comparison of years in Section 5 the modelling periods are kept the same for the different years at each site. Due to limitations on the length of the measurement campaign in 2004 results for the four month period from 1 January to 30 April are shown for RV4, whilst the eight month period from October to May is analysed for Hornsgatan, representing the major part of the studded tyre season with a month before and after the season starts and finishes.

4.1. RV4 time series

In Fig. 2 the net (traffic site minus urban background site) measured and modelled daily mean PM_{10} concentrations are shown for RV4. Statistics for these three years are shown in Fig. 3 for both the mean and the 90'th percentile daily mean concentrations. As can be seen the model reproduces the daily mean variation reasonably well for all years with an R^2 from 0.52 to 0.64. The mean and 90'th percentile concentrations are also very well represented by the model and convincingly follow the trend over the three year period.

4.2. Hornsgatan time series

In Figs. 4 and 5 the net measured and modelled daily mean PM_{10} concentrations are shown for Hornsgatan. Statistics for these eight years are shown in Fig. 6 for both the mean and 90'th percentile concentrations. In Fig. 6 the years shown represent the date at the end of the winter season, e.g. 2006–2007 is shown as 2007. For Hornsgatan observed surface wetness is also available. In Denby et al. (2013b) it was shown that use of the observed surface wetness, instead of the model calculated surface wetness to

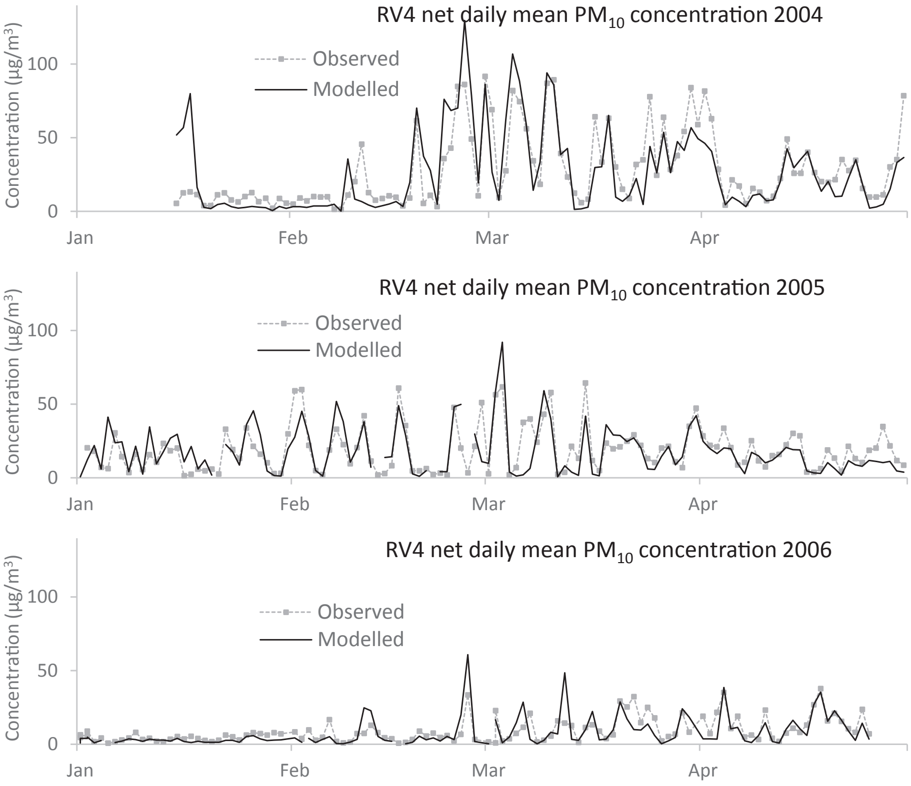

Fig. 2. Time series plots of observed and modelled net daily mean PM_{10} concentrations for the three years of data at RV4. Vertical scale is the same for all plots.

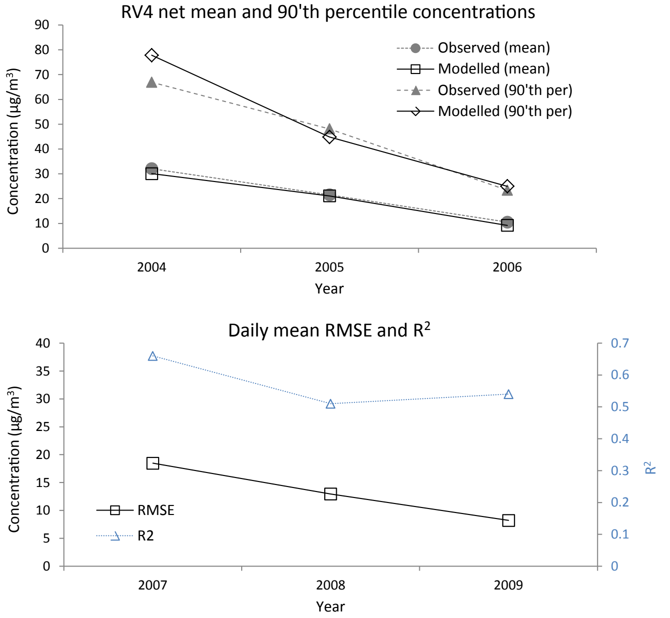

Fig. 3. Summary statistics for the three years of calculations for RV4. Shown are the net mean and 90'th percentile daily mean concentrations (top) and the RMSE and R^2 of the daily mean calculations (bottom).

prescribe surface retention of dust, can significantly improve the timing and hence correlation of the model. The plots presented in Figs. 4 and 5 are based on the modelled moisture, but statistics using both modelled and observed surface moisture are presented in Fig. 6 for comparative purposes. Using modelled moisture we find R^2 to lie in the range 0.35–0.66 but using observed moisture for retention leads to an R^2 from 0.62 to 0.90. Only on one occasion, 2012–2013, does use of the modelled moisture for retention result in an R^2 comparable to the use of the observed moisture.

The mean and 90'th percentile concentrations are very well represented by the model and follow the trend over the eight year period. Only in the first three years is the 90'th percentile overestimated by the model. Percentiles are generally improved using the observed surface moisture.

The results of the modelling shown here indicate that the model is capable of representing the observed trends that result from changes in traffic and meteorological conditions. As such the model appears to provide the correct dynamic sensitivity necessary for assessing the impact of measures. A more detailed analysis of these measures and the model sensitivity is provided in the following section.

5. Analysis of the impact of traffic measures and meteorology

There are a number of changes occurring in both traffic and

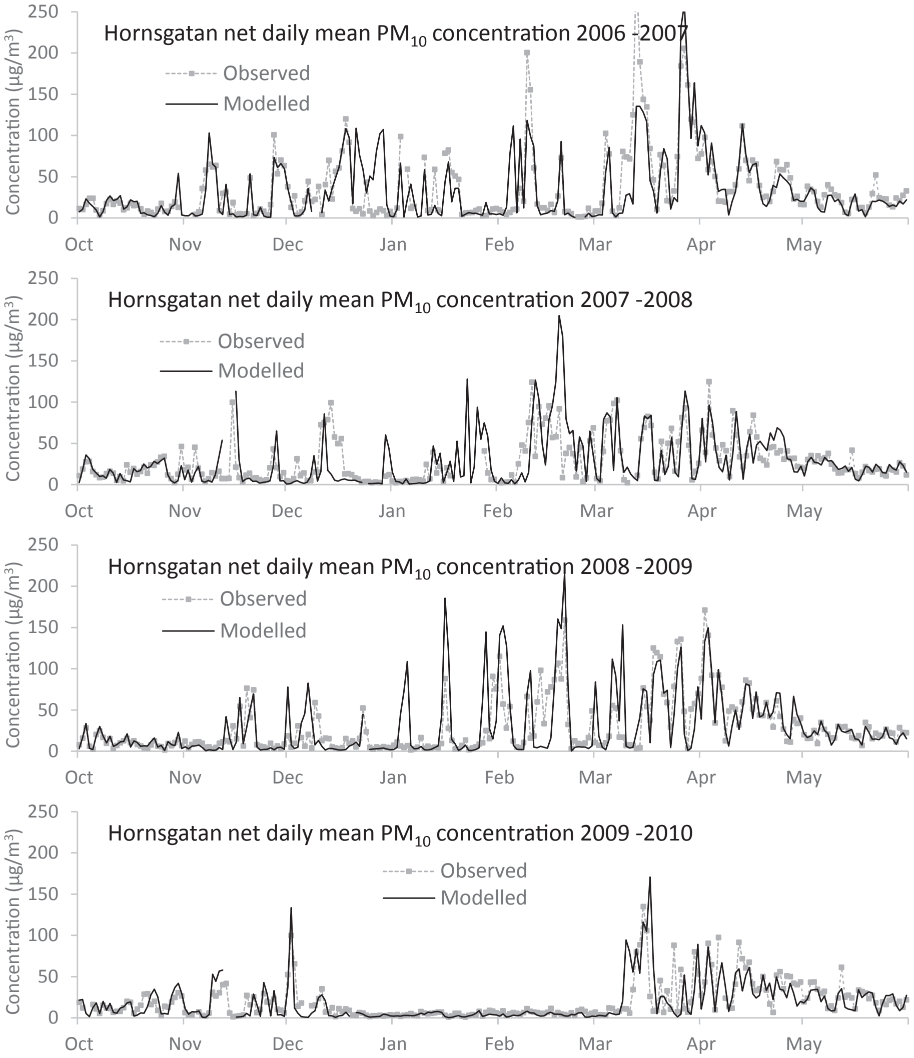

Fig. 4. Time series plots of observed and modelled net daily mean PM_{10} concentrations for the first four winter season, years 2006–2007 to 2009–2010, at Hornsgatan. Calculations shown use the modelled surface moisture. Vertical scale is the same for all plots.

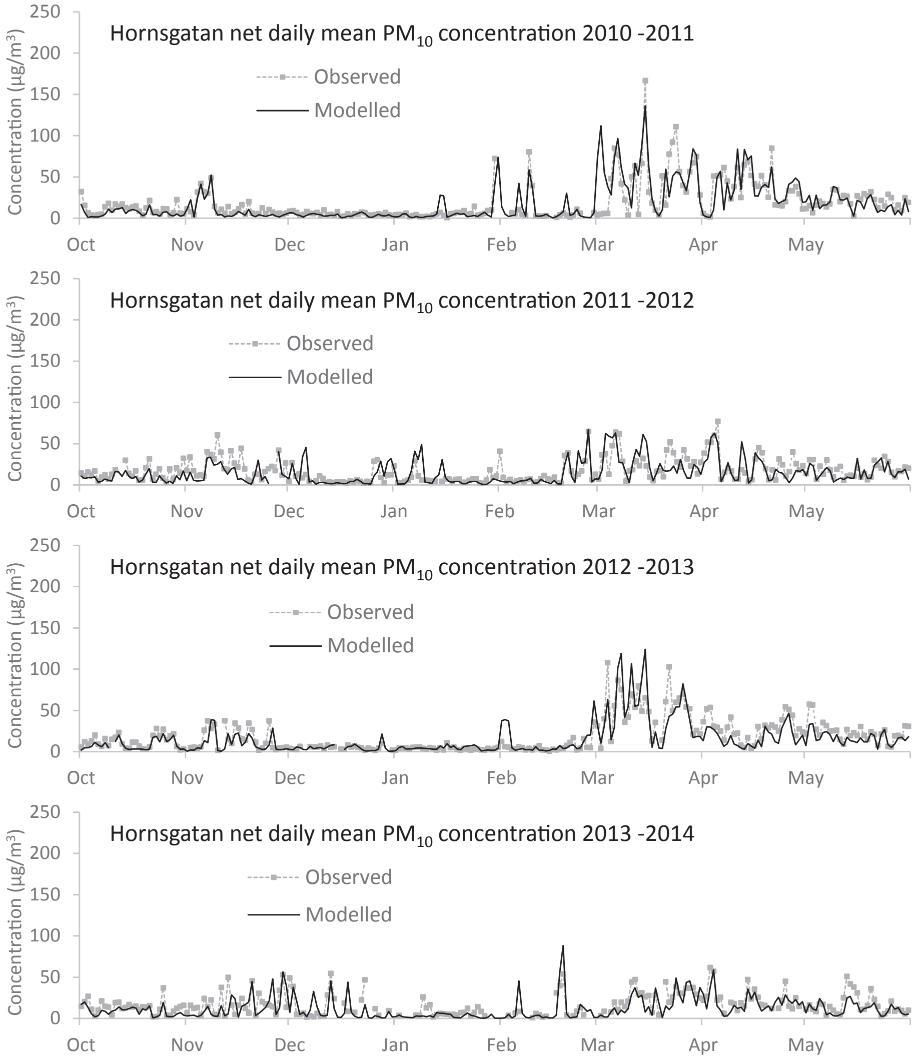

Fig. 5. Time series plots of observed and modelled net daily mean PM_{10} concentrations for the last four winter season, years 2010–2011 to 2013–2014, at Hornsgatan. Calculations shown use the modelled surface moisture. Vertical scale is the same for all plots.

meteorological conditions from year to year (Tables 1–4) that influence the yearly concentration changes seen in Figs. 3 and 6. In this section we analyse these changes in two ways, firstly by recalculating concentrations for each year using traffic data from a single reference year (first year of data for each site) and the second by an analytical assessment of the model sensitivity to changes in these input data.

5.1. Methodology for assessing traffic and meteorology impact through model recalculation

Additional calculations are carried out for both sites and for all years where a single traffic dataset, from the reference year ($traffic_{ref}$), replaces the normal traffic dataset ($traffic_{year}$) for all the meteorological assessment years ($meteo_{year}$). This provides an additional model dataset where the impact of changes in traffic conditions, as well as the impact of changes in meteorology, can be assessed for all years relative to the reference year.

We define the total change in concentrations ΔC_{total} ($traffic_{year}$, $meteo_{year}$) for a particular year as the relative difference between the concentrations $C(traffic_{year}, meteo_{year})$ and a reference year $C(traffic_{ref}, meteo_{ref})$ due to changes in both the traffic and meteorological conditions by

$$\Delta C_{total} = \frac{C(traffic_{year}, meteo_{year})}{C\left(traffic_{ref}, meteo_{ref}\right)} - 1 \tag{1}$$

This change will be presented as relative changes in both the annual mean and 90'th daily mean percentile PM_{10} concentrations.

Additionally we can separate the impact of traffic and meteorology by selecting different datasets. For traffic ($\Delta C_{traffic}$) we compare datasets with the same meteorology but different traffic and for meteorology (ΔC_{meteo}) we compare datasets with the same traffic but different meteorology

$$\Delta C_{traffic} = \frac{C(traffic_{year}, meteo_{year})}{C\left(traffic_{ref}, meteo_{year}\right)} - 1 \tag{2}$$

$$\Delta C_{meteo} = \frac{C\left(traffic_{ref}, meteo_{year}\right)}{C\left(traffic_{ref}, meteo_{ref}\right)} - 1 \tag{3}$$

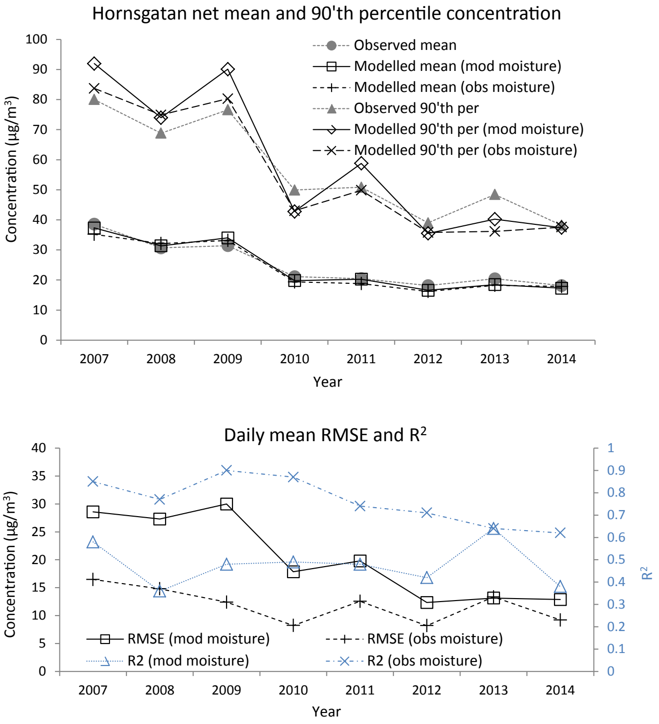

Fig. 6. Summary statistics for the eight years of calculations for Hornsgatan. Shown are the net mean and 90'th percentile daily mean concentrations (top) and the RMSE and R^2 of the daily mean calculations (bottom). Included in both plots are the statistics for the two different model calculations, using modelled surface moisture (mod moisture) or observed surface moisture (obs moisture) for dust retention in the model.

5.2. *Methodology for assessing traffic and meteorology impact analytically*

Whilst it is possible to make sensitivity studies with the model to indicate the impact of individual parameters on the calculated concentrations, e.g. changing studded tyre shares or traffic volumes, it is more useful to describe these sensitivities analytically, as this provides insight into the mechanisms whereby changes occur. To aid in this analysis a schematic model description is provided. The total annual mean concentrations C_{total} can be schematically described as follows:

$$C_{total} = f_{dis} \cdot E_{total} \tag{4}$$

where the total emission E_{total} is given by

$$E_{total} = f_{surf} \cdot W_{wear} + E_{sand} + E_{salt} + E_{exh} \tag{5}$$

Here f_{dis} is the average dispersion factor (converting emissions to concentrations) and f_{surf} is the impact of surface conditions on the wear rates (W_{wear}) which includes processes governing retention as well as loss of surface dust, e.g. drainage loss. The emissions of sand (E_{sand}) and salt (E_{salt}) are included and these are dependent on meteorology for several reasons: firstly because the activities of sanding and salting are instigated as a result of the meteorological conditions; secondly because these emissions are dependent on surface conditions, in a similar way as road dust emissions are dependent on retention through surface moisture conditions, and thirdly because salt removal is largely the result of drainage and vehicle spray processes and these are strongly dependent on the precipitation. We do not separate these meteorological dependencies in this analysis as the sand and salt contribution to total concentrations is small compared to the wear sources. The method for calculating these from the model calculations is given in Equation (12). Exhaust emissions are included (E_{exh}) but are not dependent on the surface conditions. Of these factors f_{dis}, f_{surf}, E_{sand} and E_{salt} are primarily dependent on the meteorological conditions and the factors W_{wear} and E_{exh} are primarily dependent on the traffic conditions.

The wear contribution to the emissions is due to road, tyre and brake wear. The ratio of non-studded to studded tyre road wear rates is 0.05 and the ratio of brake and tyre wear to studded tyre road wear for PM_{10} is around 0.01 (Table 5). This indicates that road wear is the major wear source so for simplicity in the analysis we ignore the brake and tyre contributions but retain the non-studded tyre wear as this can be significant when studded tyre shares are low.

Using the linear model dependency of road wear on vehicle speed (VS), on traffic volume (TV) and on average studded tyre share fraction (ST) then we can specify the total road wear for both studded ($W_{studded,\ wear}$) and non-studded tyres ($W_{non\text{-}studded,wear}$) based on the wear rates WR_{source} per vehicle (at the reference speed VS_0) as follows

$$W_{wear} \approx W_{studded,\ road} + W_{non-studded,\ road} \tag{6}$$

such that

$$W_{wear} = TV \cdot \frac{VS}{VS_0} \cdot WR_{studded}\left(ST + (1 - ST) \cdot \frac{WR_{non-studded}}{WR_{studded}}\right) \tag{7}$$

This schematic description of the model does not specifically describe suspension, but since the cause of the suspended road dust is the road wear and because suspension is controlled by the surface conditions then the changes in suspension are included in the wear (W_{wear}) and surface condition factors (f_{surf}).

Having defined this schematic overview of the model we can then assess the relative change in concentrations (ΔC) due to changes in any of the traffic and meteorological parameters for a particular year relative to the reference year, similar to Equation (1), using

$$\Delta C = \frac{C_{year} - C_{ref}}{C_{ref}} = \frac{C_{year}}{C_{ref}} - 1 \tag{8}$$

We may also describe relative changes in any particular model parameter 'X' in a similar way.

$$\Delta X = \frac{X_{year} - X_{ref}}{X_{ref}} = \frac{X_{year}}{X_{ref}} - 1 \tag{9}$$

Inserting Equations (8) and (9) into Equations (4)–(7) with $X = f_{dis}, f_{surf}, TV, VS, ST, E_{salt}, E_{sand}$ and E_{exh} gives

$$\Delta C = (1 + \Delta f_{dis}) \cdot \times \left(\begin{array}{c} \left(1 + \Delta f_{surf}\right)(1 + \Delta TV)(1 + \Delta VS)(1 + \Delta ST) \cdot F_{wear,ref} \\ +(1 + \Delta E_{salt}) \cdot F_{salt,ref} \\ +(1 + \Delta E_{exh}) \cdot F_{exh,ref} \\ +(1 + \Delta E_{sand}) \cdot F_{sand,ref} \end{array} \right) - 1 \tag{10}$$

To simplify the presentation of Equation (10) we have defined the fractional source contribution $F_{source,ref}$ of any particular source to the total concentration for the reference year. The sum of all $F_{source,ref} = 1$ and these values are derived from the reference model calculation.

Most of the sensitivities shown in Equation (10) can be indicatively derived from the input data, without any model calculation. These include ΔTV, ΔVS, ΔST, ΔE_{exh} and Δf_{dis}. The other

Table 6
Summary of the sensitivity factors to be presented in Section 5.3, derived in Sections 5.1 and 5.2.

Variable	Sensitivity factor	Derivation
Traffic		
Traffic volume	$\Delta TV \cdot F_{wear,ref}$	Hourly mean traffic data
Vehicle speed	$\Delta VS \cdot F_{wear,ref}$	Hourly average traffic speed data
Studded tyre share	$\Delta ST \cdot F_{wear,ref}$	Mean studded tyre share over the modelling period
Exhaust emissions	$\Delta E_{exh} \cdot F_{exh,ref}$	Emission factors and average hourly traffic data
Total traffic	$\Delta C_{traffic}$	Derived from calculated model concentrations, Equation 2
Meteorology		
Surface conditions	$\Delta f_{surf} \cdot F_{wear,ref}$	Derived from calculated model wear emissions, Equation 11
Dispersion conditions	Δf_{dis}	Estimated from the annual mean dispersion factor derived from NO_X emissions and in situ NO_X measurements
Sand emissions	$\Delta E_{sand} \cdot F_{sand,ref}$	Derived from calculated model sand emissions, Equation 12
Salt emissions	$\Delta E_{salt} \cdot F_{salt,ref}$	Derived from calculated model salt emissions, Equation 12
Total meteorology	ΔC_{meteo}	Derived from calculated model concentrations, Equation 3

meteorologically dependent sensitivity factors Δf_{surf}, ΔE_{salt}, ΔE_{sand} must be derived from the model calculations, using the additional reference traffic calculations described in Section 5.1. These factors are given as

$$\Delta f_{surf} = \frac{E_{wear}\left(ref_{traffic}, year_{meteo}\right)}{E_{wear}\left(ref_{traffic}, ref_{meteo}\right)} - 1 \tag{11}$$

$$\Delta E_{salt/sand} = \frac{E_{salt/sand}\left(ref_{traffic}, year_{meteo}\right)}{E_{salt/sand}\left(ref_{traffic}, ref_{meteo}\right)} - 1 \tag{12}$$

In Table 6 the individual sensitivities described in Sections 5.1 and 5.2 are listed. These individual factors represent the expected change in concentrations if no other factors were to change. Combinations of sensitivity factors must be combined using Equation (10).

5.3. Results of the sensitivity analysis for RV4

In Fig. 7 the results of the model sensitivity calculation, described in Section 5.1, are shown for RV4. Both the changes in mean concentrations and 90'th percentile daily mean concentrations are shown for PM_{10}. We see that the observed change in concentrations, compared to the reference year of 2004, is reproduced very well by the model, as already shown in Fig. 3. The change has been separated into the traffic and meteorology related impacts, Equations (2) and (3). In 2005 and 2006 the change in traffic conditions has reduced the mean concentrations by −38% and −26% respectively, similarly for the 90'th percentile. The meteorological related changes are different in both years and, for the case of 2005, also depend on whether the mean or the percentile is chosen. In 2005, a dry year compared to 2004 and 2006 (Table 2), less road dust is accumulated on the surface and more uniform suspension of road dust occurs. This results in lower road dust loading but higher mean emissions since wet removal processes of the dust loading, related to drainage and vehicle spray, are reduced. Lower peak emissions occur as a result of the lower dust loading, leading to a reduction in the 90'th percentile concentrations for this year compared to the other years. In 2006 the surface was wet or frozen for 83% of the time according to model calculations (Table 2). This meteorological situation had a significant impact on the emissions, reducing the mean concentrations by 58%.

In Fig. 8 the individual contributions from both the traffic and meteorological changes, described in Section 5.2, are shown for RV4. The reduction in speed and the studded tyre share are the major contributors to the reduction in concentrations for 2005. In 2005 the dry conditions found in that year led to an increase in mean non-exhaust emissions from the road surface by 25%, but this meteorologically related increase was reduced to just 14% due to improved dispersion conditions and the reduction in salt emissions. Only one third as much salt was applied in 2005 compared to 2004 (Table 1). For 2006 the reduction is dominated by the meteorological surface conditions, though speed and studded tyre share play a similar role as in 2005.

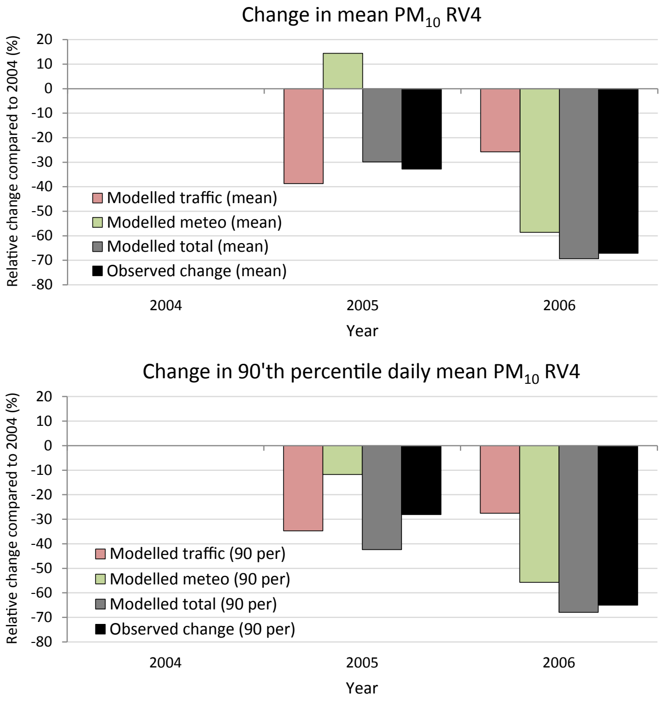

Fig. 7. Observed and modelled changes in the net mean (top) and net 90'th percentile daily mean (bottom) concentrations for RV4, relative to the reference year of 2004. Also shown are the contributions of changes in traffic and meteorology to the total change. See Section 5.1 on the derivation of these.

5.4. Results of the sensitivity analysis for Hornsgatan

In Fig. 9 the results of the model sensitivity calculation, described in Section 5.1, are shown for Hornsgatan. Both the changes in mean concentrations and 90'th percentile daily mean concentrations are shown for PM_{10}. We see that the observed change in mean concentrations, compared to the reference year of

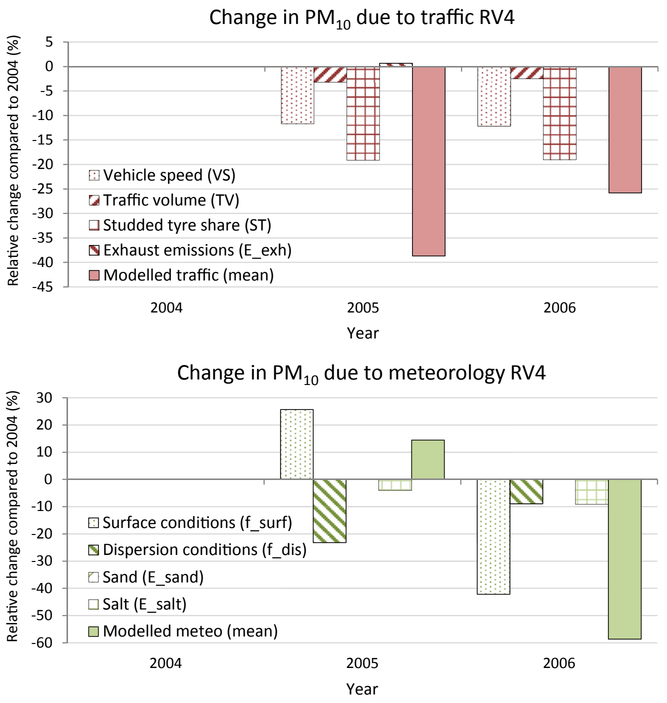

Fig. 8. Changes in net mean PM_{10} concentrations for RV4 due to changes in traffic factors (top) and meteorological factors (bottom), relative to the reference year of 2004. See Section 5.2 on the derivation of these. Also shown are the contributions of changes in traffic and meteorology to the total mean change, as in Fig. 7 (top).

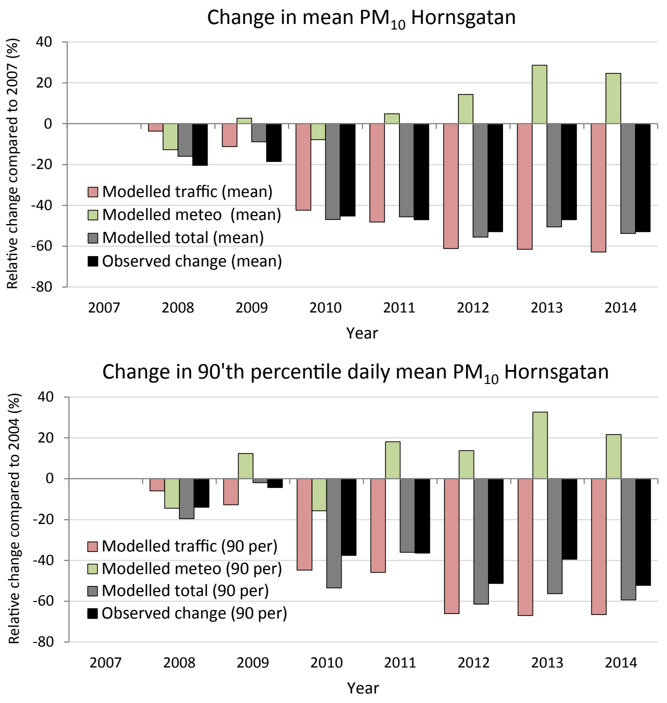

Fig. 9. Observed and modelled changes in the net mean (top) and net 90'th percentile daily mean (bottom) concentrations for Hornsgatan, relative to the reference year of 2007. Also shown are the contributions of changes in traffic and meteorology to the total change. See Section 5.1 on the derivation of these.

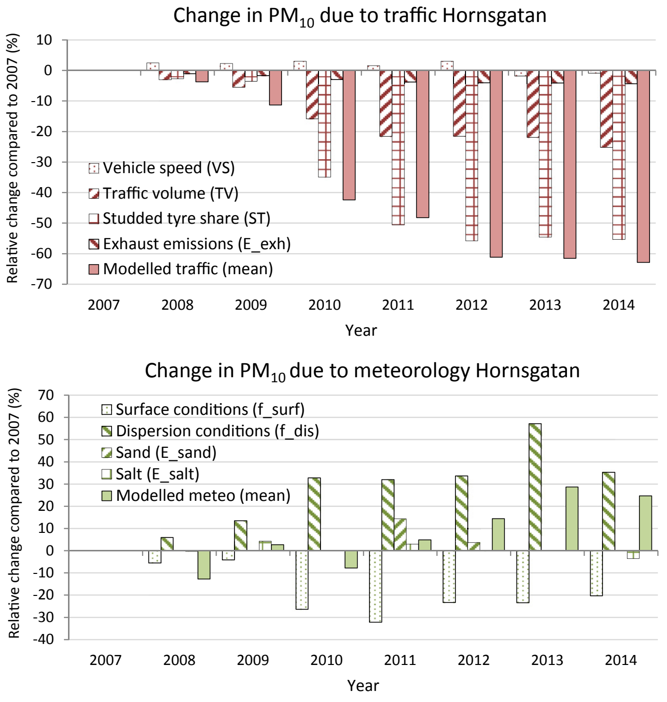

Fig. 10. Changes in net mean PM_{10} concentrations for Hornsgatan due to changes in traffic factors (top) and meteorological factors (bottom), relative to the reference year of 2007. See Section 5.2 on the derivation of these. Also shown are the contributions of changes in traffic and meteorology to the total mean change, as in Fig. 9 (top).

2007, is reproduced very well by the model, as shown in Fig. 6. The model tends to overestimate the reduction in the 90'th percentile, largely due to an overestimation of the 90'th percentile in the reference year (Fig. 6). As with RV4 the modelled change has also been separated into the traffic and meteorology related impacts, Equations (2) and (3). We see that the change in traffic conditions is the major cause of the concentration reductions, particularly since 2010 when the studded tyre ban was first introduced, and that meteorological conditions in the last three years have tended to enhance the concentrations. For the year 2010, when the studded tyre ban was introduced, we see that meteorological conditions helped in reducing concentrations. The impact of meteorology on the mean concentrations covers a range of around 40% (−12% to +28% compared to the reference year).

In Fig. 10 the individual contributions from both the traffic and meteorological changes, described in Section 5.2, are shown. The reduction in studded tyre share and traffic volume, since the introduction of the ban in Hornsgatan, are the major contributors to the concentration reductions seen. There was little change in vehicle speed during this period and the reduction due to exhaust emissions, both through reduced traffic volume and reduced emission factors, is very small. The results also show that the impact of meteorology on the concentrations is affected by both the dispersion conditions as well as the surface conditions.

The reference year of 2007 was the driest and warmest year in the eight year period (Table 4). As a result the other years, with wetter and colder conditions, see a reduction of emissions due to the surface conditions. The impact of dispersion, on the other hand, is not supported by the meteorological input data. Though the average wind speed was highest in 2007 and 2011, leading to improved dispersion conditions, the variability of average wind speed alone (~10%) cannot explain the large differences in dispersion. It is suspected that poor dispersion conditions after 2010 are due to errors in the NO_X emission factor trends used to determine these dispersion conditions. This means that NO_X emission factors for Hornsgatan were either too low from 2010 onwards or too high prior to 2010, or a combination of both. These emission factors, based on the HBEFA emission model (HBEFA, 2015) may require revision but are considered to be the best estimates available.

6. Discussion and conclusion

In this paper we have assessed the performance of the NORTRIP road dust emission model in reproducing the observed changes in net PM_{10} concentrations resulting from changes in traffic and meteorological conditions. Two roads, one in Oslo (RV4) and one in Stockholm (Hornsgatan) have been studied over a three and eight year period respectively. The aim was to see if the NORTRIP model correctly predicted changes in observed concentrations that resulted from traffic abatement measures, intended to reduce the emissions of non-exhaust particles. The model calculations were analysed in order to proportion the impact of four traffic characteristics (traffic volume, traffic speed, studded tyre share and exhaust emissions) as well as four meteorologically related characteristics (road surface conditions, dispersion conditions, salt emissions and sand emissions).

In this study we have focused on the net concentration contributions from single roads, looking at the net mean and the net 90'th percentile daily mean concentrations. For both RV4 and Hornsgatan the urban background contributes significantly, from 30% to 50%, of the total measured kerbside concentrations for PM_{10}. As such we have not addressed the issue of whether a particular measure will bring concentrations below a specified limit value. Instead we have focused on validating the model for any further use in such applications.

A methodology was described whereby the different contributing factors to the inter-annual changes in PM_{10} concentrations could be analysed. For traffic related changes this was based on the linear nature of the model process descriptions for traffic volume, traffic speed and studded tyre share. Estimating the impact of meteorology is less straight forward and the model itself is used to predict this by calculating the differences between all meteorological years using a single reference traffic year. Using this method it was possible to separate the meteorological impact between surface conditions, dispersion conditions, salt emissions and sand emissions.

The results show that the model reproduces very well the observed trends in both net mean and 90'th percentile daily net mean concentrations for both sites and the years studied. Analysis of the different causes of the changes shows that PM_{10} concentrations are affected by both traffic and meteorological conditions. For example in the year that the studded tyre ban was introduced on Hornsgatan (2010), the impact of the studded tyre ban for that year is estimated to decrease concentrations by 42% but the model also predicts that meteorological conditions additionally reduced mean concentrations slightly for that year by 8%, enhancing the impact of the ban. As a result the model correctly predicts the observed change in the net mean concentrations, relative to the reference year 2007, to be −47%. For the years following the ban (2011–2014) meteorological conditions have tended to reduce the impact of the ban by enhancing concentrations by 3%–29%. The impact of the ban itself not only reduced studded tyre share by 62% but also reduced the traffic volume by 25%. These two factors alone should result in reduced road wear of 72% which has led to an observed and modelled net concentration reduction of ~50% averaged over the last four years.

On Hornsgatan the eight month analysis period sufficiently covered the studded tyre season. The change in concentrations caused by meteorological conditions is calculated to range from −12% to +28% when compared to the reference year of 2007. This total range of 40% is almost as large as the impact of reducing the studded tyre share by half on Hornsgatan, indicating the significance of meteorology in determining road dust concentrations. For Hornsgatan the dispersion conditions were slightly more significant than the surface conditions in affecting the mean concentrations. However, since dispersion conditions have been calculated using NO_X as a tracer it is possible that errors in NO_X emission factors have influenced the dispersion estimates.

For RV4 both speed and studded tyre share reduction dominated the impact of traffic on emissions. In 2005, after the speed reduction measure was implemented, the total impact on PM_{10} emissions due to the change in traffic conditions was estimated to be −38%. However, meteorological conditions related to the drier surface for this year enhanced the total emissions so that the modelled and observed change in PM_{10} net concentrations was only −30%. In 2006 traffic conditions were similar to 2005 but the surface was much wetter and this led to a change in emissions, due solely to surface conditions, of −42%. The observed changes in the net PM_{10} concentrations were correctly modelled for both years.

Uncertainties and sensitivities of the model have been discussed in Denby et al. (2013b). It was concluded from that paper that the model had an absolute uncertainty of approximately ±15% for mean concentrations and ±19% for the 90'th percentile concentrations. In this study we find a RMSE of the mean concentrations for all the years modelled to be 7%. For the 90'th percentile this error is around 17%. The sensitivity to meteorological changes is partially the result of the surface conditions and though it is difficult to estimate the uncertainty of this we note that for Hornsgatan, where observed surface moisture conditions are available, the average frequency of modelled wet road conditions is 53.8% compared to the observations of 54.1% (Table 4). The number of correctly predicted wet and dry road conditions by the model is 83%, similar to the results found earlier in Denby et al. (2013b) of 85%.

The results presented here confirm that the NORTRIP model is capable of correctly modelling the impact of changes in traffic volume, traffic speed, studded tyre share and meteorological conditions on PM_{10} emissions and concentrations. This provides a significant step forward in non-exhaust emission modelling, making the model suitable for the assessment of measures prior to their implementation, in order to make effective decisions concerning their implementation. Other measures, such as cleaning and dust binding, have not been addressed in this paper but these will be the subject of further studies.

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