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NordFoU

NordFoU
NorDust

Nordic road dust project

Project
NORDUST – Nordic Road Dust Project

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Project manager
Karl-Idar Gjerstad, Statens vegvesen

Financial partners
Statens vegvesen, Trafikverket, Liikennevirasto, Vegagerdin

Members of the project group
Mats Gustafsson, Göran Blomqvist, Bruce Denby, Max Elmgren, Henrik Grythe, Sara Janhäll, Ida Järlskog, Christer Johansson, Sami Kulovuori, Kaarle Kupiainen, Joacim Lundberg, Aleksi Malinen, Michael Norman, Roosa Ritola, Sanna Silvergren, Ana Stojiljkovic, Ingrid Sundvor, Þröstur Þorsteinsson, Martina Stefani, Matthias Vogt

Scientific partners
VTI, Metropolia, Nordic Envicon Oy, SYKE, SLB-analys, NILU, Met Norway, University of Iceland

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Road dust is an important contributor to airborne particle pollution, especially in the Nordic countries where high road surface wear, due to studded tyre use as well as winter maintenance and operations including sanding and salting are important contributors. Even though the road dust problems are similar, the countries have tackled different parts of the problem with different research approaches, resulting in a complex knowledgebase in need of compilation. A former project, NORTRIP, started this work and implemented the knowledge into an emission model with a specially elaborated road dust focus. The model work has been used to identify knowledge gaps, intended to be filled within the NorDust project. Laboratory tests and controlled and uncontrolled field measurements as well as parametrisation and modelling has been used as tools to find, describe and implement issues concerning road dust formation, suspension and dynamics and road operation effects on emissions in facilities and sites in Finland and Sweden. The NORTRIP model has been implemented and evaluated in Iceland, not previously involved in the model development, to identify input data needs. The project has resulted in an array of findings, of which some have been possible to implement in new parametrisations in the NORTRIP model. In the complex research area of road dust dynamics, the project has also resulted in a lot of practical experiences concerning experimental and measurement designs and evaluation possibilities that future research will be able to benefit from.

Keywords road dust, PM10, NORTRIP, emission, modelling, sweeping, dust binding, road operation, traction sand, air quality, studded tyres

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Content

Background

Emission of wear particles and road dust is an air quality issue especially in the Nordic countries, where studded tyres and traction sand is used in winter, both being strong sources to road dust. Concentration of inhalable particles in our ambient air is negatively affecting public health (Thompson, 2018, Shaughnessy et al., 2015, Kampa and Castanas, 2008, de Kok et al., 2006, Kappos et al., 2004, Schwartz et al., 1999). Road traffic exhaust particles have strong effects, but their emissions are regulated and decreasing due to EURO standards and a strong global political ambition to move towards non-fossil fuels. Wear particles are, on the other hand not regulated and the emissions will grow with growing road traffic (Amato et al., 2014, Denier van der Gon et al., 2012). Electrical cars will increase wear of pavements and tyres due to higher weight and torque (Timmers and Achten, 2016). Studies on the coarser fractions associated with wear processes show that these are related to effects on e.g. airway diseases and acute mortality (Forsberg et al., 2005, Meister et al., 2012). While the emissions are not regulated for wear particles and road dust, the ambient concentrations of PM10 are subject to regulations through the EU air quality directive (European Council, 2008), measures must be taken to reduce the concentrations.

To reduce emissions of wear particles and road dust, national efforts have been made in the Nordic countries concerning use of studded tyres, more wear resistant pavement, traffic measures and better road operation. To support these efforts with knowledge, quite a lot of research has followed. Work has been done regarding emissions and properties of particle from studded tyres and pavement wear as well as from winter traction sand (Gustafsson et al., 2009, Gustafsson et al., 2019b, Räisänen et al., 2003, Räisänen et al., 2005, Kupiainen et al., 2016, Kupiainen and Tervahattu, 2004, Kupiainen et al., 2003, Kupiainen et al., 2005, Snilsberg, 2008, Aksnes, 2009). Health studies have been performed to investigate the toxicology of road dust (Karlsson et al., 2011, Lindbom et al., 2006, Hetland et al., 2000, Hetland et al., 2001, Karlsson et al., 2006, Schwarze et al., 2002, Øvrevik et al., 2005, Øvrevik et al., 2008) as well as studies on mitigation measures connected to road operation (Tervahattu et al., 2007, Männikkö et al., 2014, Gustafsson et al., 2019a, Gustafsson et al., 2019c).

Despite the common nature of air quality problems in the Nordic countries, only limited research collaboration has been done. This, together with the complexity of road dust emissions and the strong need to handle these emissions in Nordic air quality modelling, initiated the NORTRIP project (Johansson et al., 2012), starting to combine the knowledge and experiences from Nordic road dust research into a comprehensive, physically based emission model, later also called the NORTRIP model (Denby et al., 2013a, Denby et al., 2013b, Johansson et al., 2012, Norman et al., 2016). Based on the needs for improvements in physical understanding of processes in and better parametrisation of the model, identified in the NORTRIP collaboration, the NorDust project was proposed as a common Nordic research project to NordFoU.

Aim

The aims of the NorDust project are to bring together Nordic expertise in the area of road dust and to, further develop understanding and emission modelling of road dust emission processes and its impact on the concentrations of PM_{10} and $PM_{2.5}$ in ambient air.

Methods

Field tests

Test site descriptions

Tyre testing track

Tyre tests are conducted in the street called Vanha Porvoontie located in the city of Vantaa in southern Finland (60°17′40″N 025°02′25″E, Figure 1). Vanha Porvoontie is a two-lane street with estimated average annual daily traffic of 11000 vehicles and 60 km/h speed limit. The street segment used for the measurements is divided into two sections for the data processing purpose. Approximate lengths of the sections is 700 m and 1000 m.

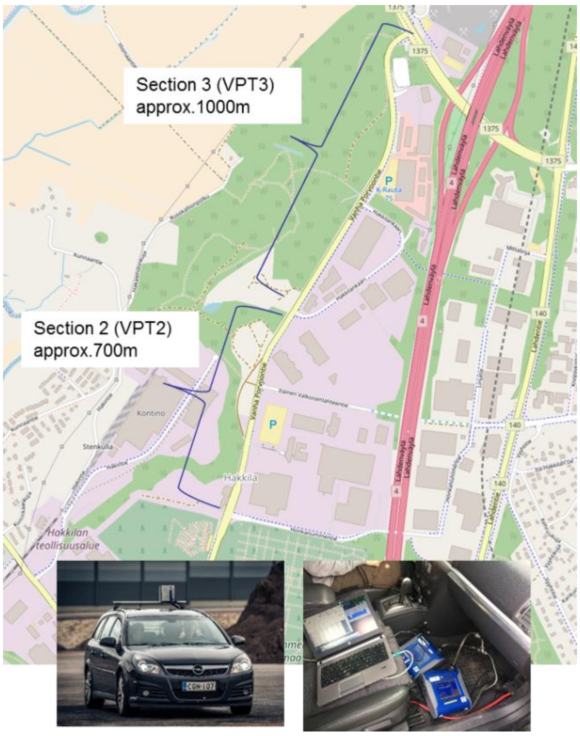


Figure 1. Vanha Porvoontie segment used for the on-road measurements of tyres with the Vectra vehicles

Vantaa

Test site located at Koisotie in the city of Vantaa is a collection depot for snow and other debris material collected from the streets. It is used by the city of Vantaa and their road maintenance contractors. Snowmelt is collected and drained out from the field on the south end; however, small water pond exists in the area year-round. The O-track and two I-tracks were defined in the field as illustrated in Figure 2. The I-tracks were positioned in such a way that allowed measurement vehicles to gain desired speed before entering the tracks. For the data processing purpose, O-track was divided into sections (S1, S2, S3, C1 and C2).

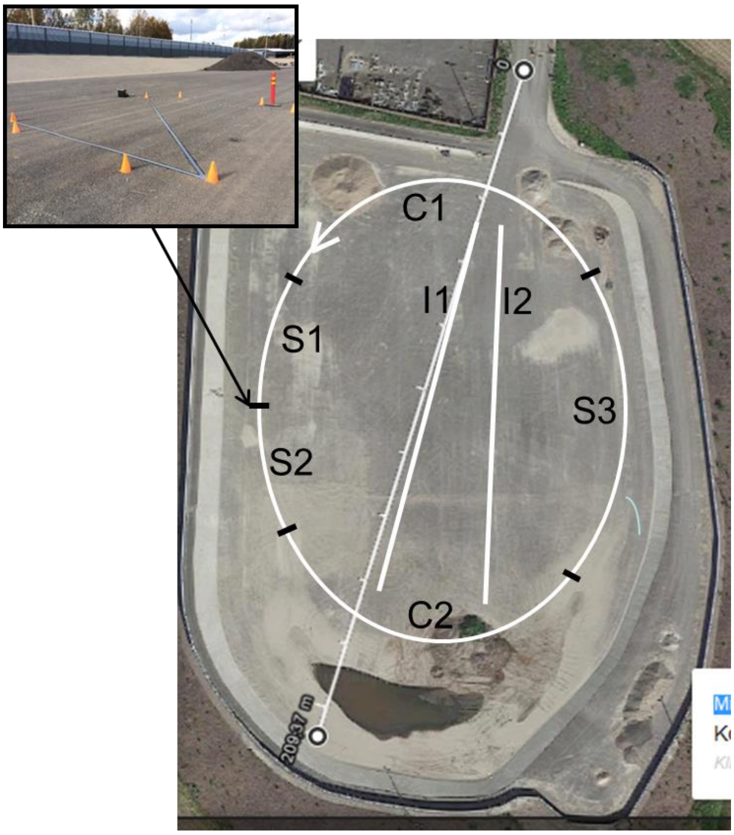


Figure 2. Test field in Koisotie, Vantaa with illustration of the test tracks.

Stockholm

Stockholm is situated close to the Swedish Baltic coast where the lake Mälaren connects to the Baltic sea (59°19′46″N 18°4′7″E). It has a humid continental climate with distinct seasons, including cold, snowy periods in winter. The number of inhabitants is about 950 000 (Stockholms stad, 2017).
In the central city, road dust and mobile suspension measurements were made on three streets with air quality monitoring stations in the Stockholm city centre (Figure 3), in the Södra länken tunnel and at an air quality site on the highway E18, north of the city centre (Figure 3).

Figure 3. Streets and measurement sites used for investigations in NorDust in Stockholm, Sweden.

Measurement techniques and methods

Sniffer

Sniffer vehicle (Volkswagen LT35 diesel van) is a unique high-technology research laboratory for air quality measurements. It provides measurements of traffic exhaust emissions under real driving conditions and measurement of non-exhaust particles (Pirjola et al., 2004; 2009; 2010). Dust sample is collected through a conical inlet at 5 cm distance from the left rear tyre. Background PM10 is measured above the front bumper.

The PM2.5 and PM10 mass concentration are monitored by two TEOMs, (Tapered Element Oscillating Microbalance; series 1400A, Rupprecht & Patashnick and Thermo Scientific Teom 1405-D), with time resolution of 10 seconds. PM10 is also monitored from bumper and behind rear tire by two DustTraks (TSI, model 8530), with a resolution time of 1 second. Additionally, size distribution of dust is measured by OPS (TSI, model3330). A weather station on the roof of the van at a height of 2.9 m above the ground level provides meteorological parameters (wind speed, wind direction, temperature, relative humidity), and a global positioning system saves the van’s speed and the driving route.

Figure 4. Sniffer vehicle

Vectra

Opel Vectra passenger car (Figure 5) is a mobile laboratory designed to measure resuspended PM10 emission from behind the tyre during operation. It is based on the TRAKER (Testing Re-entrained Aerosol Kinetic Emissions from streets) method developed in USA (Etyemezian et al., 2003). Suspended dust is collected at 5 cm distance from the left front tyre. Background PM10 is measured in front of the front bumper. PM10 concentration is monitored by two DustTraks (TSI, model 8530), with a resolution time of 1 second. Global positioning system is used for saving the information about the car's speed and route.

Figure 5 Vectra vehicle

Stationary air quality measurements

SLB-analys is responsible for the air quality monitoring in the City of Stockholm. That includes stationary measurement sites for PM10 monitoring in the city centre with five in street canyons and one urban background site placed on a roof 24 m above street level. Three of the street sites, Hornsgatan, Folkungagatan and Fleminggatan (Figure 3) were used in this study. For PM10, automatic instruments tapered element oscillating microbalance TEOM 1400ab, (Rupprecht and Pataschnik). At Hornsgatan and Sveavägen the TEOMs were equipped with both PM10- and PM2.5-inlets and a two electrical ball-valves were used to automatically switch between the two inlets. NOx is monitored with Chemiluminescence analysers (Environment AC32 M). In addition, Hornsgatan and the urban background station Torkel Knutssonsgatan was equipped with GRIMM EDM 180 which measures PM10, PM2.5 as well as coarse size distribution in 32-channels between 0.25 and 32 µm diameter. The measurement station at Hornsgatan is described in more detail in Gidhagen et al., (2004).

In the Södra länken road tunnel were two TEOM used for continuous PM10 monitoring.

At E18 test site in Danderyd were two sites placed on each side of the highway. The stations were equipped with GRIMM EDM 180 for PM-monitoring and Environment AC32 M for NOx monitoring.

Wet Dust Sampler

Road dust load was sampled using the VTI Wet Dust Sampler (WDS), which is a sampler using high pressurized water to clean a small circular road surface area during a specified time and compressed air to move the sample from the washing unit to a sample bottle. Each washing is referred to as a “shot”. The washing unit uses a spray nozzle with a filled cone spray pattern to thoroughly clean the surface (Figure 6). The sample is sieved at 180 µm, filtered and burned to determine the inorganic (and organic) dust load on the road surface. The data is given as DL180, meaning dust load smaller than 180 µm. Subsamples are often taken out for size distribution analyses and for filtrate analyses. The dust can also be analysed for chemical content after filtering.

Figure 6. The VTI Wet Dust Sampler equipment (WDS). Photo: Mats Gustafsson, VTI.

The WDS has been used in several Swedish national research projects, mainly for investigating the influence on different street and road operation measures against road dust emissions (Gustafsson et al., 2017; Gustafsson et al., 2014, 2015; Gustafsson et al., 2016; Gustafsson et al., 2012; Gustafsson et al., 2011; Janhäll et al., 2016; Järlskog et al., 2017), and is also used in Finland and Norway.

Traffic measurements at Vantaa

Traffic was created by five personal cars plus an instrumented car, Vectra (described above), running counter-clockwise from north to south. At the first round and during the meandering test, the Vectra car was used as the only car. Before entering the WDS sampling sections a coaxial cable-based traffic registration installation was mounted on the road surface. The equipment samples a range of data making it possible to identify each car and its speed, lateral position, length and width (Figure 7).

Figure 7. Coaxial cable-based traffic measurement installation on O-track. Photo: Mats Gustafsson, VTI.

During the test days, a total of 1816 passages were made during 8 periods between WDS-sampling (see Figure 8). The most important parameters for suspension are speed and lateral position. These are plotted for all rounds in Figure 8. Normally, the drivers focused on keeping a consistent wheel track, but during Round 5, an experiment with meandering of the traffic was conducted, why there are a higher number of outliers in this data.

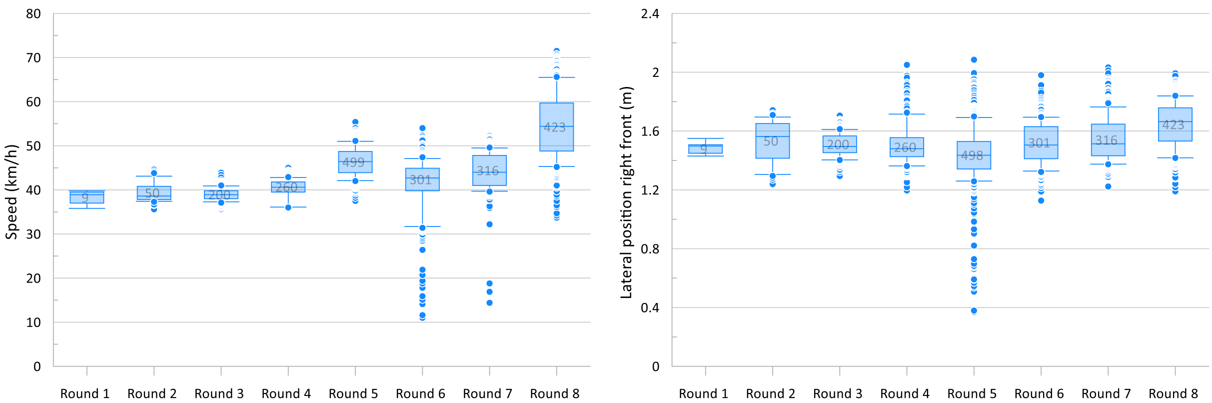


Figure 8. Speed and lateral position box plots for all traffic rounds (number off passages in the boxes). Box plots show median, first and third quartile and wiskers 10th and 90th percentiles.

Tests performed at testing track

On-road measurements of winter tyres using the Vectra instrumented car are performed at the testing track. Eight studded winter tyres with different number of studs and stud protrusion were tested (Table 1). All tested tyres were driven from 200 to 250km before the test.

Measurements were performed in the low “summertime” suspension emission level to ensure that emission caused by studs will be detected. Previous studies (EU LIFE+, 2014) demonstrated that under high suspension conditions no significant difference is detected between tyres. Reference, non-studded winter tyre was used to indicate suspension level and changes in the surface conditions during the test days. Reference tyre was measured before and after the winter tyre set. Target speed of the measurement vehicle during the tests was 50 km/h. On-road measurements were conducted in 2016 and 2017.

Table 1 Tested tyres in on-road measurements at the test truck.

Tyre	Number of studs	Manufactured	Stud protrusion before the tests *)
Nokia Hakkapeliitta 8	190	W24/2016	0.5825 mm
Bridgestone Noranza 001	190	W17/2016	0.685 mm
Continental Ice Contact 2	190	W37/2015	0.805 mm
Hankook Winter I*Pike RS	170	W19/2016	1.1025 mm
Pirelli Ice Zero	130	W33/2014	0.8725 mm
Nokia Hakkapeliitta 7	128		0.73 mm
Michelin X ice North 3	96	W11/2016	0.45 mm
Goodyear Ultra Grip**)	130	W18/2013	0.873 mm

*) average of 20 studs
**) tested only in 2017

Tests performed during Vantaa campaign

Road dust suspension experiment

On the O-track, along the western part, three WDS sampling sections (A, B, C) where defined on the track. The A section was not disturbed and dusty, sections B and C were brushed both by machine and by hand to even out the dust load. Section C was visually dustier than section B. Cones were placed three meters apart to steer the traffic in a similar way to create obvious wheel tracks (Figure 9).

Figure 9. Dust suspension test area. Photo: Mats Gustafsson, VTI.

WDS was used to sample the road dust load in transects across the sections every 20 cm. The turbidity of each sample was measured as an indicative measure for dust content. Six samples were identified to be sampled in the left and right wheel tracks. These were combined into one sample for dust load in wheel track analyses by filtering. Six samples in between wheel tracks were combined to form a sample representing that area.

Figure 10. WDS samples in profiles across the ”driving lane”.

A total of nine measurements were performed, with three profiles each (section A, B and C). Table 2shows how traffic and WDS-measurements where performed.

The suspension tests were performed by the instrumented Vectra car, which were one of the vehicles used during the traffic rounds. At the first round and during the meandering test, it was used as the only car.

Table 2. Traffic and WDS-sampling during the Vantaa campaign.

Date	Traffic round	Traffic (pas-sages)	Mean speed (km/h)	WDS-measurement	Note
2016-09-26				A1, B1, C1	Before any traffic
	1	10	38		only Vectra
				A2, B2, C2	
	2	50	39		All cars
2016-09-27				A3, B3, C3	
	3	200	39		All cars
				A4, B4, C4	
	4	20	41		only Vectra
	4	240	40		All cars
				A5, B5, C5	
	5	5	42		only Vectra, before meandering test
	5	15	41		only Vectra, mean-dering test
	5	200	45		All cars
	5	280	48		All cars
2016-09-28				A6, B6, C6	
	6	10	31		
	6	60	43		All cars, light drizzle
	6	120	39		All cars
				A7, B7, C7	
2016-09-29					Wet surface
	7	200	44		All cars
				A8, B8, C8	
2016-09-30	8	200	49		All cars, wet surface
	8	206	60		All cars
				A9, B9, C9	

Air quality measurements

The purpose of the measurements was to collect more data of road dust (PM10) generated from road, breaks and tire wear, to be able to better simulate PM10 air pollution concentrations in model calculations using for example the NORTRIP model. Measurements were performed using Lighthouse measuring devices (Lighthouse Handheld 3016-IAQ), which are hand-held airborne particle counters measuring the number of particles in different size channels (0.3 micron to 10 micron) of simultaneous counting (Figure 11). They display cumulative and differential particle count data ($PM_{0.5}$ to PM10 and TPM) that can be downloaded to a computer for further data processing. In the Vantaa campaign only PM10 was used for the analysis since this is the dominant size fraction of particles generated from road, breaks and tire wear. The Lighthouse devices also measure temperature and relative humidity. The particle density was manually set to represent the density of road dust. All PM10 values presented in the Result part are corrected from parallel measurements with TEOM in Stockholm. The time resolution of measurement was 2 seconds. Four Lighthouse devices were used (called L1, L2, L3 and L4) measuring PM10 concentrations during the Vantaa campaign period. A meteorology station was mounted to keep track on wind, temperature and humidity. For practical reasons, the placement had to be done in a placement with slightly different wind conditions than the measurement place (Figure 11).

Figure 11. The Lighthouse instruments used for measuring PM10 during the Vantaa campaign (left) and meteorology station (right).

Three different places were used for the air measurements during the campaign trying to get the most favourable dependent on wind direction. For best results the wind should be perpendicular to the roadway for upwind and downwind measurements. Trying to find the most favourable position for this the measurement setup was moved between three different places. It was also a question of cooperation with the other measurements performed during the campaign.

Two posts were placed on each side of the roadway. On the upwind side one Lighthouse device was fixed on the post 1.8 meters above ground level. On the downwind side three Lighthouse devices were fixed on three different heights of the post, illustrated in Figure 12. The heights of the Lighthouse devices were held constant both upwind and downwind moving between the three different measurement sites. The distance between the posts and the roadway was 2.85 meters on both sides. The road width between the orange cones was 3.2 meters.

Measurements were performed at different heights downwind to be able to determine the spread of the air pollution plume caused by the vehicles passing. The theory behind this measuring setup is that as long as the wind is coming from the upwind side the contribution of PM10 caused by passing vehicles will only give rise to higher concentrations on the downwind side. In the same way, the upwind side measurement will only show the background concentration. The difference in PM10 concentration between upwind and downwind measurements will represent the air pollution contribution caused by the passing vehicle (i.e. the emissions of PM10 from that particular vehicle). Using this setup, the emission factor per vehicle pass could be calculated. By subtract the PM10 levels measured on the upwind side from the levels on the downwind side the concentration of PM10 generated by each passing vehicle can be determined. This procedure with an upwind/downwind technique has previously been used by other investigators (e.g. Gillies et al., 1999; Cowherd, 1999; Etyemezian et. al., 2002).

Unfortunately, the wind was never perpendicular to the measurement setup so the intended method described above could never be used. As presented later in the Result part the passing vehicles gave rise to increased concentrations at both upwind and downwind side, sometimes even higher peaks were measured on the upwind side than the downwind side. This in discussed more in the Result part.

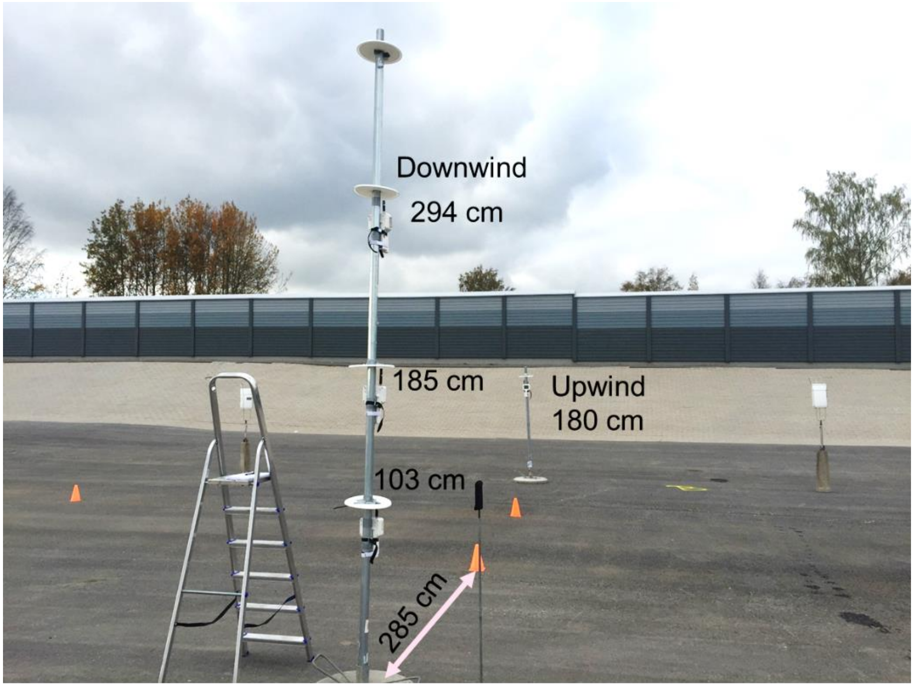


Figure 12. Heights for upwind and downwind placement of the Lighthouse devices.

Simulations of running traffic was performed by driving cars on an oval track (O-track) summing up between 20 and 100 passages per set. At site 1 and 3 (different places on the O-track) the vehicles were passing the measurement setup either on a straight or a curved place of the road (Figure 13). At site 2 (the I-track) all vehicles drove on a 100-meter straight road passing the measurement setup (Figure 14). Each vehicle passing by the measurement setup generated an air pollution plume and road dust (PM10) in that plume was measured by the four Lighthouse devices. The cars drove either in the wheel tracks or off the wheel tracks. All passages and the position on the road (in or off wheel tracks) were documented.

Figure 13. Measurement setup at site 1, driving O-track, passing the measurement setup where the road was straight.

Figure 14. Measurement setup at site 2 driving I-track.

Figure 15. Measurement setup at site 3, driving O-track, passing the measurement setup where the road was curved. At this site the Sniffer, measuring PM10 with a TEOM, was standing at the same place as the measurement setup

Crushing experiment

To investigate how the size distribution of sand used for traction control is affected by the passage of unstudded and studded winter tyres a known amount of traction sand was evenly distributed over a defined surface area on an asphalt surface. The area was enclosed by bricks on three sides to prevent the sand from leaving the area. Two tests were performed (with unstudded and studded tyres) in which one car were used to crush the sand by repeated slow overrunning (Figure 16). The size distribution of the original material was determined. After 120, 240 and 360 passages, samples were brushed from a square in the wheel track and the underlying surface sampled using WDS. Amounts and size distributions of the material was determined using both sieving and laser granulometer (Mastersizer 2000).

Figure 16. Brick-enclosed area for crushing test.

Cleaning experiment

The aim of the cleaning experiment was to evaluate the efficiency of street cleaning in reducing PM10 emission. The experiment was conducted on the I-tracks. Two machines were tested side-by-side: PIMU (Scrubber with Captive Hydrology) and CityCat 5006 (compact sweeper). The instrumented Vectra car was used to monitor change in suspension emission. Initial emission level was measured one day before the treatment. The post-treatment emission levels were measurements within the cleaned area of the I-tracks and outside of the cleaned area (Figure 17 and Figure 18). Table 3 shows timing of the measurement rounds and number of Vectra passages. Target speed for the measurements was 40 km/h. Cleaning effect was also evaluated using WDS measurements. Two profiles on separate parts of the tracks were sampled before and after cleaning.

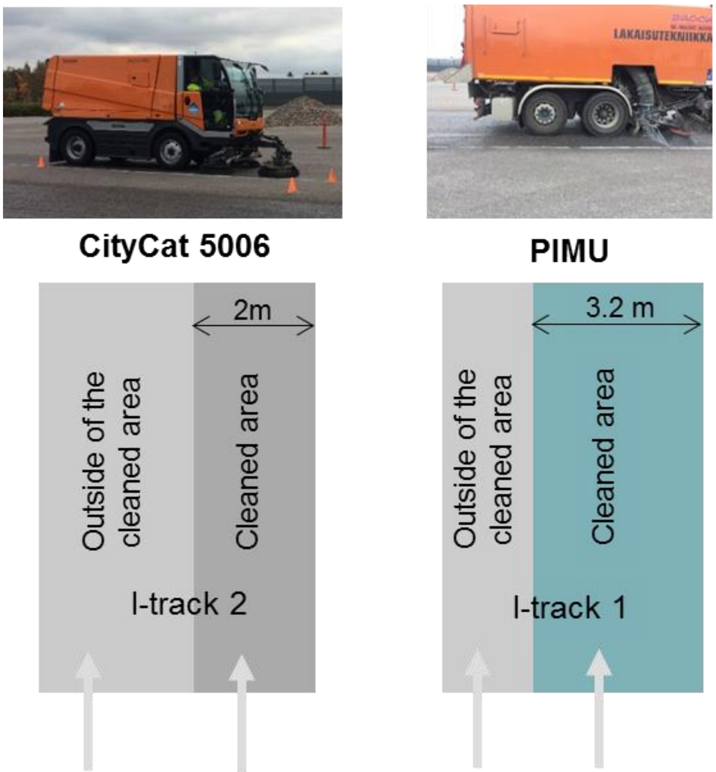


Figure 17. Street cleaning machines used for the cleaning experiment and illustration of the cleaned areas on the I-tracks 1 and the I-tracks 2. Grey arrows indicate approximate positioning of the front left tyre of the Vectra car during the measurements in cleaned and outside the cleaned area.

Table 3. The timeline for the cleaning experiment

Action	Timing	Number of passages	Purpose
1st measurement	26.9. at 17h	10	Pre-treatment level
Cleaning	27.9. at 12h		
2nd measurement	27.9. at 14h	5 (cleaned area) 5 (outside cleaned area)	1st after treatment level on the same day
3rd measurement	27.9. at 16h	5 (cleaned area) 5 (outside cleaned area)	2st after treatment level on the same day
4rt measurement	28.9. at 16h	5 (cleaned area) 5 (outside cleaned area)	3rd after treatment level on the next day

Figure 18. Wet marks on I-tracks after the cleaning.

Sanding experiment

The sanding experiment was conducted on I-track1 one day after the cleaning experiment. The aim was to demonstrate impact of sanding on the PM10 emissions. Crushed stone aggregate sieved into grain size fraction of 1-5mm was applied on the south half of the I-track. Mass of applied sand was 150g/m^2.

Figure 19. Sand application on the I-track1.

The initial PM10 emission level was measured by Vectra one hour before the treatment with 5 passages. Two follow-up measurements were done on the same day. During the 1st and 2nd follow-up measurement five cars, including Vectra, made 20 and 10 passages, respectively. Mean traffic speed was 30 km/h during the first measurement after the treatment, and 40 km/h during the second. The mean PM10 concertation measured by Vectra was calculated for the treated and non-treated part of the I-track1.

Tests performed during Stockholm campaign

E18 measurements

Mobile measurements of the PM10 emission were done by Sniffer and Vectra vehicles. Measurements took place on the morning following the WDS sampling at E18. The measurements were done with three different target speeds (50, 60 and 70km/h) on the bus lane towards south and right lane towards north. Southbound right and middle lane and northbound middle and left lane were driven with 70km/h speed. For the data processing purpose, measured segment of the E18 was divided into three sections of equal length (Figure 20).

Figure 20. Division of lanes on E18.

WDS-measurements were made in a transect across all three lanes in the northward direction of the road (Figure 21). Samples were taken every 20 cm in a 13,8 m long profile, in which turbidity was measured. Six-shot combined samples were also taken in the three left wheel tracks and the three between wheel tracks surfaces for filtration and DL180 calculation.

Figure 21. WDS sampling at E18.

Mobile tunnel measurements

Mobile tunnel measurements were conducted at Södra länken (Figure 22) with Sniffer. The aim was to investigate how tunnel is affecting to road dust emission and dust variation along the road surface on a highway. Green sections are inside a tunnel and blue sections are outside the tunnel. Sniffer made total of 4 rounds. Because there was maintenance work in the tunnel during night time, only one measurement was performed at Södra länken.

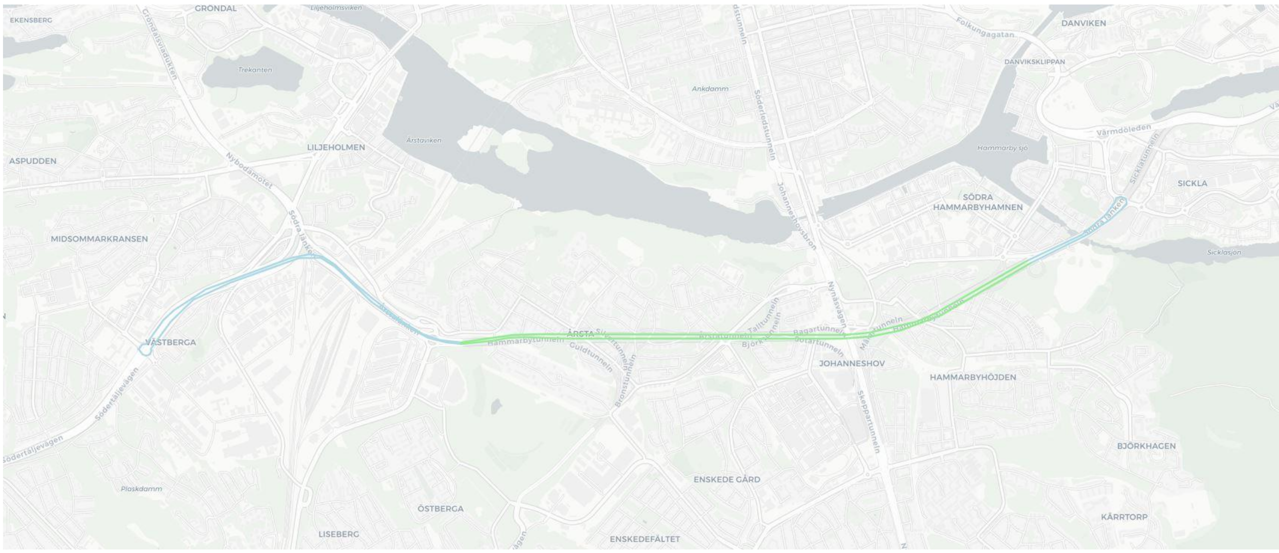


Figure 22. Södra länken measurement route

Mobile street measurements

Measurements with the Sniffer vehicle were conducted on specifically designed urban route to include four streets with air quality monitoring: Fleminggatan, Folkungagatan, Hornsgatan and Sveavägen. An overview of mobile street measurements is given in Table 3.
In each of the test streets Sniffer made from 2 to 6 passages during the measurement rounds. In order to investigate lateral variation of the suspension emission, passages were made on different lanes.

Table 3. Overview of the mobile street measurements

Date	Time	Street	Passages
4.4.	12:00	Fleminggatan	3
		Folkungagatan	2
		Hornsgatan	4
	22:00	Fleminggatan	4
5.4.	2:00	Sveavägen	2
		Fleminggatan	4
	12:00	Fleminggatan	2
		Folkungagatan	4
		Hornsgatan	5
		Sveavägen	1
	22:00	Fleminggatan	2
		Hornsgatan	4
		Sveavägen	6
6.4.		Fleminggatan	4
		Hornsgatan	4

Cleaning evaluations with WDS

Evaluation of the street cleaning was conducted on Fleminggatan and on Hornsgatan. The cleaning on Fleminggatan was conducted with a DisaClean vacuum sweeper and took place after midnight on April 5th, 2017. The mobile measurements of the PM10 emission using the Sniffer vehicle were done two times before the treatment and four times during the two days after the treatment. WDS measurements were made before and after street sweeping. Measurements were performed in profiles from the kerb over the cycle path and the first driving lane every 20th centimetre.

On Hornsgatan a combination of high-pressure water flushing and DisaClean vacuum sweeper was used at around 10-11 o'clock on 6th of April 2017 (Figure 23). Two flushing machines drove before and the vacuum sweeper followed behind. A similar method has previously shown good results on dust load in studies in Trondheim (Järlskog et al., 2017).

Figure 23. Flushing machine followed by a vacuum sweeper on Hornsgatan, 6th of April 2017.

Traffic dislocation test with WDS

To investigate if and how traffic reduces a known dust load, traffic on Hornsgatan was forced to move half a meter to the right by using movable traffic signs (Figure 24).

Figure 24. Traffic dislocation test, where road signs were used to push traffic slightly to the left in driving direction.

WDS comparison

During the project time, Nordic Envicon Oy acquired a WDS equipment (WDS III). During the campaign in Stockholm, measurements were made to compare the WDS II (VTI) to WDS III. Since no filtering laboratory resources were available at the time, focus was on comparing turbidity in profile samples. Comparisons were made on Fleminggatan. In first test, on 2017-04-05, samples were taken in one single profile every 25 cm, alternating between WDS II and III. In the second test, on 2017-04-07, six profiles were with 25 cm between samples in profiles and 20 cm between profiles along the street. All samples were analysed using the same type of turbidity meter (HI88713 ISO Turbidity Meter from Hanna Instruments) at VTI and Nordic Envicon Oy.

Laboratory studies

VTI road simulator study

The road simulator (Figure 25) consists of four wheels that run along a circular track with a diameter of 5.3 m. A separate motor is driving each wheel and the speed can be varied up to 70 km/h. The wheel axles have different lengths, positioning the wheels in different distances from the centre, and an ex-centric movement of the central vertical axis is used to slowly side shift the tyres over the full width of the track. Wheels on axles 1 and 3 are at the track edges, while wheels on axles 2 and 4 are running closer to the middle of the track. Any type of pavement can be applied to the simulator track and any type of tyre can be mounted on the axles. An internal air-cooling system in the hall is able to temperate the simulator hall to below 0°C.

Figure 25. The VTI road simulator. Photo: Mats Gustafsson, VTI.

A pavement ring, used for a previous wear test, including 14 different asphalt pavements of types stone mastic asphalt with different maximum aggregate sizes, SMA6, SMA8 and SMA11 with granodiorite rock, tested for texture development was used for the tests. The SMA pavement construction is wear resistant and commonly used in Nordic countries. The current rock quality and the smaller aggregate sizes (6 and 8 mm) are meant for use in Denmark, where no studded tyres are used. Smaller aggregate size makes the SMA less noisy than coarser aggregates.

Six studded tyre models were tested. The choices where made from the tyres tested using the instrumented test car Vectra on the testing track (see above), with varying number if studs. All tyres had the dimensions 205/55 R16.

Table 4. Tested tyres in the road simulator study

No	Tyre	Number of studs per tyre
1	Nokian Hakkapeliitta 8	189
2	Hankook Winter Pike	169
3	Bridgestone Noranza	190
4	Continental Conti ice 2	189
5	Michelin X ice North 3	96
6	Pirelli Ice Zero	130

For all analyses, a 15-minutes mean value of PM2.5, PM10 and number concentration at the end of each simulator run was used.

Regarding concentration of PM2.5 and PM10, two different techniques were used.

- *Tapered Element Oscillating Microbalance (TEOM)*
  The instrument is based on gravimetric technique using a microbalance. A value of mass concentration PM10 is given every 5 minutes. The method is certified for air quality standard monitoring within the EU.
- *DustTrak (DT)*
  Two of these optical instruments were used during the measurements; one measured mass concentration PM2.5 and the other PM10. The time resolution of the sampling was 3 s for both instruments.

Particle size distributions describe how airborne particles are distributed in size according to mass and number (volume and surface area is also a possibility, but not of interest in this study). The size distributions were measured using an APS (Aerodynamic Particle Sizer) model 3321 (TSI, USA) measuring mass distribution and an SMPS-system (Scanning Mobility Particle Sizer) model 3934 (TSI, USA) measuring number distribution. The SMPS-system was setup to measure and count particles from 7.37 nm to 311 nm. The APS was equipped with a PM10 inlet and hence, measured particles with aerodynamic diameter from 0.523 µm to 10 µm. Size distributions of particles measured with the SMPS system are presented as number size distributions and particles measured with the APS are presented as mass size distributions. This is because the fine fraction below 1 µm makes up very little of the mass but contain most of the particles while the coarser particles are very few but dominate the mass concentration.

When presenting data from APS and SMPS it is common to normalize the measured particle mass distribution. The normalization means that measured mass for a specific particle size range (=dM) is divided by the logarithm of the measured particles size interval = d log(dp) (often written as dlogDp). This means that mass distributions measured using instrument with different particle size intervals could easily be compared.

The conditions in the road simulator hall are drifting during a test day, due to frictional heat warming the pavement, tyres and air. To handle this, a test sequence where the same tyre set is run first and last on each test day was used. For five test days, with five test runs a day, a suggested sequence is shown in Table 5.

Table 5. Used test sequence in road simulator.

	Run1	Run2	Run3	Run4
Day 1	1	5	4	1
Day 2	2	6	4	2
Day 3	3	1	6	3
Day 4	4	6	1	4
Day 5	5	3	2	5

The test sequence is performed as follows:

1. Tyres are mounted (always the same tyres on the same rim and axle)
2. Cooler is turned off
3. Simulator is started and accelerated to 50 km/h.
4. After 1 hour, simulator is stopped.
5. Cooler and a large air filtering fan are started to reduce deposition and lower the PM10 concentration to initial level
6. Tyres are switched to next tyre set
7. When PM10 concentration reaches initial level (TEOM PM10), cooler and air filtering fan are turned off and simulator started for next test.

Tyre inflation pressure is checked between each test.

Statistical evaluation of road simulator data

Six studded winter tyres were compared regarding different measures of particle emissions. Some tyre properties are shown in Table 6.

Table 6. Properties of the tyres used in the study.

Tyre no.	Number of studs per tyre	Mean stud protrution (mm)	Mean stud force (N)	Mean stud mass (g)
1	189	1.31	177	0.80
2	169	1.59	202	0.85
3	190	1.29	190	0.86
4	189	1.51	191	0.73
5	96	1.41	209	0.88
6	130	1.19	245	0.95

Statistical analysis method for PM10, PM2.5 and number concentration

The choice of an experimental design depends on the details of the analysis and vice versa and need to be decided upon simultaneously. Here, we start by describing the statistical analysis procedure.

For each suggested analysis, emission data are assumed to consist of tyre effects, background behaviour and a random component. The main focus of this study is to compare tyres. Four analyses were used, where the difference between analyses is which of two approaches that should be used for tyre effects and which of two approaches that should be used for background behaviour. The background behaviour part of the model is needed because conditions in the road simulator hall that may have an influence on particle emissions are drifting during a test day. Though changes in the environment may not be of main importance when comparing tyres, they may coincide with the experimental design of the tyres and be falsely interpreted as tyre effects. By modelling the possibly uninteresting general behaviour, it is eliminated from the comparisons between tyres.

Main analysis (1st analysis)
In the main analysis, the tyre effects are modelled as constants that do not change between or within days and that sum to zero. The general behaviour is modelled as straight-line background behaviour during the days, one line for each day. General behaviour and tyre effects were analysed simultaneously with multiple linear regression and general linear models. Depending on the coding scheme for tyres, the tyre effects can be chosen to express differences between each of the tyres and an average of all tested tyres or differences between pairs of tyres. Both these coding schemes have been used in various parts of the following text.

Statistical analyses of tyre properties (2nd analysis)
In this second analysis, tyre effects are modelled as functions of tyre properties that are supposed to be able to explain the particle emissions such as number of studs and stud protrusion while the background is still modelled as one straight line for each day. Multiple linear regression was used for this analysis.

Comparing the two ways of analysing tyre effects
The first and second analysis use two different approaches to model tyre effects. In the main analysis, the tyre effects are simply a set of constants without any lower level structure. This may be the best approach when comparing tyres "as is". To understand what the tyre effects really consist of it is advantageous to, if possible, explain the differences between tyres as a function of important tyre properties. Practically, with the types of analyses performed in the current study the following questions can be addressed:

- First analysis–are there any differences between tyres if we are not looking for an explanation to such differences?

- Second analysis–are there any differences between tyres that can be explained by number of studs, stud protrusion etc?

It is not generally possible to combine the two approaches. Tyre effects cannot be explained both as constants and as function of tyre properties in the same analysis.

The second approach is preferred if the model fits good to the data. It does not only tell if there is a difference between tyres but also how that difference can be explained. The model is also smaller in the sense that fewer parameters are estimated. On the other hand, the model that fits best to the data is preferred. For any analysis, there should not exist important explanatory variables that are not in the model. It is simply a difficult task to choose between models if there is not one that is smallest, has best fit and have coefficients that make sense without any conflict with prior knowledge or assumptions.

Statistical analysis of background behaviour (3nd analysis)
In the main analysis, the general behaviour (or background behaviour) is modelled only as straight lines without any lower level structure. There may of course be situation where the effect of changes in temperature etc. is the main focus. In this third analysis, the background behaviour is modelled as a function of variables in the experimental environment that are supposed to be able to explain the particle emissions (humidity, road temperature etc.) that are also recorded during the experiment. That is the same change in approach for the experimental environment part of the model as was discussed above for the

tyre part. Multiple linear regression is used for this analysis. If the aim was to really find out how varying humidity, road temperature and tyre temperature can explain variation in particle emissions, the third analysis could be used but one should force these variables to vary during the experiment.

Statistical analyses of tyre properties and environment variables (4th analysis)
Though it is not generally possible to combine the two approaches, it is possible to choose one approach for the tyres part and one for the environment part of the model separately. The change in approach from first to second analysis and the change in approach from first to third can be used separately, as they have been discussed above, or combined. The 4th analysis is the last combination where both tyre effects and background is modelled as functions of their properties.

Comparing analyses.
The four models need to be compared in the same sense as was discussed in section NNN. Model comparisons are discussed further in section NNN.

Design of experiment
The six tyres were tested during five days with four runs per day. The design was planned to be optimal for pairwise comparisons of tyres in the main analysis. The differences between two tyres is expressed as a regression coefficient. For one design, there are 15 such comparisons. With these numbers, the design cannot be symmetric resulting in that all comparisons do not have the same standard error. We assume that the best plan is the one that has minimum value of the maximum standard error among all pairwise comparisons in the main analysis. The solution was to search for the most efficient design by scanning through a huge set of randomly generated possible designs. Preliminary results indicate that it is efficient to use the same tyre on the first and last run each day and the search algorithm was tuned to only scan through such designs. The procedure does not guarantee that we found the best design, but it has a high probability that the chosen design is the best or at least close to being the best (Table 7).

Table 7. . Chosen design for analyses.

	Run 1	Run 2	Run 3	Run 4
Day 1	1	5	4	1
Day 2	2	6	4	2
Day 3	3	1	6	3
Day 4	4	6	1	4
Day 5	5	3	2	5

The experiment is not designed to find the best estimates of the effects of changes in the environment variables (the 3d/4th analysis). In fact, the environment is controlled to keep air temperature close to constant which causes estimates of temperature effects to have low precision.

NORTRIP model development

One of the aims of the measurement campaigns was to provide improved data for describing a number of parameterisations in the NORTRIP road dust emission model. Several experiments were aimed at addressing the following processes:

1. Relating mobile measurement data to dust loading and emissions
2. Determining cleaning efficiencies and cleanable dust load
3. Sand crushing and lateral migration of sand
4. Size distribution of surface and ambient air road dust emissions
5. Relating surface texture to model processes

In addition, relevant data from earlier experiments, MORS2, were used to describe:

6. Wet removal of water and salt

Not all these experiments were successful in providing new parameterisations for NORTRIP.

Relating mobile measurement data to dust loading and emissions

Simultaneous measurements of dust loading and mobile PM concentrations are needed to determine the relationship between mobile suspension measurements (µg/m^3) using Sniffer/Vectra with surface dust loading (g/m^2) and eventually to the actual emissions (g/veh/km). This could be derived from the Vantaa campaign or other measurement campaigns, e.g. Stockholm, where both parameters are measured near simultaneously. A conversion factor can then be determined. Complications involve the fact that the mobile measurements only sample suspendible dust. This may be addressed by estimating the non-suspendible dust load, e.g. on streets this could be 10- 20 g/m^2 or at Vantaa this can be the apparent limit in the wheel tracks by the end of the experiment.

We make the conceptual model that the amount of suspendible dust DL_{sus} under traffic conditions is the difference between the 'between' wheel track (BWT) and the 'in' wheel track (WT) dust loading. In other words, all the suspendible dust in the wheel tracks has already been suspended.

$$DL_{sus} = DL_{BWT} - DL_{WT} \qquad (1)$$

This may be a good estimate for heavily trafficked roads but for the Vantaa campaign there was not enough traffic to totally remove all the suspendible dust in the wheel tracks.

Due to meandering a vehicle will spend a certain fraction of it's time on the edge or between the wheel tracks f_{BWT}. So the suspension from the passage of one wheel (S_{sus}) in g/m can be written as:

$$S_{sus} = f_{sus}\, f_{BWT}\, DL_{sus}\, W_{tyre} \qquad (2)$$

where f_{sus} is the fraction of suspendible dust that is suspended by the passage of one tyre and W_{tyre} is the width of the tyre. If the sniffer signal is directly and linearly related to the suspension S_{sus} then we can write

$$C_{sniffer} = k_{sniffer}\, f_{sus}\, f_{BWT}\, DL_{sus}\, W_{tyre} \qquad (3)$$

Where $k_{sniffer}$ is the proportionality constant in the relationship $C_{sniffer}=k_{sniffer} S_{sus}$. From previous experiments, and also from the Vantaa campaign, the factor f_{sus} is of the order of 0.01 – 0.001 veh^{-1}. For Vantaa the e-folding vehicle number is around 200 veh, 400 tyres in each wheel track, giving an $f_{sus} =0.0025\ tyre^{-1}$. This is typically the suspension rate for loose available dust in the wheel tracks. The time spent in the suspendible dust region f_{BWT} is not known but can be estimated from meandering information from real traffic situations and may be of the order of 0.1 to 0.01. The factor $k_{sniffer}$ is not known but we can try to derive this from the available data where road dust loading and Sniffer measurements have been performed simultaneously.

Cleaning efficiencies and cleanable dust load

An important question to be answered is the efficiency of cleaning methods since this is one of the few measures that can be implemented to reduce road dust loading. Frequent cleaning has been seen to have little impact on ambient air concentrations (Gustafsson et al., 2011)). It is also not known if cleaning efficiencies are different for different particle sizes. In the NORTRIP model a parameterisation is used to describe the size dependent cleaning efficiency but information is generally not available to quantify this. The aim then is to improve the cleaning efficiency parameters in the model for different particle sizes and different cleaning methods

Road dust load measurements in Stockholm show ambiguous results when it comes to cleaning (Gustafsson et al., 2019c). There appears to be a redistribution of dust but no clear reduction. However, other measurements in Trondheim (Janhäll et al., 2016, Snilsberg and Gryteselv, 2017), Finland (Kulovuori et al., 2019) and in controlled experiments (Gustafsson et al., 2011)have shown significant reductions of road dust after cleaning. One hypothesis is that when the road is very dusty then cleaning works (a lot of material is available for cleaning) but when it has recently been cleaned then the road dust is no longer available for cleaning anymore (Gustafsson et al., 2019b). Is there a minimum threshold before cleaning becomes effective? Is there a relationship between this and surface texture? Can cleaning efficiency be quantified as fractional removal or should it be an absolute value?

To quantify the cleaning efficiency as a function of size distribution then two measurements can be used. Road dust sampling with size distribution before and after cleaning and measurements of road dust collected in the cleaning trucks (total dust collected after a number of kilometres and size distribution). If measurements in trucks and on road are available at the same time, which they are not, then the difference in size distribution can provide a relative efficiency for size dependent cleaning efficiency. We will make use of before and after measurements using the WDS to provide information on cleaning efficiency and particle size dependence.

Sand crushing

Within NORTRIP an algorithm exists that simulates the crushing of sand (or other materials) by transferring a fraction of one particle size mass bin down to the next particle size mass bin. This algorithm requires the parameters that describe the mass transfer as a fraction of the larger size bin transferred per vehicle passage. Dependence on speed and vehicle type is also possible. At the moment this parameter is unknown so crushing experiments were carried out at Vantaa to provide a first estimate of these parameters. This experiment involved driving a vehicle backwards and forwards over a short but contained track covered with sand. The sand was sampled three times after 120 passes each using sweeping and the WDS. These samples were analysed for their size distribution and the difference between the samples was assessed.

PM2.5/PM10 ratio of surface and ambient air road dust emissions

Currently the NORTRIP model uses a fixed ratio of DL2.5/DL10=5% and DL10/DL180=28% for road dust wear. DL2.5/DL10 was based mainly on ambient air measurements after removal of the estimated exhaust contribution and DL10/DL180 was based on laboratory measurements in the road simulator (Snilsberg, 2008). However, previous measurements of in-situ road dust indicate this ratio to be higher for DL2.5/DL10 15-25% and for DL10/DL180 to be slightly lower on average but with a greater range of 5% – 40 %.

A range of measurements have been made in NORDUST including, Sniffer, Vectra, ambient air, road simulator ambient air and surface sampling allowing an assessment of the fractions PM2.5/PM10, DL2.5/DL10 and DL10/DL180. Samples taken before and after cleaning are also available on a variety of surfaces. We can analyse these results to see if it is possible to update the size ratios used in NORTRIP in a consistent manner.

Relating surface texture to model processes

Surface texture may be an important parameter for a number of processes. Prior to the campaigns the following questions were posed regarding surface texture: From all the measurements available, where surface texture has been measured, can we deduce anything that will relate surface texture to the processes of suspension, dust loading or wet removal? Do we have any measurements of dust loading that can relate surface texture to the non-suspendible portion of the road dust? Do we have sniffer measurements and dust loading measurements together with surface texture measurements? Do any of the road simulator results help?

Measurements of surface texture have been made during the campaigns, but these did not vary sufficiently in order to derive meaningful relationships. So, no usable data was found to determine these relationships. This then remains an open question for further analysis and has not been further addressed here.

NORTRIP implementation in Iceland

The NORTRIP model was applied for two different time periods, 2012 and 2016. During the data collection all necessary input data was either retrieved from the competent authorities or inferred or modelled starting from real measurements. The Icelandic authorities responsible for collecting the different data are listed in Table 8.

Table 8. Type of data collected at different Icelandic institutions.

Type of data	Institution	Website
Traffic data Activity data	Vegagerdin - The Icelandic Road Administration	road.is
Studded tyres count	City of Reykjavik	
Air quality data	Umhverfisstofnun - The Environmental Agency of Iceland (UST)	https://www.ust.is/einstaklingar/loftgaedi/maelingar/
Weather data	Vedurstofan - The Icelandic Meteorological Office (IMO)	en.vedur.is

The chosen road is at the intersection between Miklabraut and Grensasvegur. Miklabraut is one of the main streets leading into the town centre and the traffic volume is high, especially during the rush hours in the morning and late afternoon. Reykjavik lays on a peninsula, with the town centre towards the central part of it. The structure of the town is characterized by a strong suburban development and a division from residential and commercial areas leading to important daily traffic flows into the centre in the morning and out of the centre in the late afternoon. In addition to the suburban areas of Reykjavik itself, the traffic arises also from other municipalities such as Kopavogur, Mosfellsbaer, Gardabaer and Hafnarfjördur. According to the Reykjavik Municipal Plan 2010-2030 the use of private cars was 75% in 2011, public transportation is used by 4% of the population and 19% are pedestrians and cyclists (Hjaltason, 2014).

Figure 26 shows the road map of the Icelandic Road Administration and the location of the test area. It should be mentioned that within the City of Reykjavik, the communal roads are administered by the city itself, while the roads shown in Figure 26 are under the administration of the Icelandic Road Administration.

The road stretch is open and there are three lanes plus a dedicated bus lane in direction downtown (W) as well as one lane to turn left into Grensasvegur and one to turn right into Grensasvegur. Into the other direction, out of downtown (E), there is the same road configuration.

In addition of being one of the main roads towards the city centre and out, at the crossing between Miklabraut and Grensasvegur there is one air quality monitoring station run by the Environmental Agency. This is the most complete available air quality station close to traffic within the city of Reykjavik, there are several other mobile monitoring stations which change location according to the need of monitoring, run both from the city of Reykjavik and the Environmental Agency. Figure 27 shows an orthophoto of the test area and the location of the air quality station Grensasvegur (GRE).

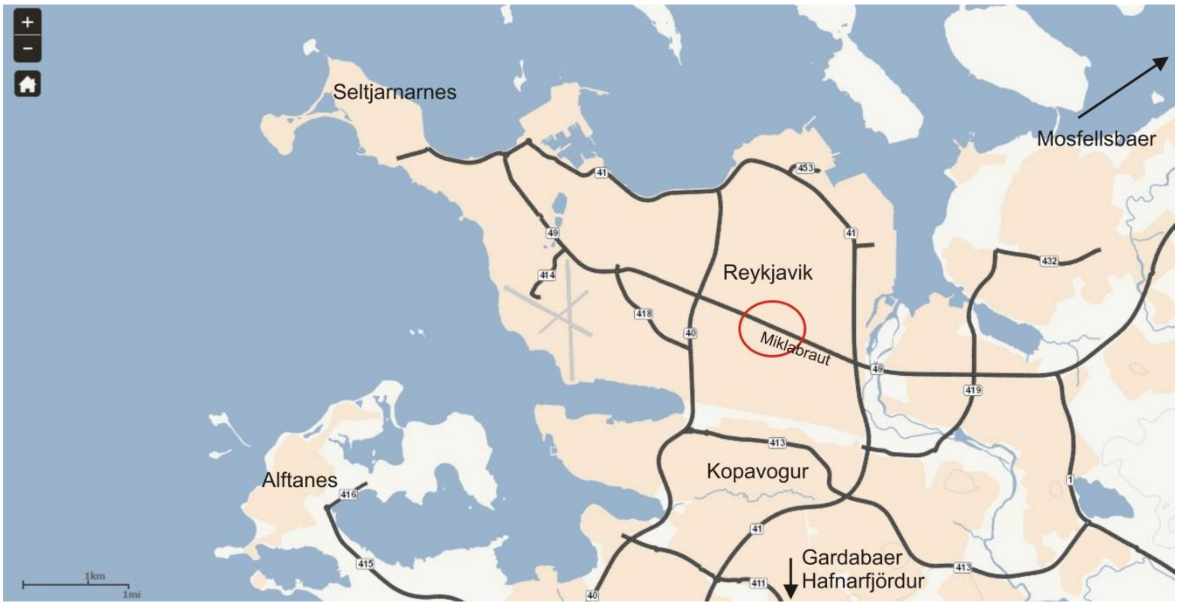


Figure 26. Road stretches (black) leading into Reykjavik and administered by the Icelandic Road Administration Seltjarnarnes, Kopavogur, Gardabaer, Hafnarfjördur and Mosfellsbaer are the surrounding municipalities. The red circle shows the location of the investigated road stretch at the crossing Miklabraut/ Grensasvegur. (modified from http://vegasja.vegagerdin.is/eng/).

Figure 27 The ortophoto shows the details of the surroundings of the investigated road stretch. Miklabraut has the number 49 according to the system of the Road Administration. In red the air quality measurement station GRE - Grensasvegur (modified from http://vegasja.vegagerdin.is/eng/).

The input data for the NORTRIP model are time series, hourly data regarding traffic, meteorology, activity in terms of salting, ploughing and cleaning and air quality. Table 9 to Table 13 give an overview of the available datasets and available input parameters which will be discussed in detail in the following subchapters.

Table 9. Traffic data input.

Traffic	Volume	Speed
2012	Modelled according to ADT, SDT, WDT and NOX*WS values for weekends/weekdays	Inferred from speed limits
2016	Modelled according to monthly daily averages and NOX*WS values for weekends/weekdays	Inferred from speed limits

ADT- average daily traffic; SDT - summer daily traffic; WDT- winter daily traffic; WS- wind speed

Table 10. Meteorology data input.

Meteorology	Radiation	Temperature	Humidity	Precipitation	Cloud Cover
2012	GRE*	GRE*	GRE*	IMO station Nr. 1475	none
2016	GRE*	GRE*	GRE*	IMO station Nr. 1475	none

**roof of measurement station*

Table 11. Activity data input.

Activity	Salting	Ploughing	Cleaning
2012	Modelled from measurements	Modelled from measurements	measured
2012	Modelled from measurements	not available	not available

Table 12. Road surface conditions.

Surface conditions	Road temperature	Road moisture
2012	none	none
2016	none	none

Table 13. Air quality data input.

Air quality	PM10 traffic	PM10 Back-ground	PM2.5 Traffic	PM2.5 Back-ground	NOx traffic	NOx Back-ground	Emissions (Ex/NOx)
2012	GRE	FHG, HVAL	GRE	FHG, HVAL	GRE	FHG, HVAL	Yes
2016	GRE,	FHG, KOP	GRE	FHG, KOP	GRE,	FHG, KOP	Yes

**GRE: roadside, FHG: town park; KOP: roadside, suburb; HVAL: road side, suburb*

Data collection and assumptions

Not all the needed data needed for NORTRIP are available or measured in Iceland. Therefore, starting from the available datasets, some of the input data have been modelled or inferred. The following sub-chapters explain how hourly data have been retrieved or modelled.

Traffic Data

The needed traffic data are total traffic volume per hour, light duty vehicles per hour, heave duty vehicles, vehicle with summer tyres, winter tyres and studded tyres for each vehicle category (light and heavy) and vehicle speed.

There is no hourly traffic count available at the investigated road stretch, but there are averages and traffic counts available for the different time periods.

For 2012, the Road Administration has published the average daily traffic (ADT), the summer daily traffic (SDT) and the winter daily traffic (WDT) (http://www.vegagerdin.is/upplysingar-og-utgafa/umferdin/umfthjodvegum) for the road nr. 49 - stretch 03. The road nr. 49 according to the nomenclature of the Road Administration corresponds to Miklabraut and the road stretch 03 is the closest one with a traffic counter to the investigated road stretch (Figure 27). The average daily traffic (ADT) was used for the months of October, November, April and May; the summer daily traffic (SDT) for the months of June, July, August and September and the winter daily traffic (WDT) for the months of January, February, March and December.

These daily averages were used, together with the NOx multiplied with wind speed (WS), to calculate the traffic variations during the day and the differences between weekdays and weekends. Differences due to holidays were not considered. Figure 28 shows the winter daily traffic (WDT) for the year 2012. These traffic counts are used for the months January, February, March and December 2012 and the difference of traffic between weekdays and weekends is clearly visible. The main morning weekdays traffic peak hours are between 8.30 and 10.30 and the main afternoon weekday traffic occurs between 16.30 and 18.30. During the weekends, Saturday and Sunday, the total amount of cars per hour is lower and there are no rush hours.

For the year 2016, monthly averages are available from the Road Administration and the same calculation with NOx*WS was applied to obtain the hourly and weekdays variations for each month. According to a written communication from the Road Administration during both years 97% of the traffic flow on Miklabraut was light traffic and 3% heavy traffic.

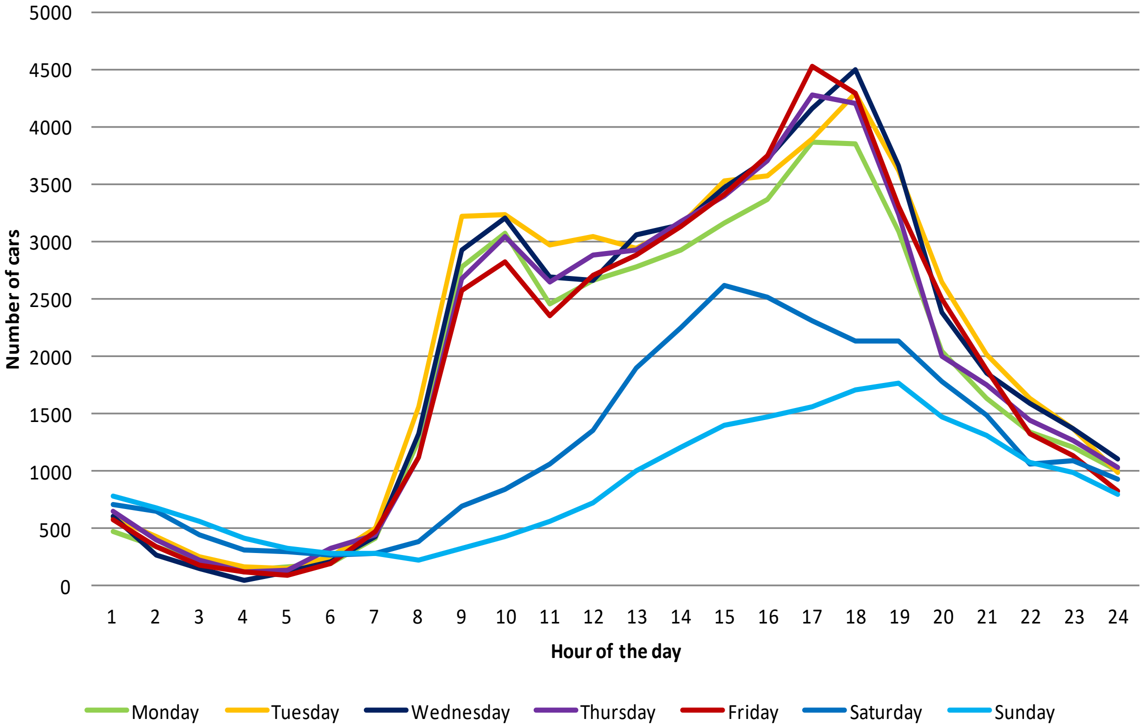


Figure 28. Winter daily traffic (WDT) average multiplied with NOx*WS to obtain the hourly traffic variation as well as the differences in between weekdays for winter months (January, February, March, December) of 2012. The difference between weekdays and weekends is clearly shown by the amount of traffic during morning and afternoon peak hours.

Every year the City of Reykjavik carries out a count of the number of studded tyres. This count is carried out by the Engineering firm EFLA and from the documentation the ratios of studded tyres during the wintertime were modelled. The tables are provided by the City of Reykjavik, Department of Planning and Environment.

Studded tyres are allowed within the city borders between 31 October and 15 April of each year, taking into consideration the meteorological variability of Icelandic winters. The percentages of the studded tyres were used to model the winter tyres, and presumably with or without studs. It was assumed that heavy traffic (3% of the total traffic volume) is less likely to use studs in town and therefore the percentages in Figure 29 are not used for the heavy traffic. It is also unclear, if all cars are equipped with winter tyres during the winter period. There is no rule stating the mandatory use of winter tyres, but that the car must be equipped reflecting the weather conditions. Very often all year tyres are used, which are not accounted for in the NORTRIP model.

The use of studded tyres has increased over the years, and the Figure 30 shows a clear difference between 2012 and 2016.

The speed of the traffic is not measured at the road stretch. Therefore, the maximum speed is used, even though there is a traffic light at the crossing Miklabraut and Grensasvegur and there are speed variations.

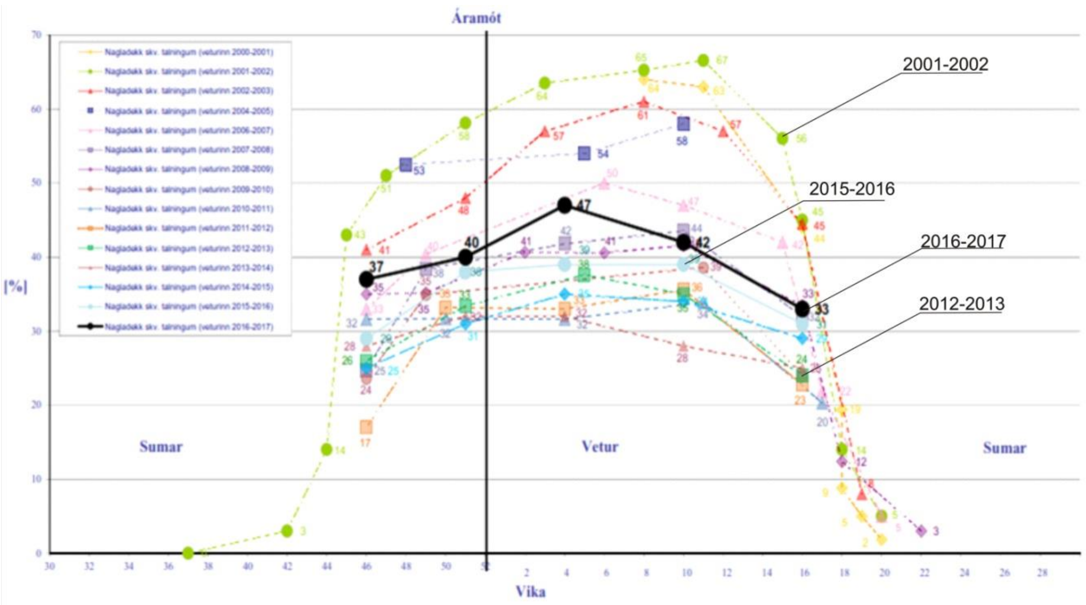


Figure 29. Use of studded tyres in Reykjavik, from 2000-2001 to 2016-2017: (extract from EFLA, data given by the City of Reykjavik, Department for Planning and Environment).

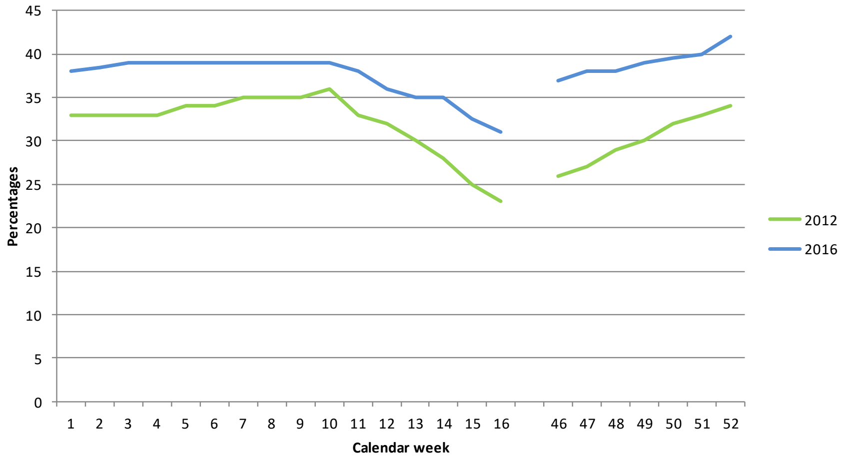


Figure 30 Studded tyres count of 2012 and 2016. The percentages show that the use of studded tyres has increased over the years. (Data from EFLA, given by the City of Reykjavik, Department for Planning and Environment).

Meteorological Data

The meteorological data are mostly taken directly from the air quality station at Grensasvegur, as it is a complete measurement station. These include the air temperature at 2 m (T2m, °C), the wind speed (FF, m/s) and wind direction, the humidity (RH, %) the global radiation and pressure. The rain data (mm/hr) are taken from the weather station Nr. 1475 which is located 1.5 km in direction SW from the air quality station. Snow data are not considered, as the weather station measures snow as melted water in mm.

Activity Data

The activity data is subdivided in salting, sanding, ploughing, cleaning and road wetting. **Sanding** is not used in Reykjavik for roads, only salt is applied. Ploughing and salting happens mostly at the same time as the salt, only in the form of Na, is applied when ploughing. The roads are cleaned on average once a year, at the end of the winter between April and May, which varies according to the weather conditions from year to year.

For the year 2012, the Icelandic Road Administration made available upon request the following data:

- 24-hour average of salting amount in g/m² is given for the blue area shown in Figure 31
- data about every salting passage (hourly) and dosage;
- hourly passage of ploughing.

As hourly data are needed, the 24-hour average is divided by hours in which one or more vehicles were passing along that road stretch. For example, on 1 January 2012, the salting device passed the road stretch between 13-14, 14-15 and 15-16 and the 24-hr dosage was 16 g/m². Dividing 16 by the 3 hours a dosage of 5.3 for the relative hours of passing is obtained while during all the other hours of the day the dosage is 0. The same principle was used for the passage of the ploughing device, in this case a passing at a certain hour gives a 1 and a non-passing a 0.

Road wetting is not implemented yet in Iceland but according to the Road Administration every time a ploughing or salting vehicle passes, the road will be wet as in dry conditions the salt will be sprayed wet.

For the year 2016 the amount of salting (24 hr average) is available, without the exact passing time of the vehicle. Therefore, the sprayed amount was distributed over the day randomly.

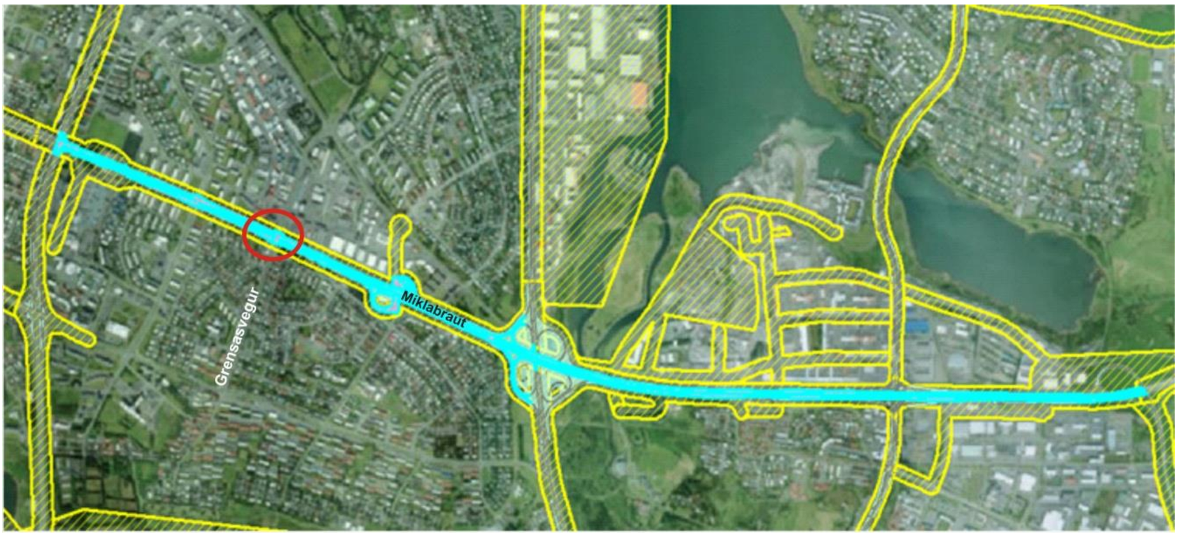


Figure 31. Road stretches for which 24-hour average of salting amount is given. Blue stretch area, A = 171 950 m²; blue stretch length, L = 5640 m; blue stretch average width of roadway, w = 30.5 m; lane width 3.75 m; average number of lanes on blue stretch 8.1. Data and image from the Road Administration upon request.

Air Quality Data

The most complete air quality station run by the Environmental Agency of Iceland is located in Grensasvegur (GRE), at the crossing with Miklabraut and determined the choice of the road stretch for which NORTRIP was implemented.

The observed PM10, PM2.5 and NOx values come from Grensasvegur station and the background data come from different air quality stations: Fjölskyldu- of Husdyragardurinn (FHG) in Reykjavik, located around 1.1 km NNE from the test area within a municipal park area, Kopavogur - Dalsvegur (DAL), located 4.9 km S within a residential area, Hafnarfjördur - Hvaleyrarholt, located 9.8 km SSW in a residential area and very close to the seaside (Figure 32). The need of using that many background stations arises from the problem, that air quality data in Iceland are discontinuous and not all parameters are registered during all periods. FHG is the best background location due its vicinity to the test area but also since it is located within a green area and it is not directly affected by road traffic.

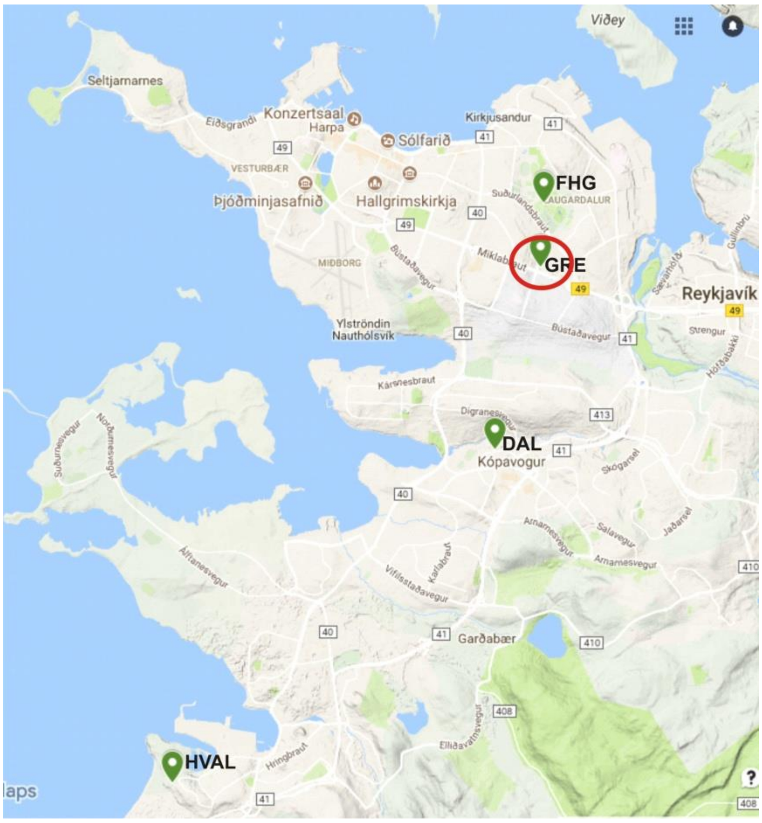


Figure 32. Overview of the available air quality stations: GRE- main air quality station, observed values; FGH - DAL-HVAL background stations.

Air quality data check

Before implementing the necessary Excel files for the model run, the available air quality measurements were checked for completeness. Very often either the observed air quality data or the background data or both present large gaps and these periods need to be excluded during modelling. The 2012 dataset shows that NOx data for both measurement stations, GRE (observation station) and FHG (background) are complete, but the PM2.5 from FHG are missing from 1 January 2012 to 1 April 2012 (Figure 33).

In Figure 33 the hourly PM and NOx values measured at the two stations GRE (observed values) and FHG (background) station are compared to find data gaps for the year 2016. PM2.5 data for FHG are not available for the whole year. From 1 July 2016 to 9 July 2016 there are no measurements at either station, between 13 July 2016 and 30 August 2016 there are no NOx data from GRE and from 15 November 2016 to the end of the year there are NOx data from both stations and PM2.5 from GRE missing.

10-minute averages from the measurement station Kopavogur - Dalsmari were converted into hourly values. Figure 34 shows the comparison between the two datasets.

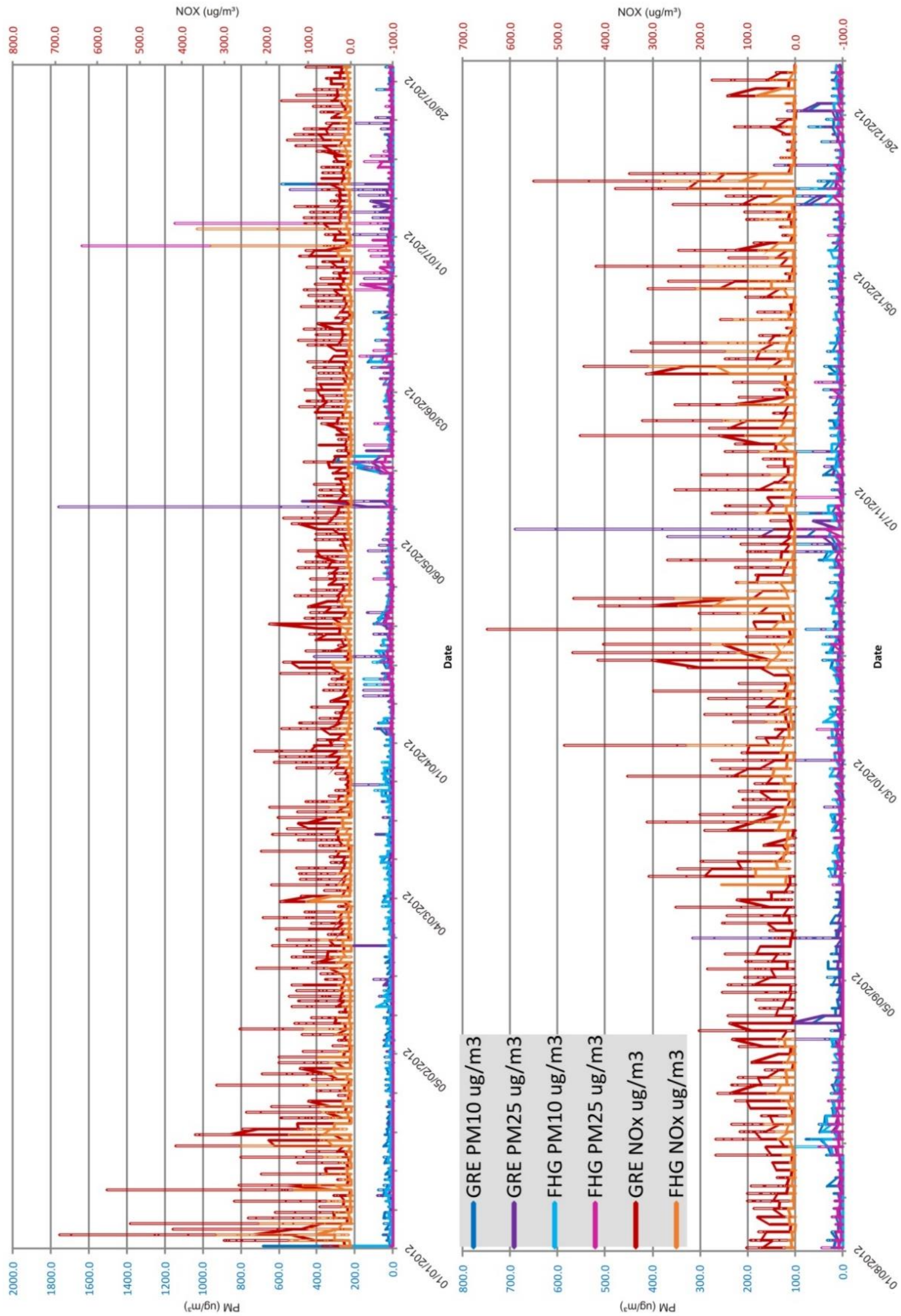


Figure 33. Comparison of hourly data of Grensasvegur (GRE) air quality monitoring station (observed data) and the background station Fjölskyldu-og Husdyragarddurinn (FHG) 2012. PM10 GRE in blue, PM2.5 GRE in violet, PM10 FHG in light blue, PM2.5 FHG in pink and the axis is on the left (blue); NOx GRE in red, NOx FHG in orange with the axis to the right (red).

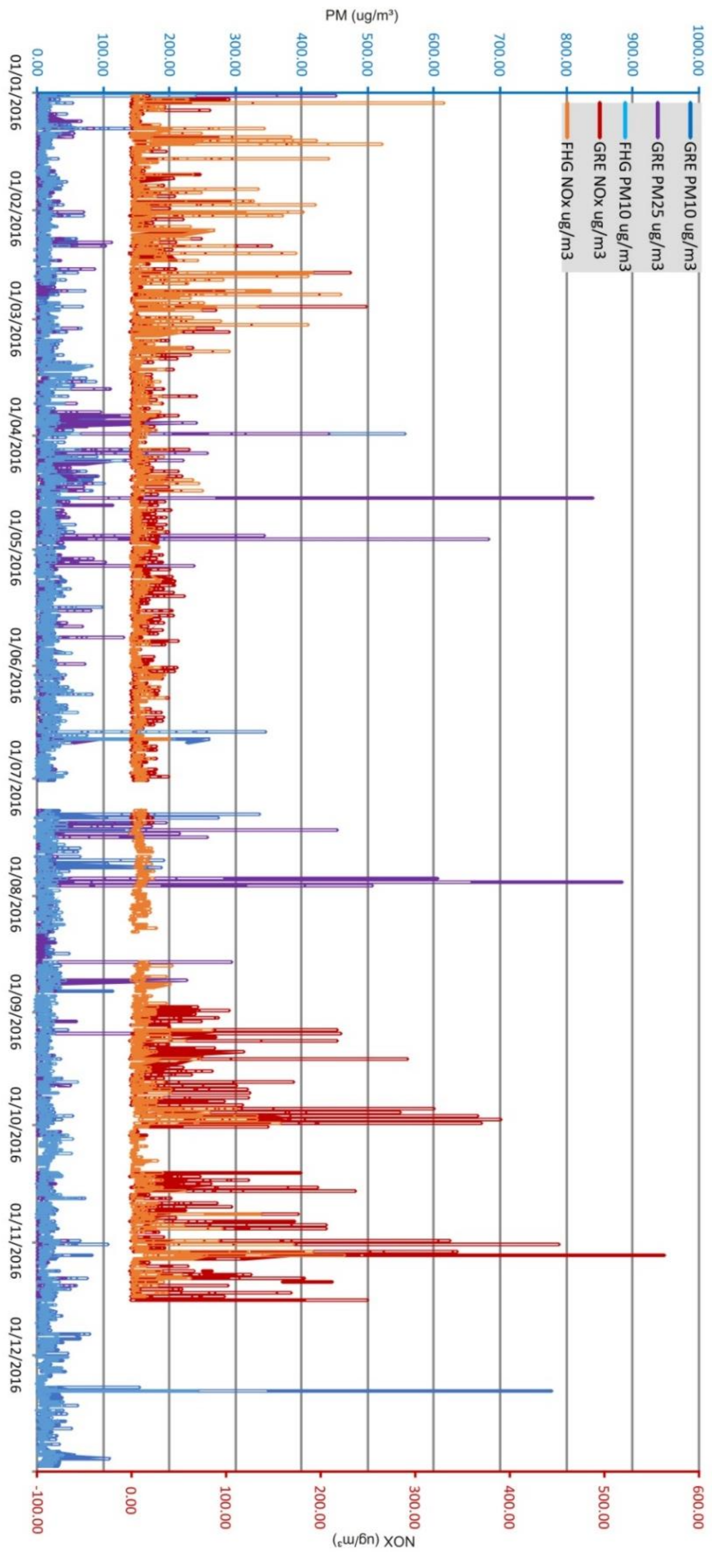


Figure 34. Comparison of hourly data of Grensasvegur (GRE) air quality monitoring station (observed data) and the background station Fjölskyldu-og Husdyragardurinn (FHG) 2016. PM10 GRE in blue, PM2.5 GRE in violet, PM10 FHG in light blue and the axis is on the left (blue); NOx GRE in red, NOx FHG in orange with the axis to the right (red).

Results

WP1 Field tests

On-road measurements of modern winter tyres

Results of the on-road winter tyre measurements are presented in Figure 35 as median PM10 emission measured by Vectra instrumented car behind the tyre. Based on the results for the reference tyre, overall suspension level was low and without significant change during the test days in both years. The emission from studded tyres was more than fourfold compared to the reference non-studded tyre.

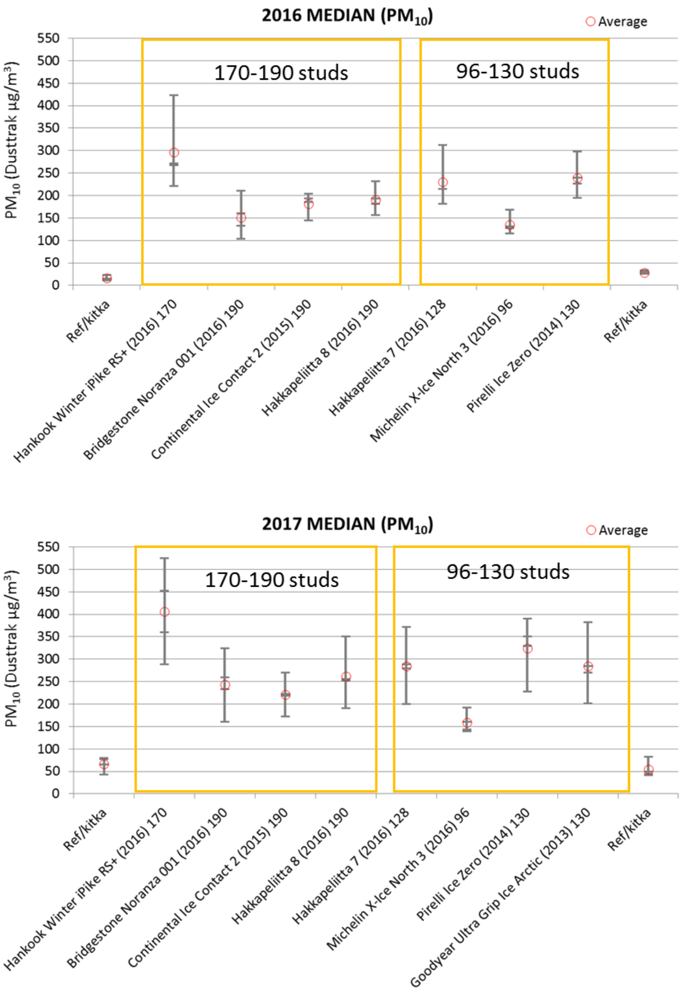


Figure 35 Median PM10 emission measured by Vectra instrumented car for different studded tyres in 2016 (top) and 2017 (bottom). Line markers show four measured values (2 direction x 2 test track sections) for each tyre. Non-studded winter tyre is used as a reference (Ref/kitka).

In both measurement campaigns similar variation between tyres was observed. The lowest emitting tyre was the one with the lowest number of studs. However, tyres with the highest number of studs were not the highest emitting which indicates that number of studs alone does not explain differences in the emission.

In Figure 36 PM10 emissions measured in 2016 and 2017 for all tested studded tyres are plotted as a function of the number of studs, stud protrusion and number of studs multiplied by the stud protrusion. For the tested tyre set, stud protrusion explains the increase in PM10 emission better than the number of studs alone or combination of the two parameters. However, emissions may be affected by other factors that were not taken into account here, such as tyre tread and rubber characteristics.

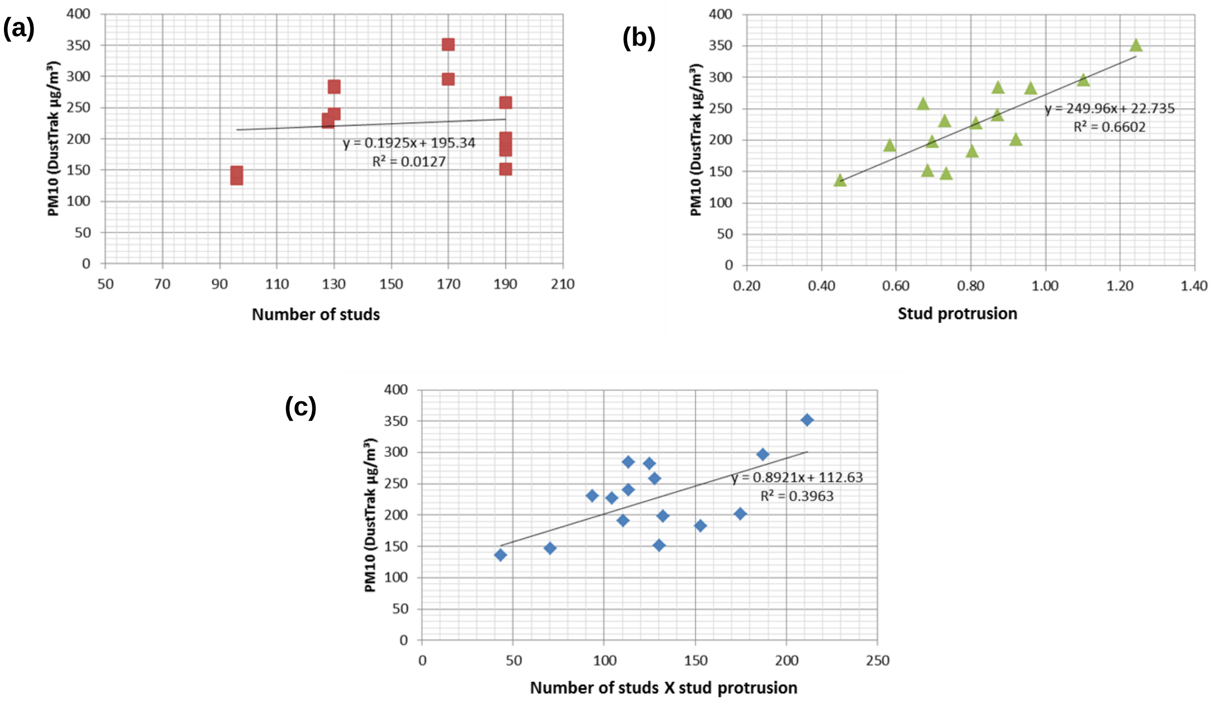


Figure 36 PM10 emission measured by Vectra instrumented car behind the tyre as function of number of studs (a), stud protrusion (b) and number of studs * stud protrusion (c). Figures include results for all tested studded tyres during the measurement campaigns in 2016 and 2017.

Vantaa campaign

Road dust suspension experiment

In Figure 37, the road dust load (DL180) in and between wheel tracks for each section during the suspension experiment is shown. The data overall reflects the initial choices with a dusty, unbrushed surface (A), a brushed clean surface (B) and a brushed, dustier surface (C). The first measurement is undisturbed by traffic, why in and between wheel tracks is not relevant. As can be seen, the variation between the two surfaces is rather large, both within and between sections.

After the first traffic In Section A, DL180 is higher than the initial load, but then decreases, especially clear, in wheel tracks until measurement 7, which shows a slight increase in dust load. Measurement 8 displays the highest values, likely caused by rain redistributing the dust load, while number 9, again, is on the same level as number 7.

According to the Vectra suspension test (Figure 38), suspension decreases with number of passages up to about 200–250, but thereafter is stable even if speed is increased. This indicates that the dust load available for the tyre suspension forces at a certain speed, contributes to the suspendible fraction to a certain limit, after which suspension is constant and consisting of only loose dust. The unsuspendible fraction will be constant after this, as long as the circumstances are constant (traffic speed, road surface wetness etc.)

During the meandering test, the Vectra signal increases markedly when the vehicle leaves the wheel tracks and suspends dust accumulated outside them (Figure 38 and Figure 39). Mean suspension emission was by a factor 3.4 higher during passages with the meandering compared to the driving in the wheel tracks.

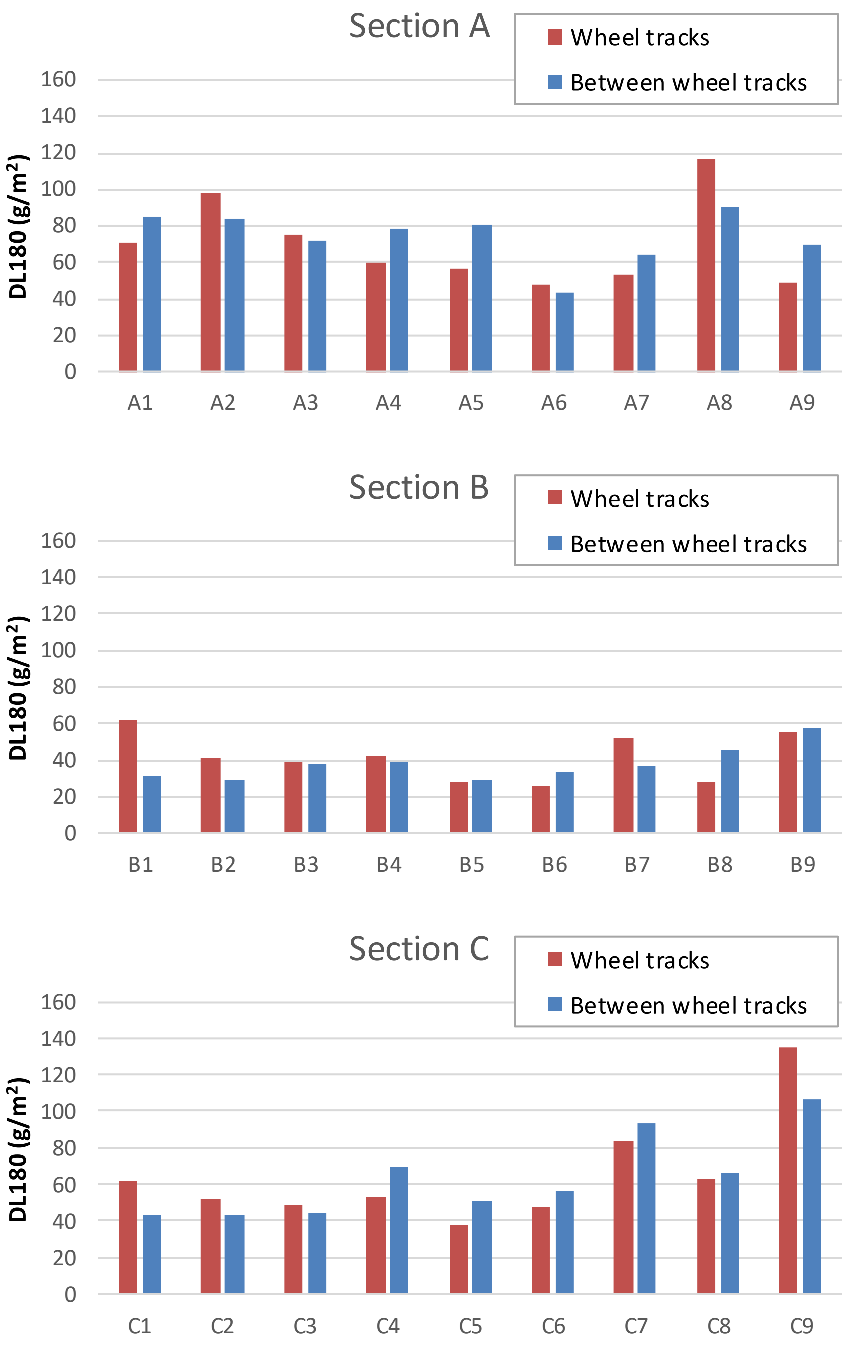


Figure 37. DL180 in and between wheel tracks in section A, B and C at all measurements.

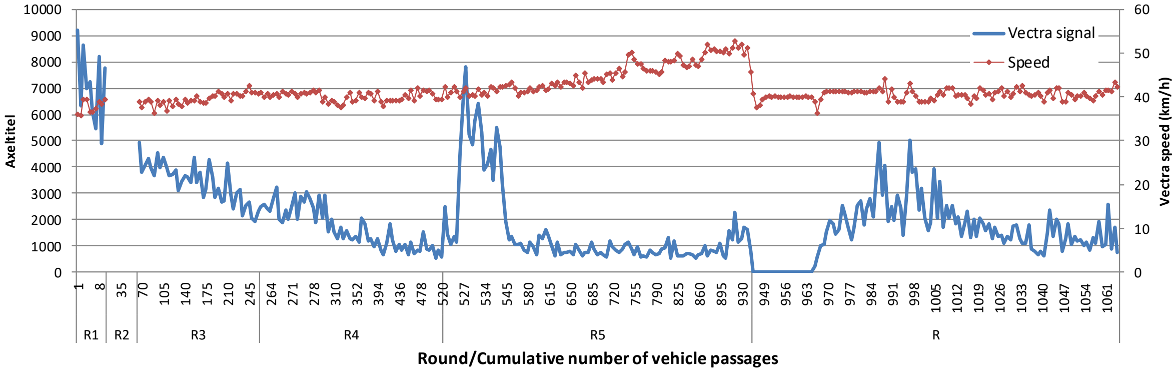


Figure 38. Vectra signal during the suspension test. Peak at start of R5 is caused by the meandering test.

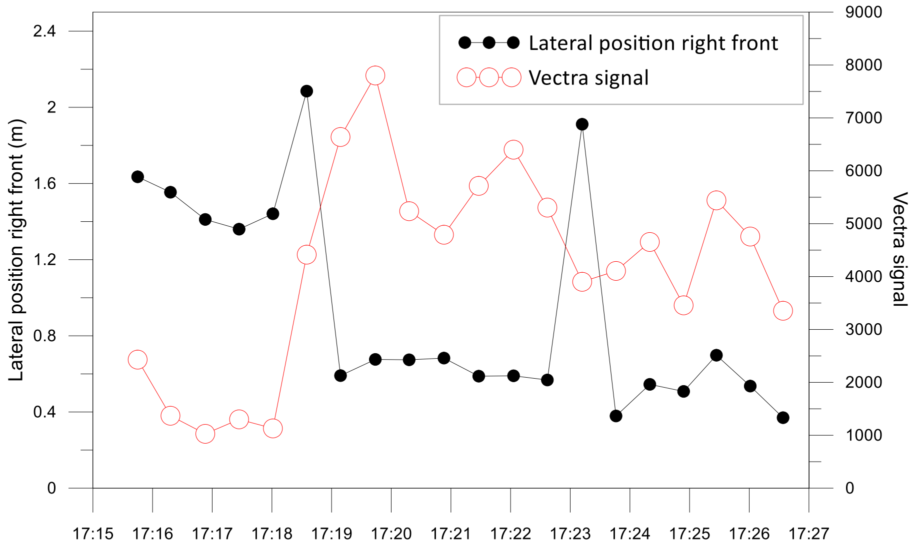


Figure 39. Example of effect on Vectra particle signal when the lateral position of the vehicle changes from running in wheel track to running in between wheel tracks.

Meteorology

From an air pollution measurement perspective there were mostly unfavourable wind directions during the whole time period of the Vantaa campaign (i.e. not perpendicular to the roadway). Both tracks were monitored on stretches with a north-south direction and the wind, when it was over 1 m/s were normally southerly (Figure 40).

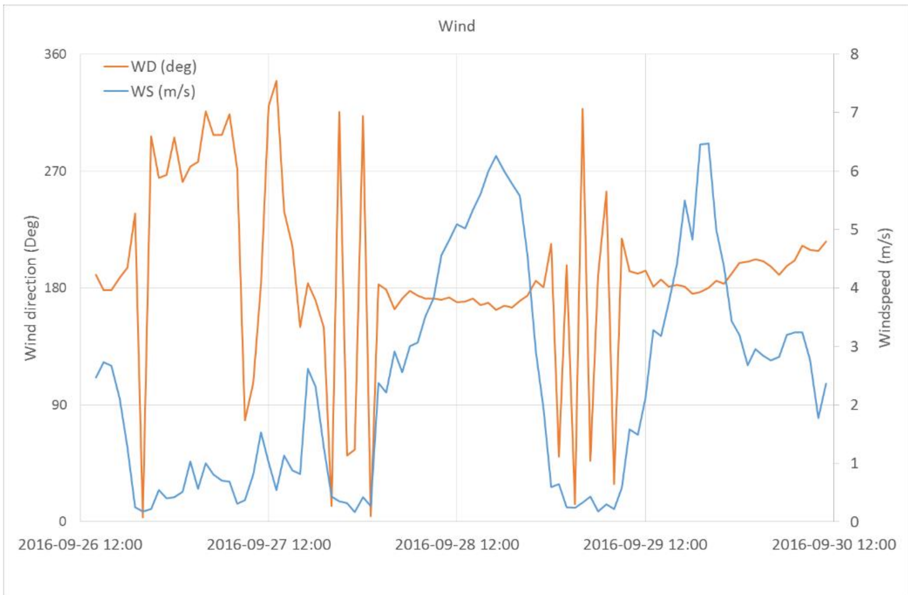


Figure 40. Wind direction and wind speed during the Vantaa campaign.

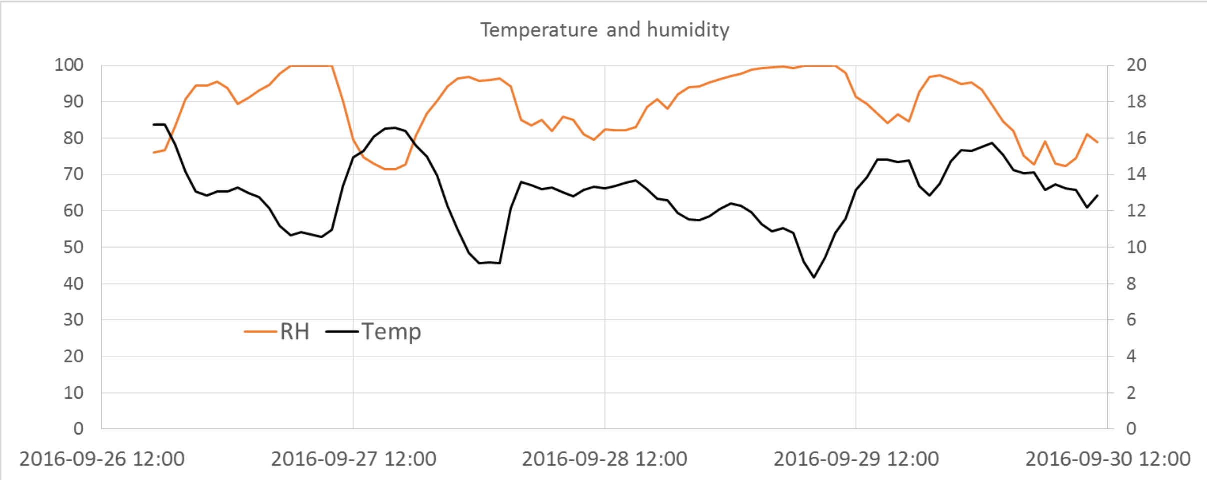


Figure 41. Temperature and humidity during the Vantaa campaign.

Due to the wind direction the measurement setup was not ideal. Therefore, there is a lot of noise in the measurement data showing high concentrations measured on both the upwind and the downwind side. Sometimes there were only increased levels of PM10 on the upwind side which was completely the opposite from the desired results. Due to this the intended method could not be used for the air measurement data. Therefore, PM10 concentrations for all positions are shown in the following figures (that is, the upwind concentration has not been subtracted from the downwind concentrations).

On the first and second days (Sep 26 and 27), measurements were performed at the O-track site 1. Figure 42–Figure 48 show data collected driving through the measurement setup at different times. The passages differed in time interval and the position on the roadway. Each black dot represents a passage through the measurement setup.

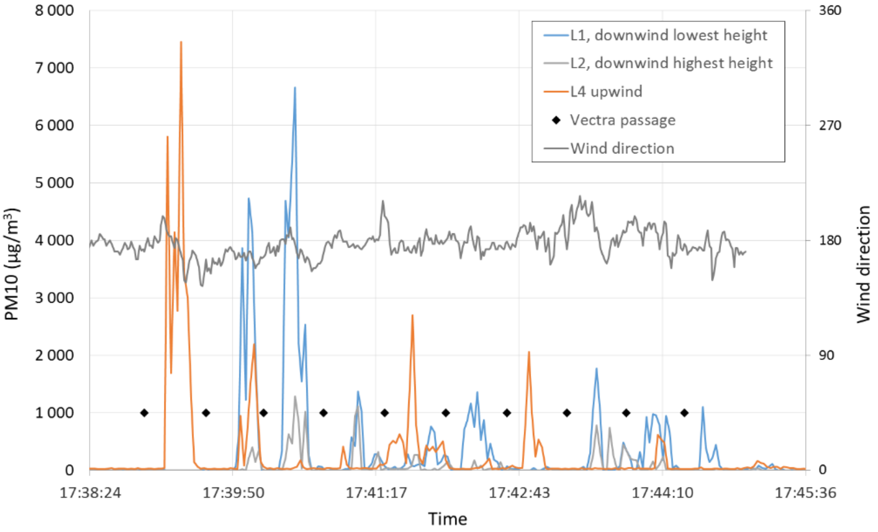


Figure 42. 10 rounds, only Vectra driving in O-track at site 1.

The highest peaks in the PM10 concentrations was observed for the first passages, Figure 42. A lot of road dust was available for resuspension. However, the concentrations decreased fast and already during passage 11 to 60 were the concentrations significant lower, Figure 43. Also visible in Figure 43 is that single peaks could not be detected when several cars were driving at the same time.

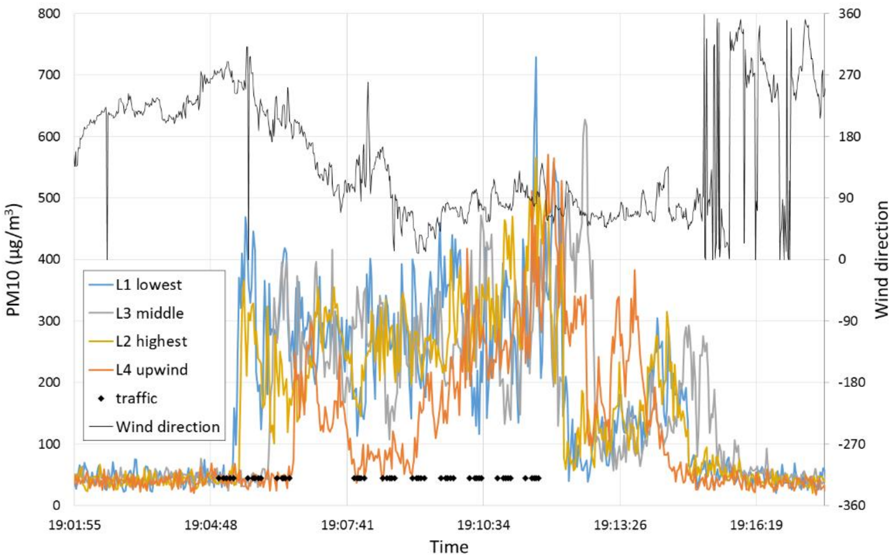


Figure 43. All cars driving 50 passages in O-track at site 1.

The second day at the site 2016-09-27 started with misty conditions. Unfortunately, cannot the PM instrument handle these conditions and did not deliver any useful data during that period.

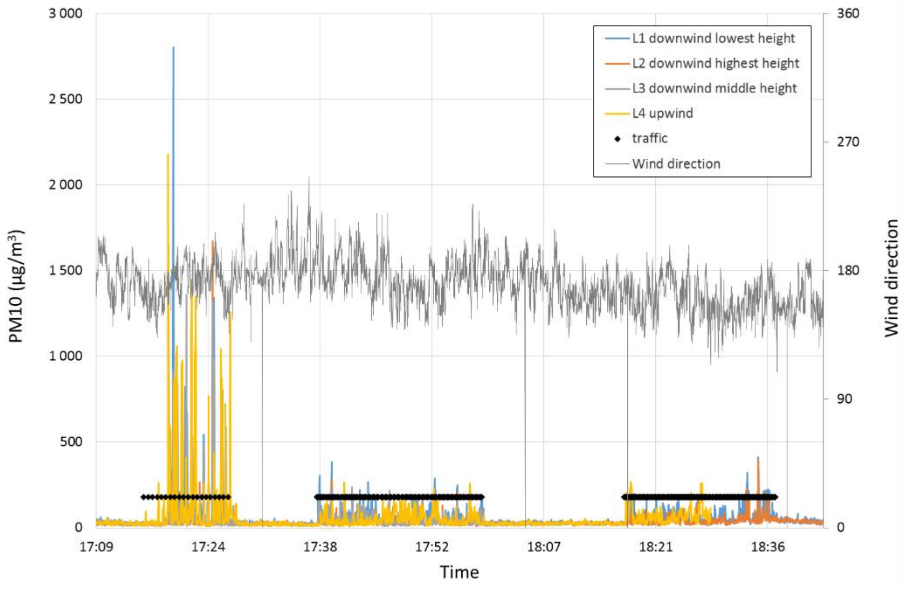


Figure 44. Vectra driving 20 single rounds (first 5 in old track and following 15 off track) followed by all cars driving 2 times 100 passages in track, in O-track at site 1.

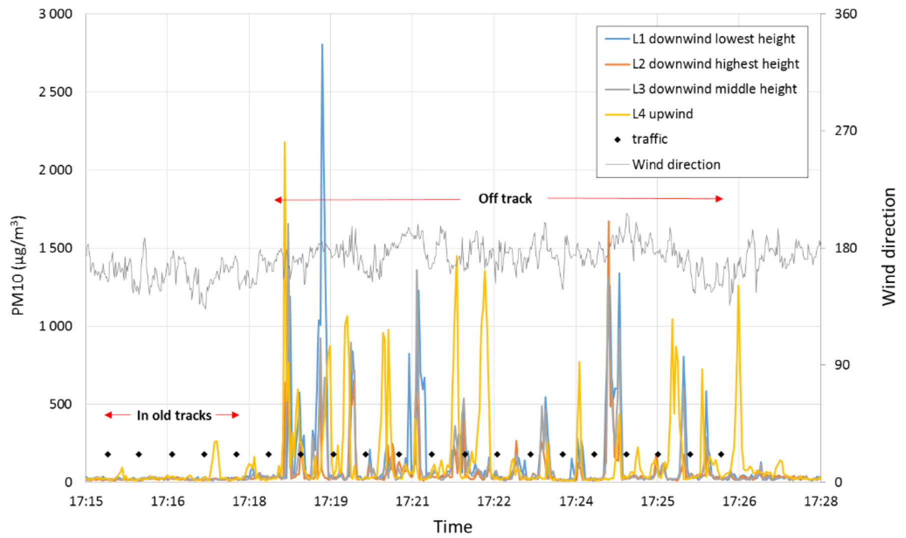


Figure 45. Vectra driving 20 single rounds (first 5 in old track and following 15 off track).

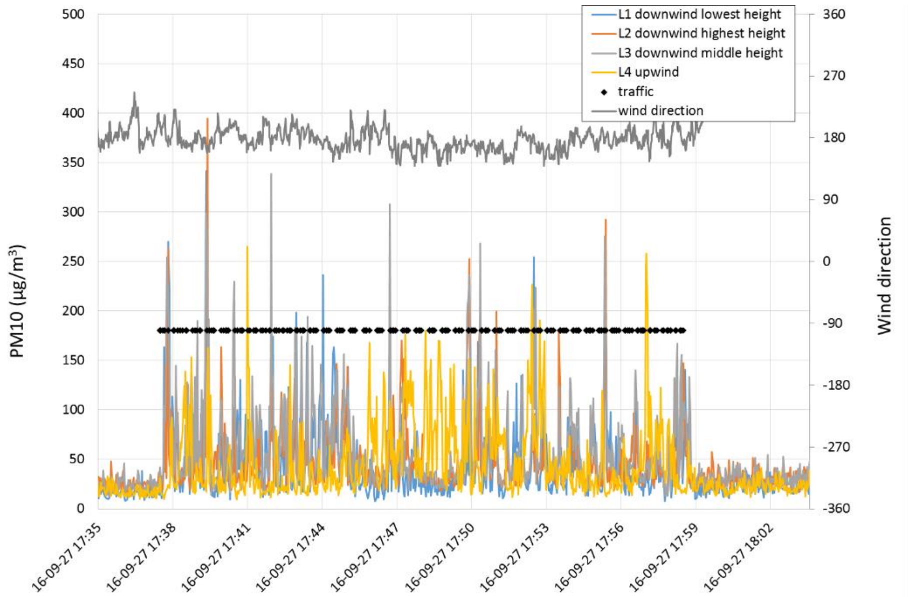


Figure 46. All cars driving 100 passages in track, in O-track at site 1.

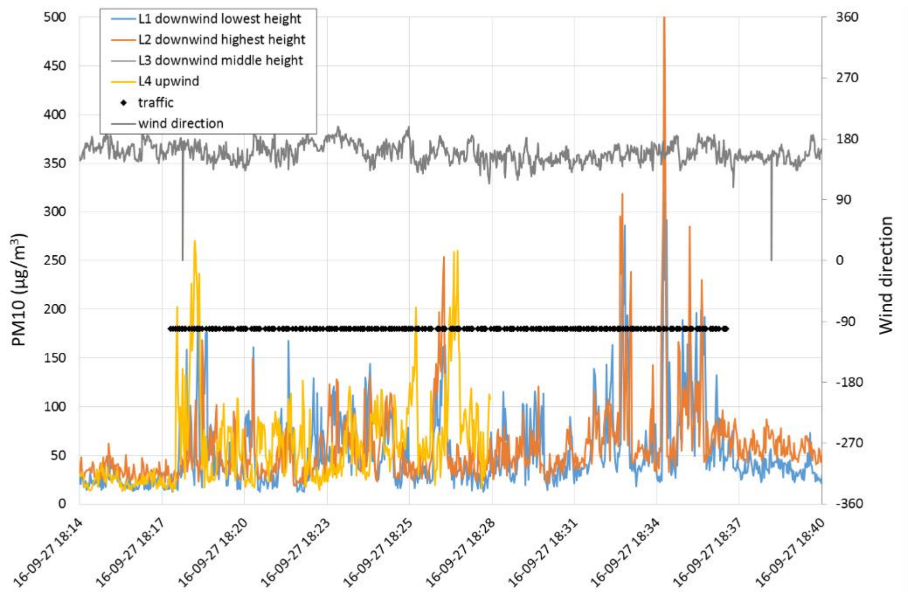


Figure 47. All cars driving the last 100 passages in track, in O-track at site 1.

On the afternoon the second day the measurement setup was moved to site 2 on the I-track. Unfortunately, the wind direction was so that no useful data could be collected from these measurements.

The third day started with new measurements at site 1 on the O-track. Since the data seemed to be too noisy when many cars drove with short intervals, this time only Vectra did single rounds. First Vectra was driving 20 single rounds at 40 km/h with measurements in west and wind from the south, see Figure 48. As shown in the figure the data was noisy and it was impossible to get any useful data from it. Therefor the measurement setup was moved to a new location (site 3) for more favourable wind direction. At site 3 the measurements were in south west direction and wind from the south. At this location the Sniffer, measuring PM10 with a TEOM, was standing at the same place as the measurement setup. Figure 48, Figure 49 and Figure 50 show Vectra driving 20 and 20+10 rounds, respectively.

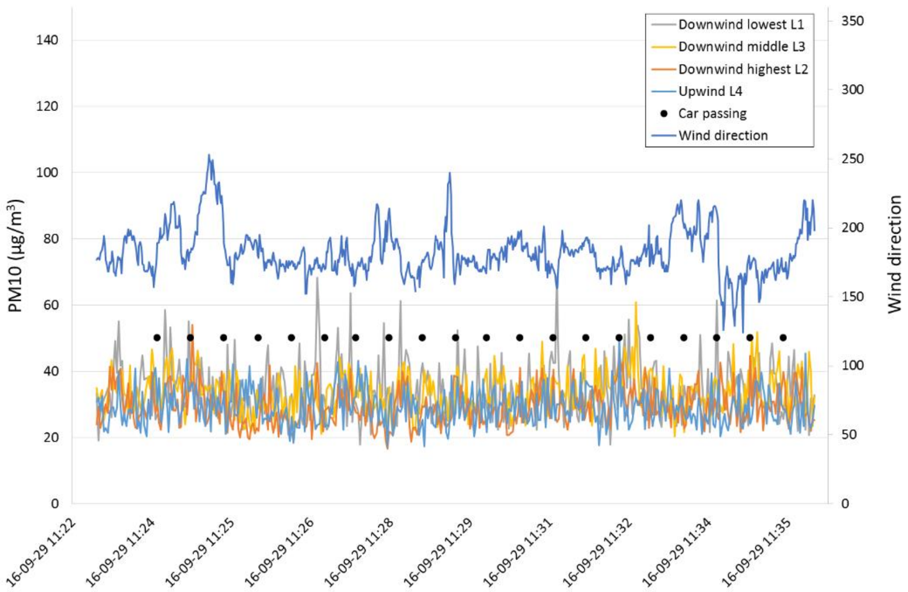


Figure 48. Vectra driving 20 single rounds in track at 40 km/h with measurements in west and wind from the south at O-track site 1.

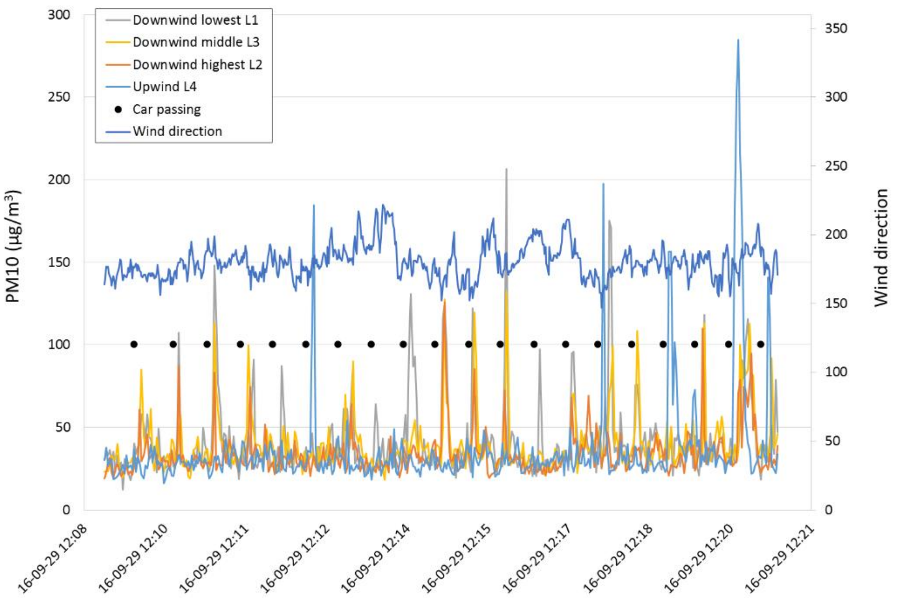


Figure 49. Vectra driving 20 single rounds in track at 40 km/h with measurements in south west and wind from the south at O-track site 3.

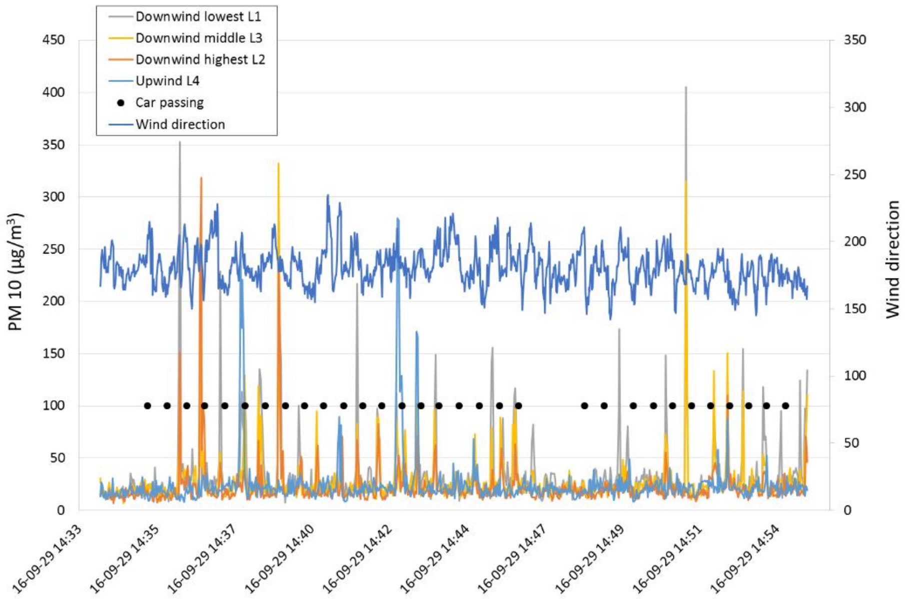


Figure 50. Vectra driving 20+10 single rounds in track at 40 km/h with measurements in south west and wind from the south at O-track site 3.

Conclusions:

- Mostly wrong wind direction
- Fast decreasing concentrations
- Much higher when driving off-track
- No signal from sanding
- Surprisingly not highest concentrations at lowest height
- If the cars were passing too often the plume was spread and the data got very noisy
- If the wind was not blowing perpendicular to the road track (or close to perpendicular) the increased concentration measured when a vehicle passing the measurement setup was increased at both upwind and downwind side

Sanding experiment

During the sanding experiment, samples were taken in and between wheel tracks after 20, 210 and 599 vehicle passages and the amount and size distribution of the sand was determined. In Figure 51 and Figure 52, the successive reduction in relation to traffic can be seen. In the wheel track sand is reduced more than in between wheel tracks. After 599 passages, the reduction is about two thirds of the initial amount in wheel track and about one third of the initial amount between wheel tracks. The main reduction is in the coarser fractions from about 0.8 mm and up. In wheel tracks the reduction is higher with increasing size, while the largest particles in the size distribution seem to be less affected than particles of about 4 mm between wheel tracks. This is likely an effect of the different suspension forces acting on the surfaces.

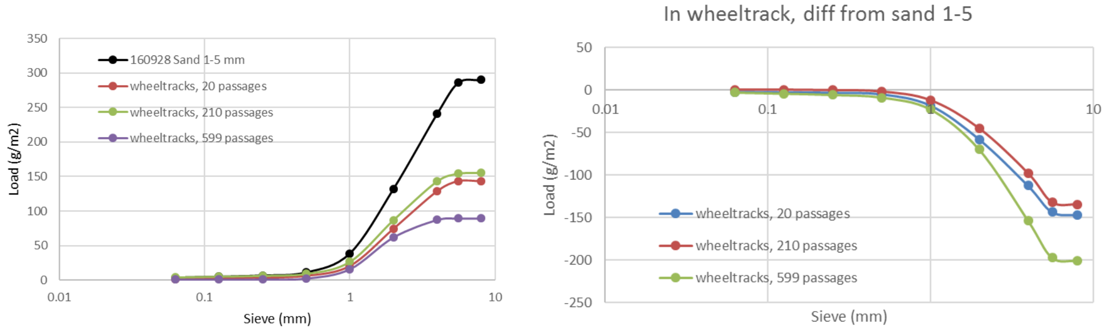


Figure 51. Original sand and brushed sand load and size distribution in wheel tracks.

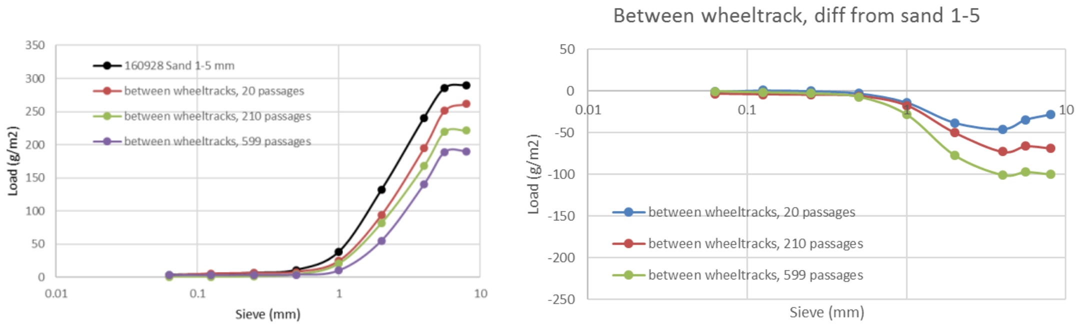


Figure 52. Original sand and brushed sand load and size distribution between wheel tracks.

Sanding results are presented in Figure 53. The emission level for different measurement rounds represents a mean value of all data points recorded by the Vectra car during the round. The results are given for the treated ("sand") and non-treated ("noSand") segment of the I-track1. The non-treated segment was on the down flow side of traffic.

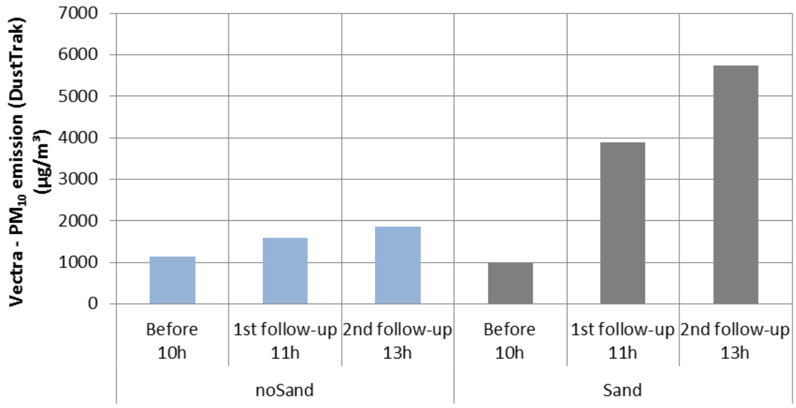


Figure 53. Measured PM10 emissions before and after the application of sand. "noSand" refers to the non-treated I-track1 segment and "Sand" to the treated segment.

During the first and second measurement after the application of sand the emission on the sanded segment was four and six times higher compared to the pre-treatment level, respectively. Mean traffic speed was higher during the second follow-up measurement which may contribute to the higher measured emission. An increase of emissions was observed also on the non-treated segment. This can partly be explained by the migration of sanding material along the road due to the traffic flow.

Visual inspection showed that after 100 vehicle passages, sanding material was removed from the wheel tracks in the treated segment of the I-track1. Performed sanding experiment does not demonstrate traction control practice used in the real-life as traction sand is rarely applied on the dry road surface. However, in the urban street environment portion of the applied sanding material remains on the street shoulders and may be redistributed after snow and ice melt and surfaces dry out.

In order to evaluate the emission changes on the treated segment, the concentrations were adjusted based on emission concentrations measured on the non-treated segment which served as a reference.

Following reference adjustments were done for the emissions measured on the treated part of the I-tracks:
1. The emissions before the treatment (on treated sections) were adjusted to match the emission on the reference section before the treatment.
2. Changes of the reference section emissions (after the treatment of the other sections) were taken into account relative to the situation before the treatment.
3. After the treatment the emission changes of the treated sections were estimated as a relative change (%) against the emission level of the reference section during the same time period.

Estimated increase in the emission on the treated segment was 180% after one hour and 100 vehicle passages, and 250% after 3 hours and additional 50 vehicle passages.

Crushing experiment

The crushing experiment resulted in ambiguous results. The sieved coarse material (0.063–8 mm) do not show much changes between the round of crushing. A general tendency towards smaller fractions compared to the uncrushed material can be seen but is not consequently being finer and finer as one would expect (Figure 54). For the material being crushed by studded tyres the differences are small and for the more obvious changes in the material being crushed by friction tyres, the material becomes coarser again and very similar to the original material after 360 passages.

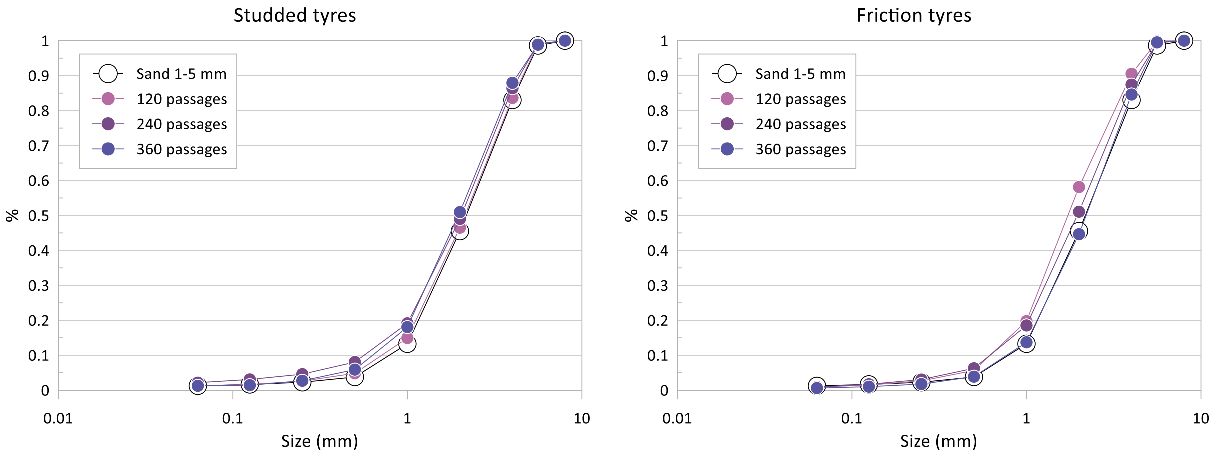


Figure 54. Cumulative size distributions for coarse fractions (0.063–8 mm) sampled efter crushing rounds.

Studded tyres seem to affect the finer fractions more than the friction tyres, resulting in markedly finer size dsitributions than the original material. After 120 passages, the distribution is the finest, but after 240 and 360 passages, the distribution grows a little coarser again, which is difficult to explain. For friction tyres, the size distributions are only slightly finer after crushing, with no obvious trends (Figure 55).

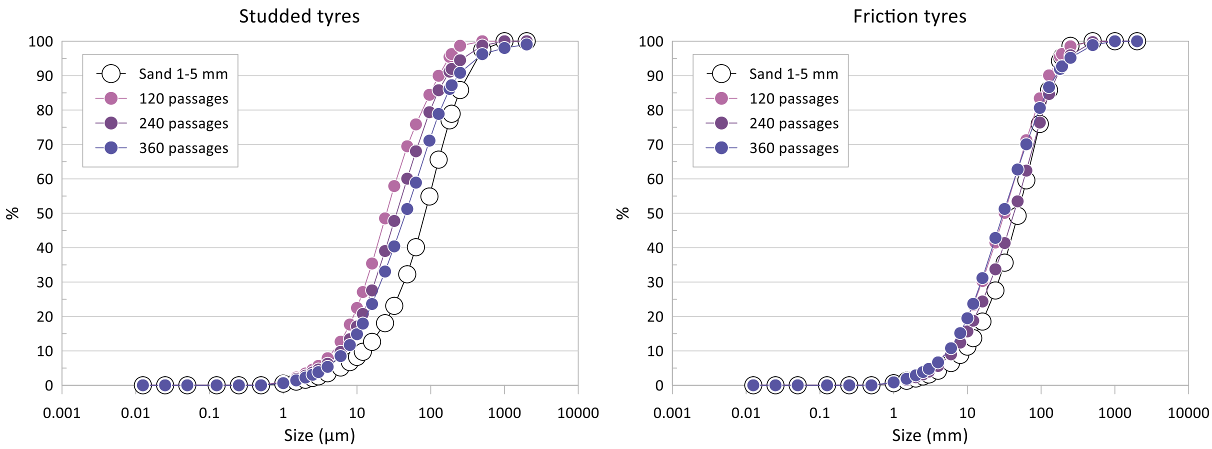


Figure 55. Cumulative size distributions for fine fractions (0.0125–2000 µm) sampled efter crushing rounds.

Cleaning experiment

Figure 56 shows emission from the cleaned area and outside of the cleaned area for the tested vehicles used for the street cleaning, CityCat 5006 and PIMU. The cleaning took place on the September 27th, at noon. Mobile measurements were performed as soon as the surface dried out after the treatment. The first two follow-up measurements were done on the same day. The third measurement was done on day after the treatment. Overall, measured emission level on the I-tracks is considered to be high compared with the urban street standards.

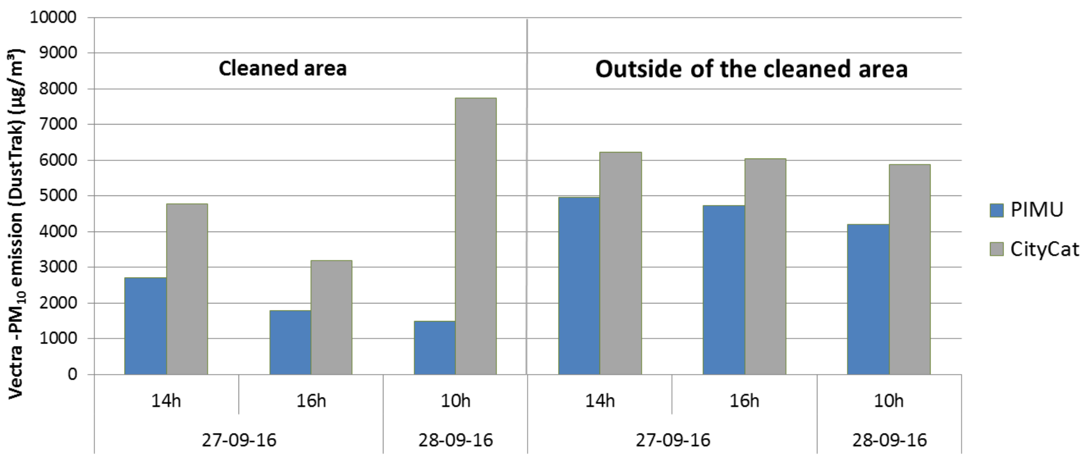


Figure 56. The PM10 emission level measured on the cleaned area and outside of the cleaned area for the two cleaning machines, CityCat 5006 (grey bars) and PIMU (blue bars).

Relative impact of the cleaning on emissions was calculated after the reference adjustments similarly as described in the previous section. In case of the cleaning experiment, non-treated part of the I-tracks served as reference with the assumption that emission level in this area before the treatment and during the first follow-up measurement remained unchanged. The changes in the reference emission levels were small during the experiment.

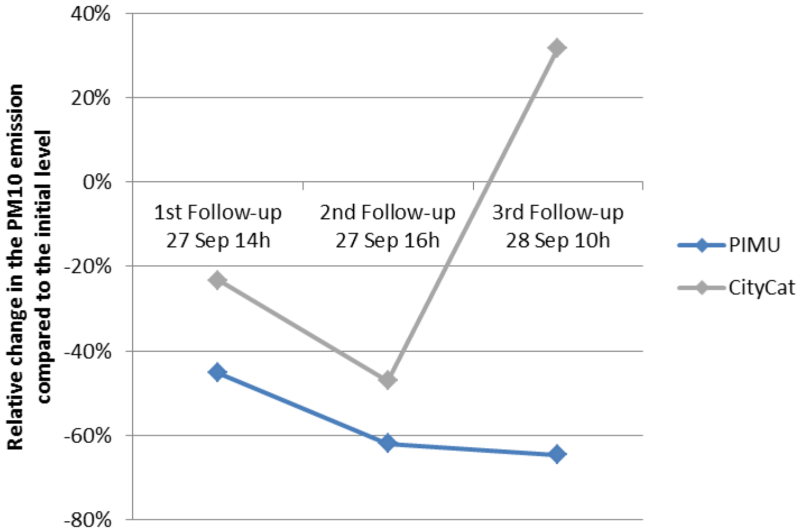


Figure 57. Impact of the cleaning on the PM10 emissions measured by the Vectra car given as reference corrected relative change compared to the initial level.

The results presented in Figure 57 show that both machines decrease PM10 emissions on the day of the treatment. Mean reduction was 35% and 54% for the CityCat 5006 and PIMU, respectively. The effect for the CitCat 5006 was limited to several hours. For PIMU, emissions lower than the initial levels were detected also one day after the treatment. Possible explanation may be that CityCat mobilizes the dust previously sealed in the pavement texture and temporally prevents its suspension due to the added moisture, whereas PIMU removes it more efficiently.

As opposed to the Vectra measurements, the WDS profiles could not show any obvious differences in dust load (approximated through turbidity) between profiles before and after cleaning (Figure 58). The variability across the track was considerable and reflects the non-typical appearance compared to a real road, where low dust amounts in wheel tracks and high amounts in-between are normally obvious. The high variability over short distances across the track is probably similar along the track and is likely a result of similar variability in texture. Since the WDS cannot sample in the same spots before and after cleaning, these kinds of variations are difficult to evaluate. If the bulk of the sample is coarser than PM10, which is the fraction measured by Vectra, differences will be even more difficult to evaluate.

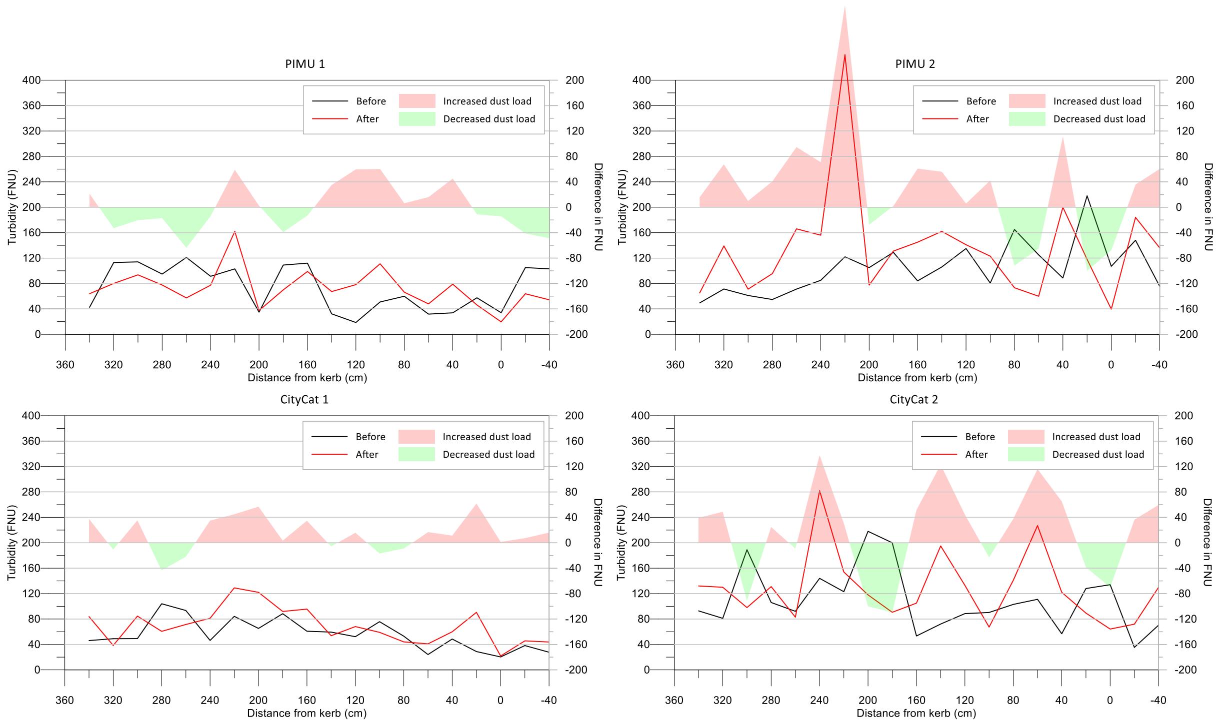


Figure 58. Results of the WDS profiles before and after cleaning.

Stockholm campaign

E18 measurements

The WDS measurements made across all three lanes in northbound direction, exposed a highly variable pattern, with high dust loads outside wheel tracks and very low in wheel tracks (Figure 59). The lane K3 had slightly higher dust loads in wheel tracks compared to K1 and K2, probably due to lower traffic amounts in this lane.

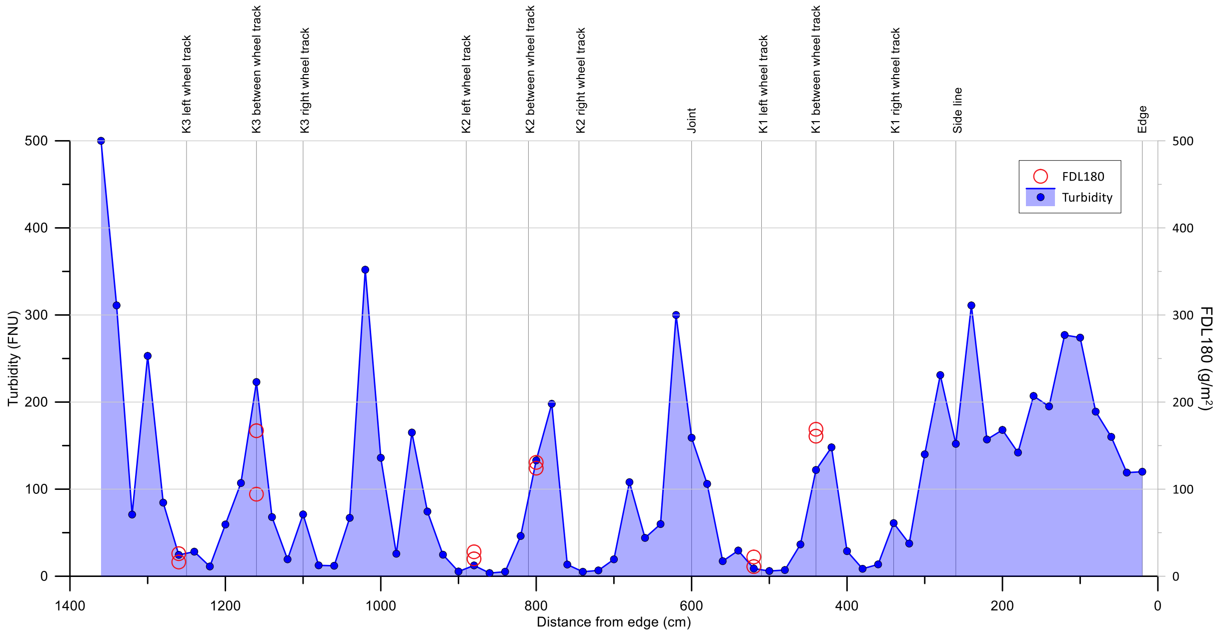


Figure 59. Turbidity as a dummy for dust load variation and actual dust load (FDL180) from the edge across three driving lanes in north-bound direction on E18.

The texture in the wheel tracks is lower than in between wheel tracks (Figure 60).

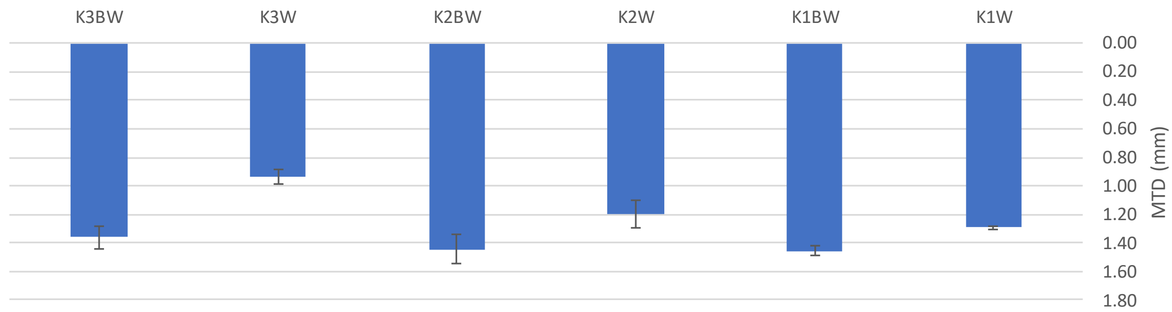


Figure 60. Mean texture depth (MTD) in and between wheel tracks at E18.

If the texture is plotted against DL180 and sand/grit (coarser than 180 µm) in WDS samples (Figure 61), the coarser material has a clearly increasing trend with increasing texture depth, while the DL180 is equally low in the wheel tracks and about five times higher in between wheel tracks. In the prevailing traffic conditions on the road with high speeds and high traffic amounts, fine material is effectively removed from the wheel tracks even though texture increases, while coarser material is less affected by tyre action and turbulence and therefore a coarser texture increases the amounts of these particles. Between wheel tracks, the tyre action is very sparse and turbulence much lower, why both coarser and finer dust can accumulate.

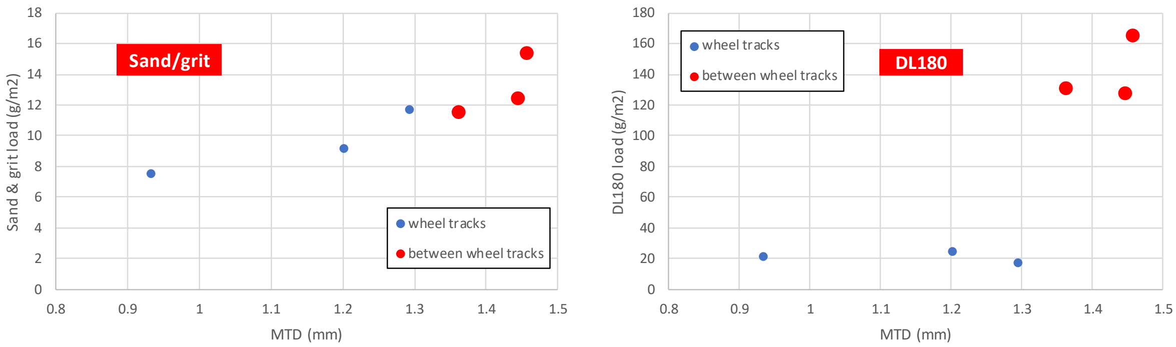


Figure 61. Loads of sand/grit and DL180 plotted against texture (MTD) in and between wheel tracks.

The results of the mobile measurements at E18 were processed to evaluate along-road and lateral variation of the PM10 emissions as well as impact of speed on suspension. In order to avoid impact of acceleration the data recorded by Vectra car was filtered to include only points with acceleration between -0.7 m/s^2 and 0.7 m/s^2. Additionally, vehicle speed is allowed to be ± 3km/h from the target speed.

Along-road variation is evaluated using the Vectra measurements with the 70 km/h target speed due to the better measurement resolution compared to Sniffer. For the data processing purpose measured segment of the E18 was divided into three sections of equal length (Figure 62).

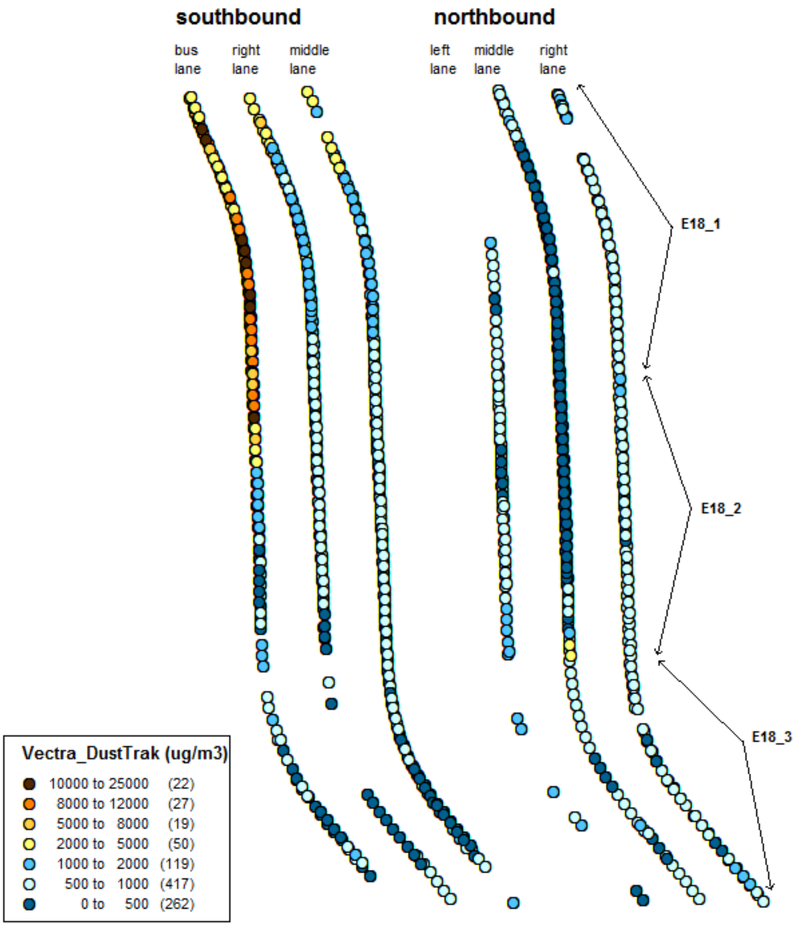


Figure 62. PM10 emission measured with Vectra along the E18 at 70 km/h. The dots represent data records that fulfil requirements regarding speed and acceleration.

The PM10 emission shows the largest variation along the southbound bus lane. Based on the visual inspection, gravel and deposits of dust were present on the shoulder of the bus lane in the section E18_1 towards south. The highest median emission (Figure 63) value was observed for this section. The variation for other sections was less significant.

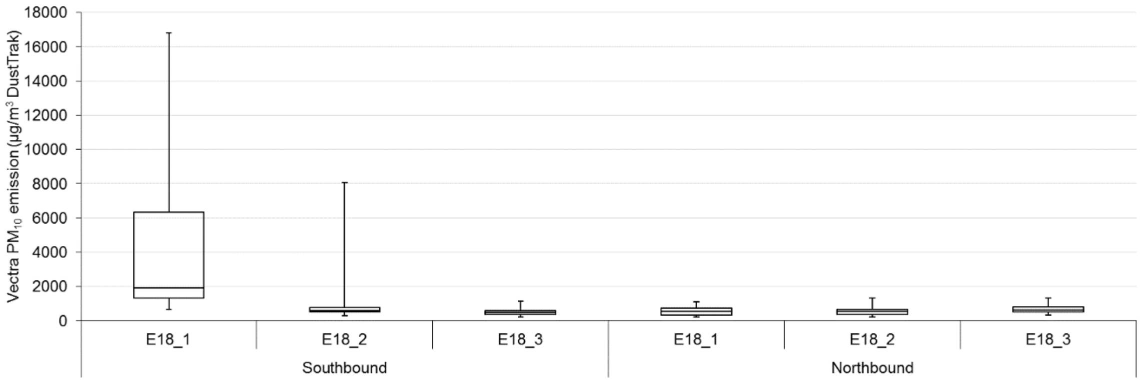


Figure 63. Box-and-whisker plots showing PM10 emission distribution for different sections of E18 measured by the Vectra car. In the plot the ends of the box are the upper and lower quartiles, the median is marked by a vertical line inside the box and whiskers extend to the 2nd and 98th percentile.

Mean PM10 emissions measured by Vectra and Sniffer for different lanes of the E18 are presented in Figure 64 and Table 14. The Sniffer shows higher absolute emission values in all cases compared to Vectra except for the southbound bus lane. The TEOM data saving setup is causing the delayed influence of dust sources in the northern part of the bus lane on the Sniffer results. The emission ratio for Sniffer and Vectra is 3.6, as average over all lanes. For the northbound direction both vehicles show similar variation of the emission levels between lanes.

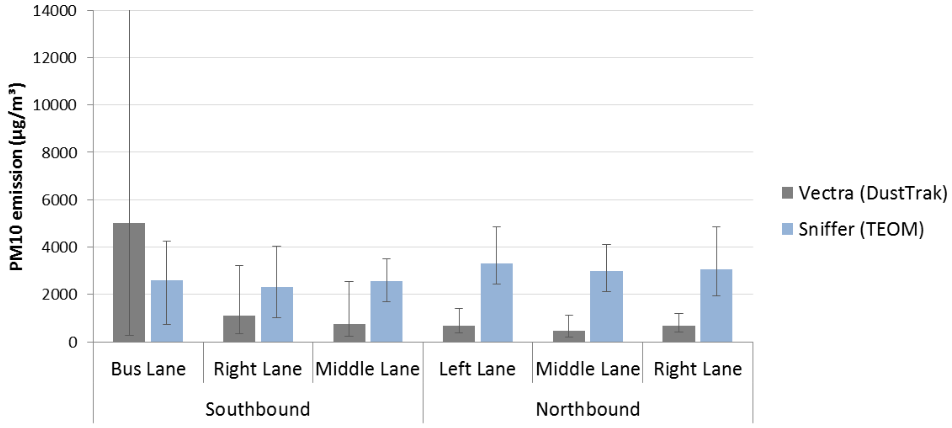
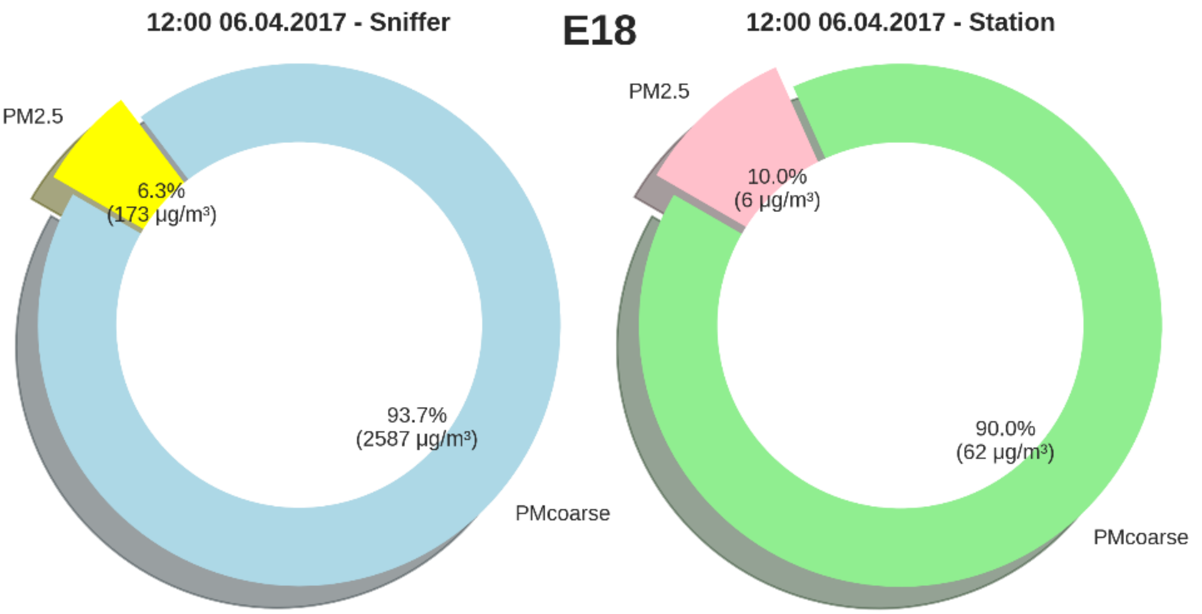


Figure 64. Mean PM10 emission level measured for different lanes on E18 with Vectra and Sniffer. Error bars represent 2nd and 98th percentile values.

Table 14. PM10 emission (µg/m³) measured by Vectra and Sniffer as mean values for different lane.

		Sniffer (TEOM)	Vectra (DustTrak)
Southbound	Bus Lane	2611	5007
	Right Lane	2312	1088
	Middle Lane	2563	736
Northbound	Left Lane	3292	693
	Middle Lane	2998	464
	Right Lane	3059	685

The variation of emissions, both along-road and lateral, can partly be explained by the position of the measurement vehicles. Suspension of dust may increase significantly when driving outside of the wheel tracks. Measurement vehicles are usually positioned in the middle of the lane, but vehicles may shift from the central line if required by the traffic or when changing lanes. The latter was the likely reason for the high emission points in the beginning of the right and middle lane towards south (Figure 62).



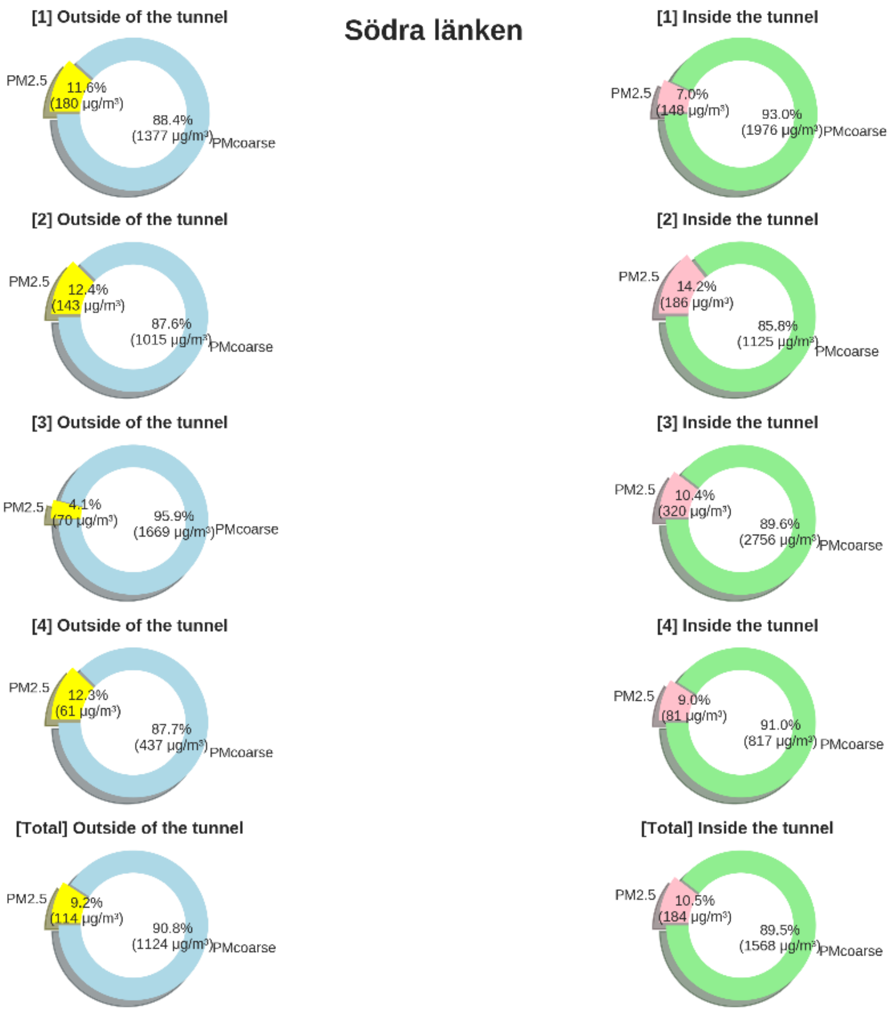
Date	Condition	Speed km/h	PM10 µg/m³	PMcoarse µg/m³	PM2.5 µg/m³	Ratio % [PM2.5:PM10]
14:00 06.04.2017	Sniffer	66.0	2761.3	2587.4	173.9	6.3
14:00 06.04.2017	Station	0.0	68.9	62.1	6.9	10.0

Figure 65. Comparison of measured percentage of PM2.5 and PM10 concentrations on highway E18 from Sniffer vehicle and from SLB measurement station.

Figure 65 is showing measured PM percentages from E18. Sniffer data is combined average from all the lanes and both directions. Station data is average from the same time period as Sniffer was measuring road surface. Assumption is that vehicle emissions has affected more to station data and increased the PM2.5 concentration compared to Sniffer results.

Mobile tunnel measurements

Results in Figure 66 show that there wasn't any clear difference when measuring similar road inside and outside of the tunnel. Average concentrations were lower on outside sections. However, average driving speed inside the tunnel was higher and that will increase the concentration.



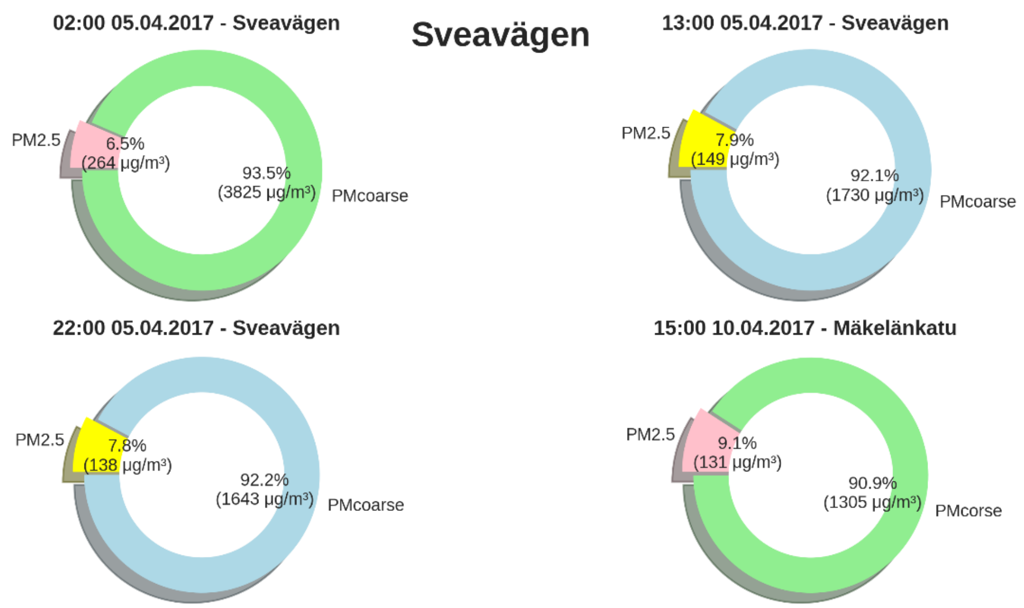
Round	Location	Speed km/h	PM10 µg/m³	PMcoarse µg/m³	PM2.5 µg/m³	Ratio % [PM2.5:PM10]
1	Outside	37.0	1558.0	1377.8	180.2	11.6
2	Outside	30.0	1158.8	1015.2	143.5	12.4
3	Outside	48.0	1740.6	1669.7	70.9	4.1
4	Outside	39.0	498.6	437.2	61.4	12.3
Total	Outside	38.5	1239.0	1125.0	114.0	9.2
1	Inside	72.0	2124.3	1976.2	148.1	7.0
2	Inside	33.0	1312.1	1125.2	186.9	14.2
3	Inside	67.0	3077.4	2756.7	320.6	10.4
4	Inside	41.0	898.0	817.0	81.0	9.0
Total	Inside	53.25	1753.1	1568.9	184.2	10.5

Figure 66, Sniffer PM results from tunnel measurements. Outside means the road section before entering the tunnel or after exiting the tunnel.

Mobile street measurements in Stockholm city street

Figure 67 is showing Sniffer concentrations from Sveavägen. On Sveavägen dust binding was performed during the night of 5.4. Decreasing on concentrations is clearly seen after the dust binding, less than half from initial level.

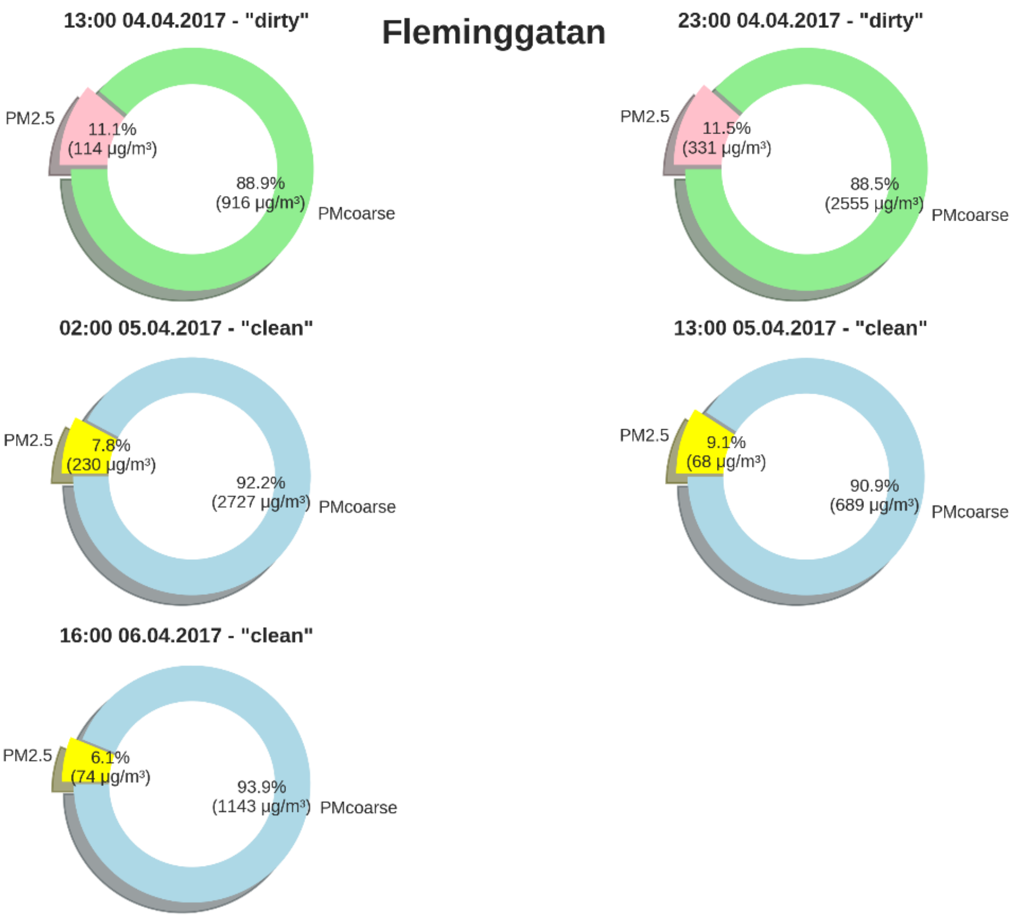
Also, the relatively PM2.5 ratio is increasing. Reason is most likely that the exhaust emissions can be seen on the concentration more clearly when the dust from the road surface is bound.
As a comparison, Figure 67 also shows Sniffer concentration from Helsinki. The location Mäkeläkatu, is quite similar to Sveavägen, a multilane street on an urban area.



Date	Condition	Site	PM10 µg/m³	PMcoarse µg/m³	PM2.5 µg/m³	Ratio % [PM2.5:PM10]
02:00 05.04.2017	Dirty	33.0	4090.2	3825.8	264.3	6.5
13:00 05.04.2017	Bound	31.0	1879.2	1730.1	149.1	7.9
22:00 05.04.2017	Bound	31.0	1781.3	1643.2	138.1	7.8
15:00 10.04.2017	Dirty	26.4	1436.4	1305.3	131.1	9.1

Figure 67, Sniffer PM results from Sveavägen, including PM levels from Mäkelänkatu, Helsinki.

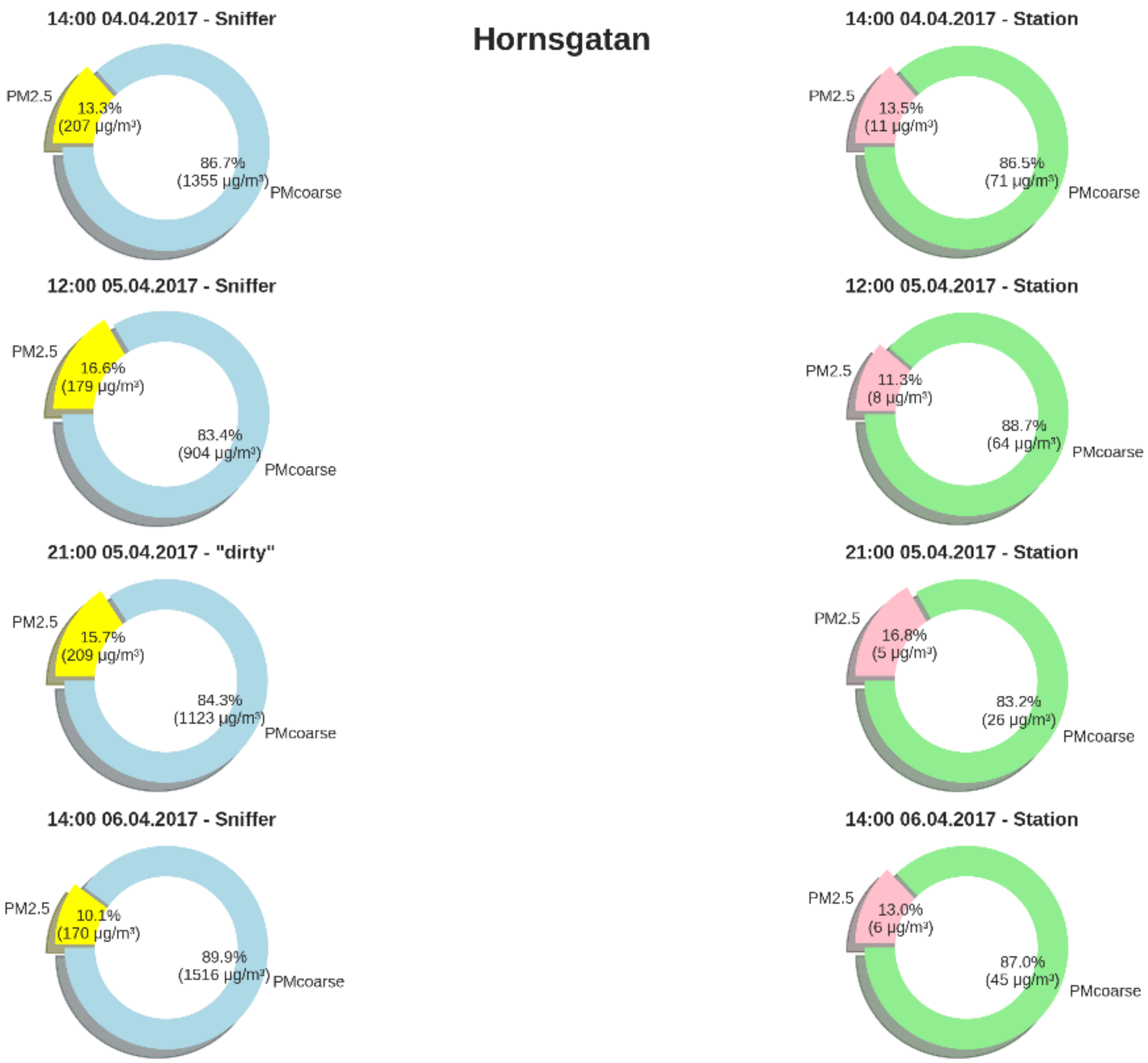
Figure 68 shows that PM10 increased slightly right after the sweeping. However, the PM2.5 was instantly decreasing.



Date	Condition	Speed km/h	PM10 µg/m³	PMcoarse µg/m³	PM2.5 µg/m³	Ratio % [PM2.5:PM10]
13:00 04.04.2017	Before	21.0	1031.1	916.7	114.4	11.1
23:00 04.04.2017	Before	36.0	2886.9	2555.4	331.5	11.5
02:00 05.04.2017	After	43.0	2958.6	2727.9	230.7	7.8
13:00 05.04.2017	After	20.0	758.5	689.7	68.9	9.1
16:00 06.04.2017	After	24.0	1218.1	1143.2	74.9	6.1

Figure 68. Sniffer PM results from Fleminggatan, before and after the cleaning

Figure 69 shows that the cleaning didn't affect directly to Sniffer overall PM concentrations. Similar trend can be seen from station data. Avg. measuring speed was lower on 5.4 and that will decrease the overall concentration.



Date	Condition	Speed km/h	PM10 µg/m³	PMcoarse µg/m³	PM2.5 µg/m³	Ratio % [PM2.5:PM10]
14:00 04.04.2017	Before	30.0	1563.3	1355.8	207.5	13.3
12:00 05.04.2017	Before	25.0	1084.0	904.4	179.6	16.6
21:00 05.04.2017	Before	35.0	1333.7	1123.7	210.0	15.7
14:00 06.04.2017	After	31.0	1687.7	1516.9	170.8	10.1

Date	Condition	Site	Grimm PM10 µg/m³	GRIM PMcoarse µg/m³	Grimm PM2.5 µg/m³	Ratio % [PM2.5:PM10]
14:00 04.04.2017	Before	Station	71.3	60.2	11.2	15.7
12:00 05.04.2017	Before	Station	64.3	56.1	8.2	30.9
21:00 05.04.2017	Before	Station	26.4	21.1	5.3	20.2
14:00 06.04.2017	After	Station	45.3	38.6	6.8	14.9

Figure 69. Sniffer PM results from Hornsgatan, before and after the cleaning

Because some issues with OPS instrument, size distribution is measured only from Hornsgatan, before and after cleaning of the street. The size distributions (Figure 70) show that most of the particles are coarser than 1.5 µm. The number concentration level is lower after cleaning, but there seem to be no shift in the size distribution caused by cleaning.

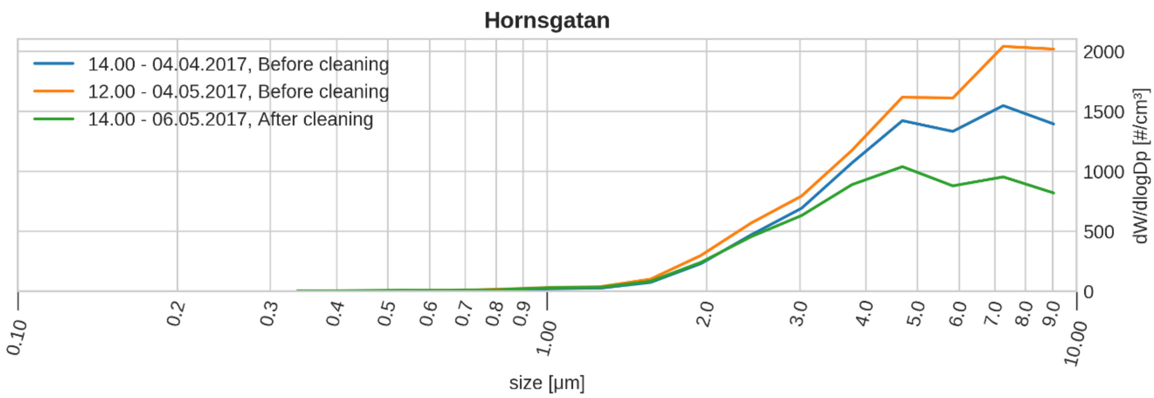


Figure 70. Measured size distributions from Hornsgatan

Stationary air quality measurements

The PM10 and PM2.5 (when available) from the street sites in central Stockholm during the campaign are presented in Figure 71 as 15-minute averages.

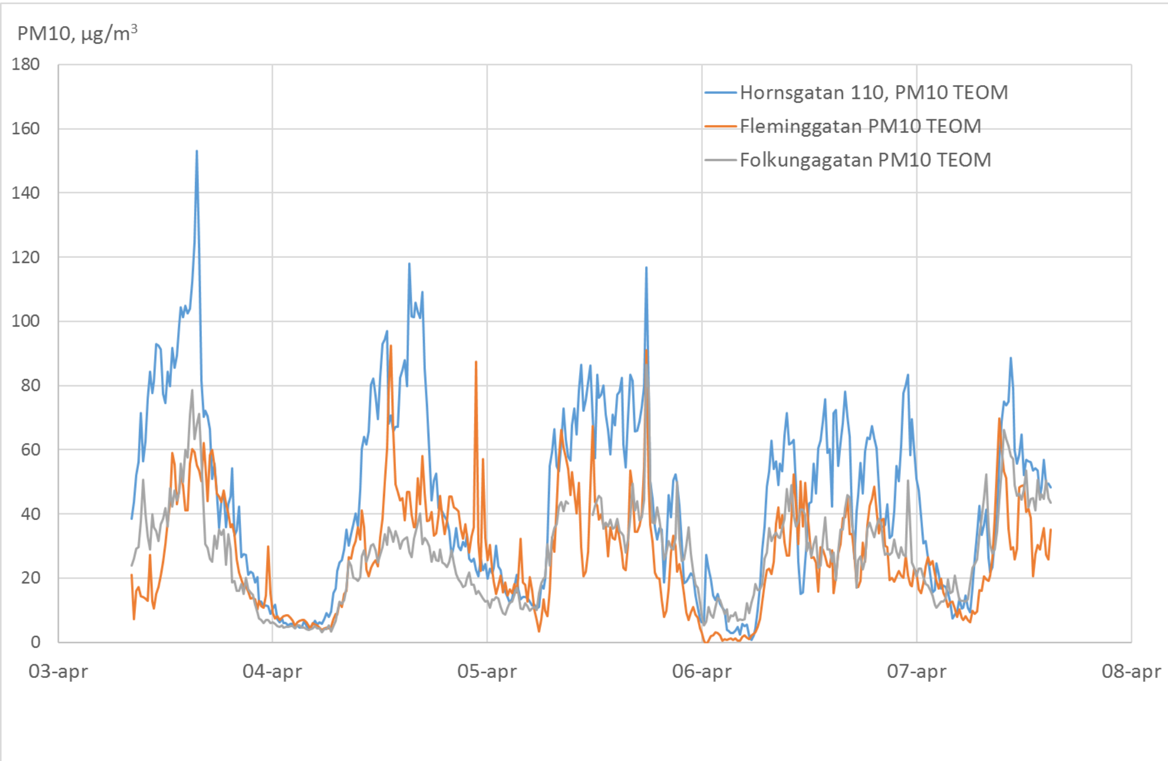


Figure 71. Observed PM10-concentration at the street sites in Stockholm during the NORDUST campaign.

More detailed experiments were performed on Hornsgatan including cleaning experiment. Both instruments measuring PM10 as well as PM2.5 and street surface wetness at Hornsgatan is presented in Figure 72. The PM2.5 is only a small fraction of the total PM10 measured at Hornsgatan. The cleaning experiment shows an increase in street wetness before lunch on Thursday the 6th April. A sharp decrease in PM10-concentration was observed during the period with wet street.

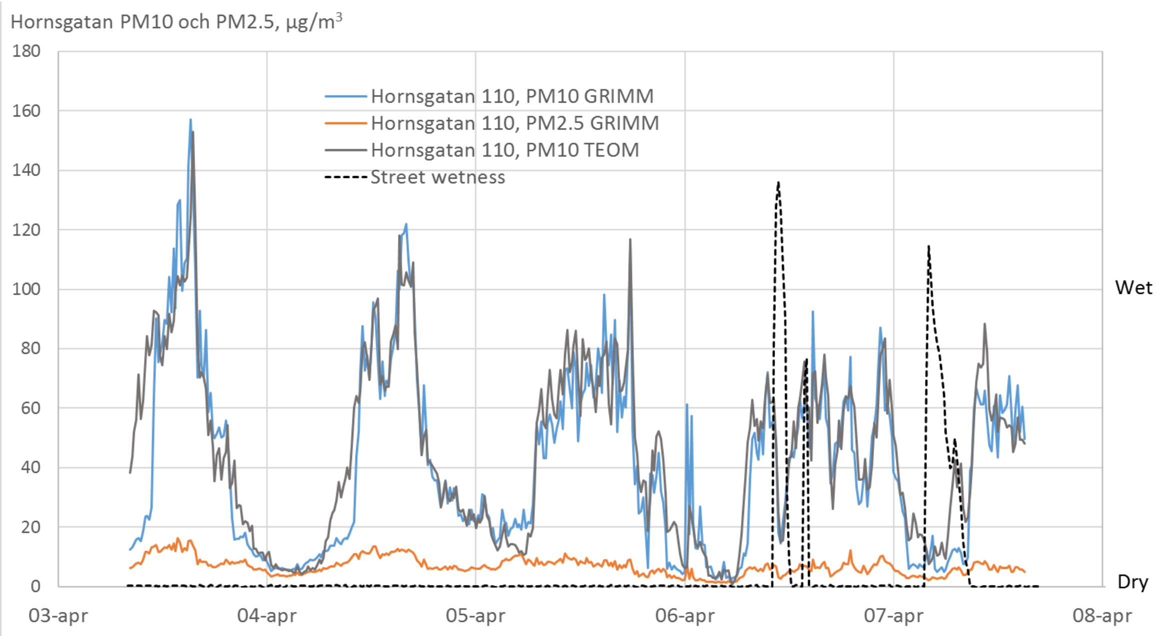


Figure 72. PM10, PM2.5 and street surface wetness at Hornsgatan during the NORDUST campaign.

Evaluation of cleaning Hornsgatan

An experiment to test the effect of flushing followed by vacuum sweeping can be seen in Figure 73. where both PM10 instruments (TEOM and Grimm) shows in 15 minutes time resolution the PM10 concentrations on the experiment day, April 6 2017. The direct effect of flushing the road surface with water is very clear, around 11:00 when the street cleaning was conducted the concentrations of PM10, on both instruments, dropped substantially and remained low for an hour before reaching back to similar levels as before the cleaning.

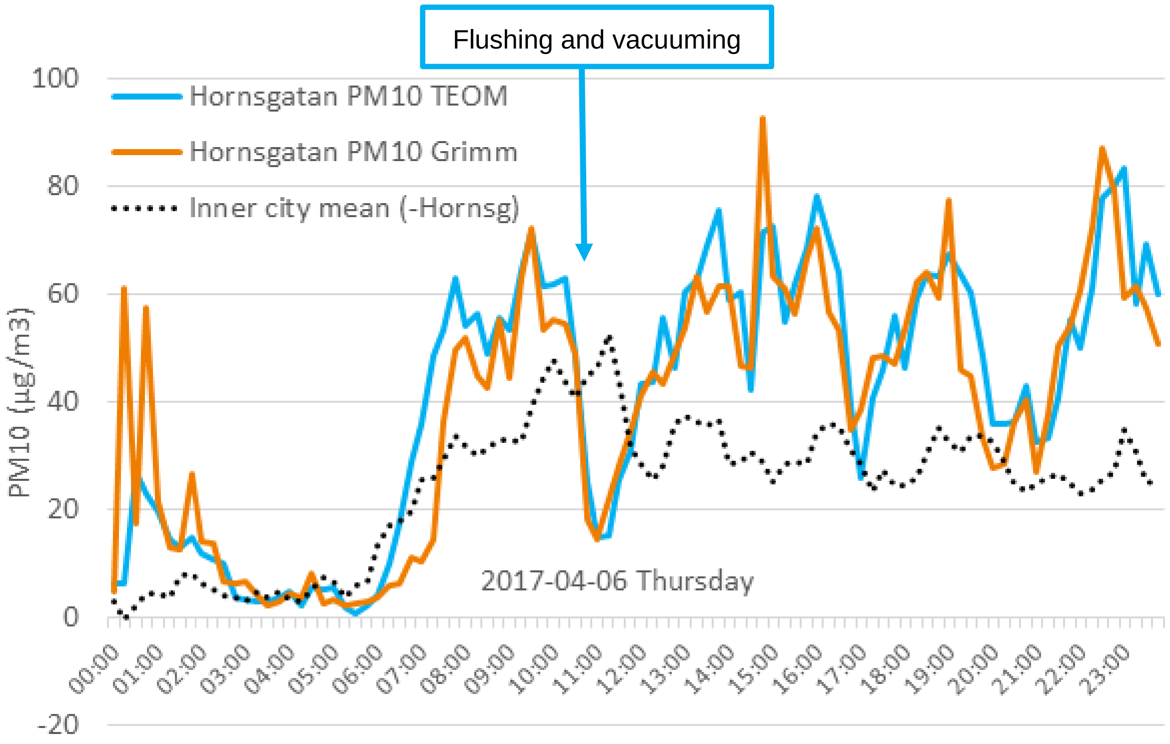


Figure 73 The effect of street cleaning with vacuum can be seen by looking at the PM10 concentrations measured with TEOM Grimm for every 15 minutes during the experiment of cleaning Hornsgatan, which occurred at 11:00 Thursday April 6 2017. Three other inner-city measurement stations also measure PM10 and a mean value is shown as the black dotted line in the figure. TEOM is the blue line, Grimm the orange.

Emission factors Hornsgatan

During the Stockholm campaign emission factors for PM10 were calculated for Hornsgatan. Both based on measurements and from the NORTRIP model (Figure 74).

Figure 74. Calculated PM10 emission factor at Hornsgatan from NORTRIP during the Stockholm campaign.

Emission factors for the measurement campaign in Stockholm 3–7 April 2017 was calculated using detailed vehicle composition data from measurement campaign in autumn 2017 conducted by the City of Stockholm. Where license plates from all vehicle passing vehicles at Hornsgatan was sorted after vehicle type (personal car, light duty vehicle, heavy duty vehicle and bus), fuel (petrol, diesel, ethanol E85, gas, fully electric), and euro class (pre-euro to euro 6) resulting in 141 possible brackets for each passing vehicle to end up in, all of these brackets were then linked to emission factors for NO_x in HBEFA 3.3. Data was assimilated in 15 minutes intervals and thus the calculated emission factor for NO_x is given as a mean of all vehicles within those 15 minutes. One work week (Monday-Friday) of vehicle measurement data was used to make a daytime variation in NO_x emission factors for Hornsgatan. To calculate the PM10 emission factor for Hornsgatan a method described in Ferm & Sjöberg (2015) was utilized. The equation is applicable if you have the NO_x emission factors for the traffic of interest and have measurement data from a curb side station and a background station for both NO_x and PM10. The equation used is:

$$EF_{PMx} = EF_{NOx} \frac{\Delta PMx}{\Delta NOx}$$

where ΔPMx and ΔNOx are the differences between the curb side measurements and the background measurements, the fraction is multiplied by the emission factors for NO_x. This method assumes that NO_x and PM10 is diluted and dispersed in the exact same way. In Figure 75 the results following the method above are shown as a time series from the measurement campaign week in Stockholm 3-7 April 2017. Only daytime hours are included in the graph, because at night the background measurement station sometimes measure higher concentrations than curb side, leading to negative emission factors for PM10. Both measurement stations, curb side and urban background, has exactly the same instrumentation as described in the method.

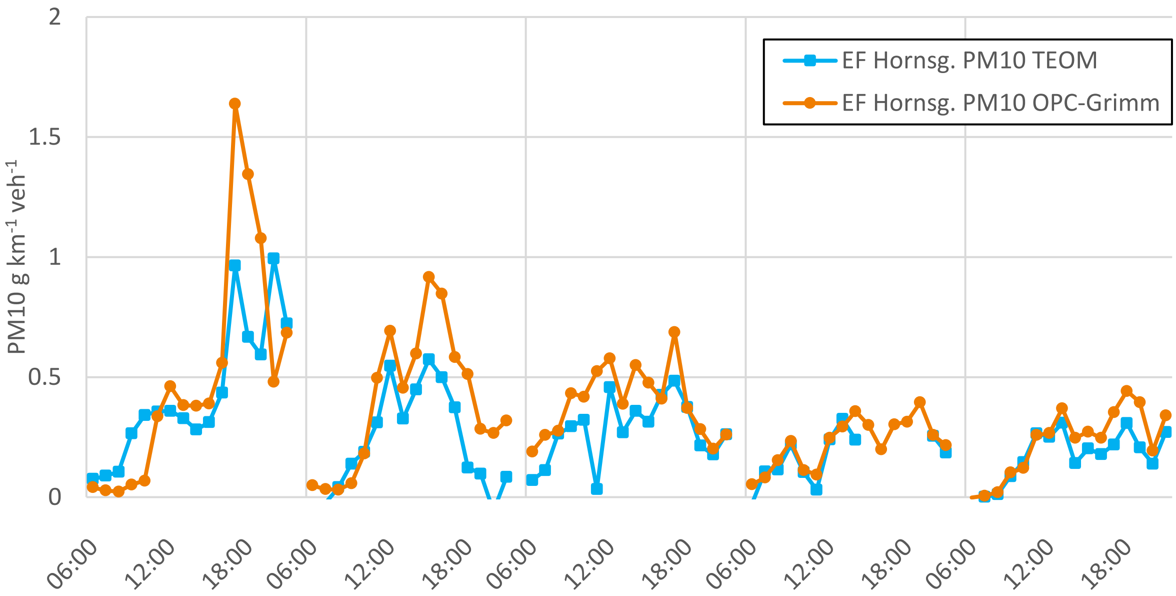


Figure 75. Time series of emission factors for Hornsgatan during the field test campaign in Stockholm 3 - 7 April 2017. Emission factors solely for daytime hours 06:00 – 21:00. Comparison between emission factors calculated from PM10-data from both TEOM 1400AB (blue line) and Grimm EDM 180 (orange line).

Size distributions

The size distribution of coarse particles is measured by the GRIMM EDM 180 at Hornsgatan, E18 as well at a street site in Uppsala. The volume-size distribution from these three sites (Figure 76) shows some differences that could be related to the different traffic patterns and road operation activities. Hornsgatan and Kungsgatan in Uppsala have relatively low speeds (40-50 km/h) while the E18 is a highway with a speed of 70-90 km/h. Hornsgatan was, during March 2017, cleaned with vacuum technique and treated with CMA as dust binding (Gustafsson et al., 2018). When comparing Hornsgatan with Kungsgatan in Uppsala there were more larger particles (>3 µm) in Uppsala than at Hornsgatan. This could be a result of the intense cleaning at Hornsgatan removing the larger particles. At E18 there were more smaller particles (<3 µm) found compared to the city streets. Could the higher speed be the reason for more smaller particles at E18?

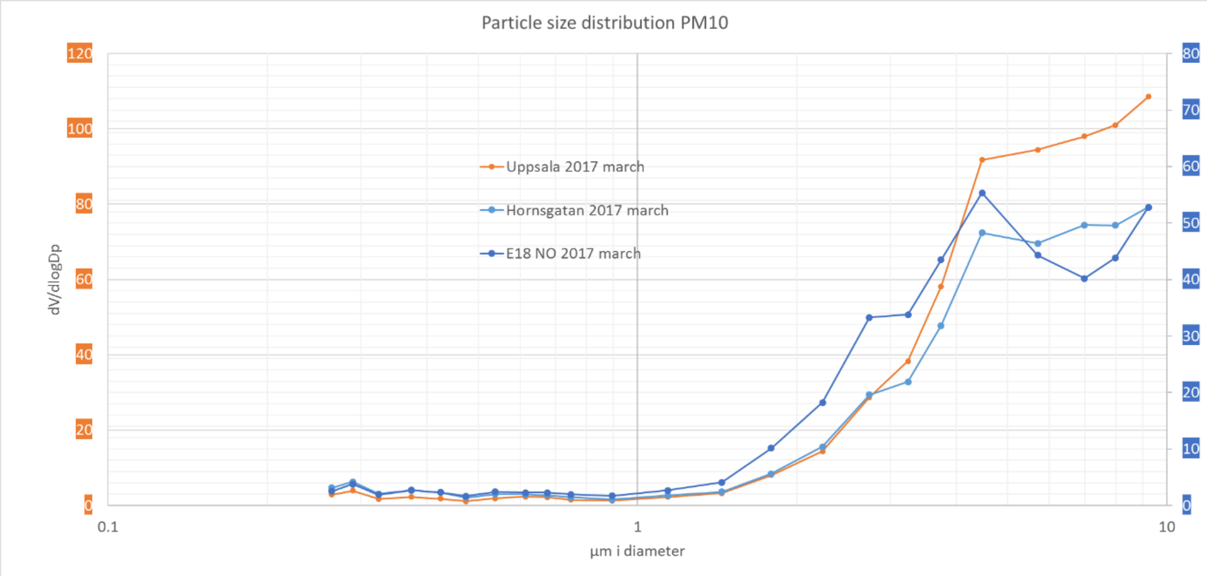


Figure 76. The daytime (07:00-19:00) mean volume size distribution during March 2017 from Hornsgatan, E18 and Uppsala Kungsgatan. Only dry street conditions are considered. Observe the different scales on the y-axes.

Cleaning with vacuum was performed at Hornsgatan with a total of 40 occasions during the winter 2016/2017. During the winter season 2017/2018 the vacuum cleaning was not used at all. The difference between the size distributions (Figure 77) indicated that more larger particles (>3 µm) were present in March 2018 compared to March 2017 which could be caused by the lack of vacuum cleaning in 2018.

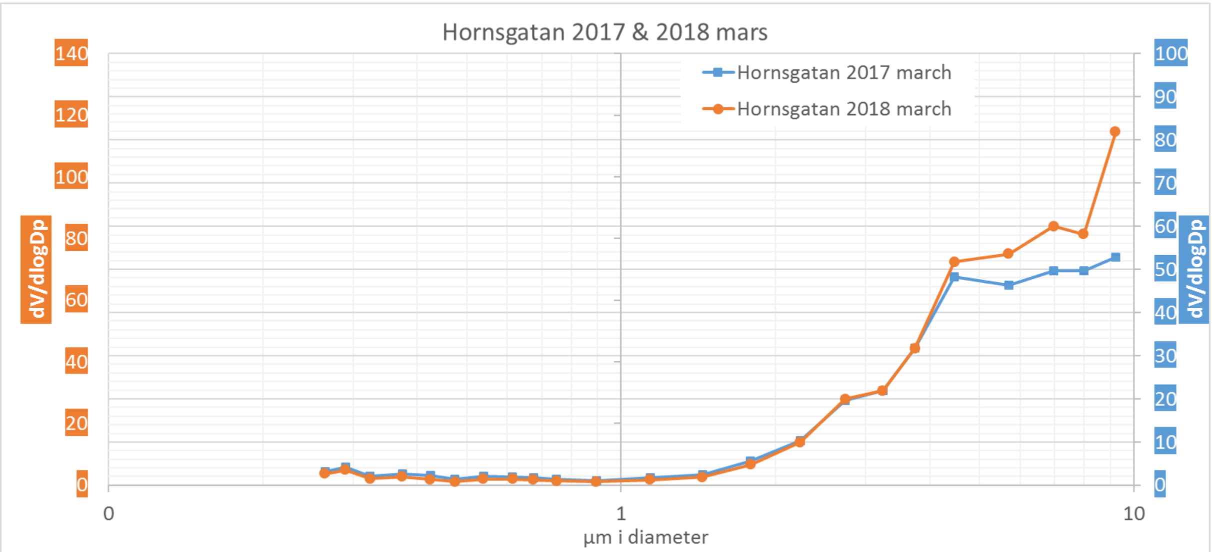


Figure 77. The daytime (07:00-19:00) mean volume size distribution during March 2017 and 2018 from Hornsgatan. Only dry street surface is considered. Observe the different scales on the y-axes.

Tunnel measurements

The PM10-concentrations from the stationary measurements in the Södra länken tunnel are higher than at the streets in the City, Figure 78. There concentrations in the tunnel is less affected by the out-door meteorology and the concentration are about the same every day.

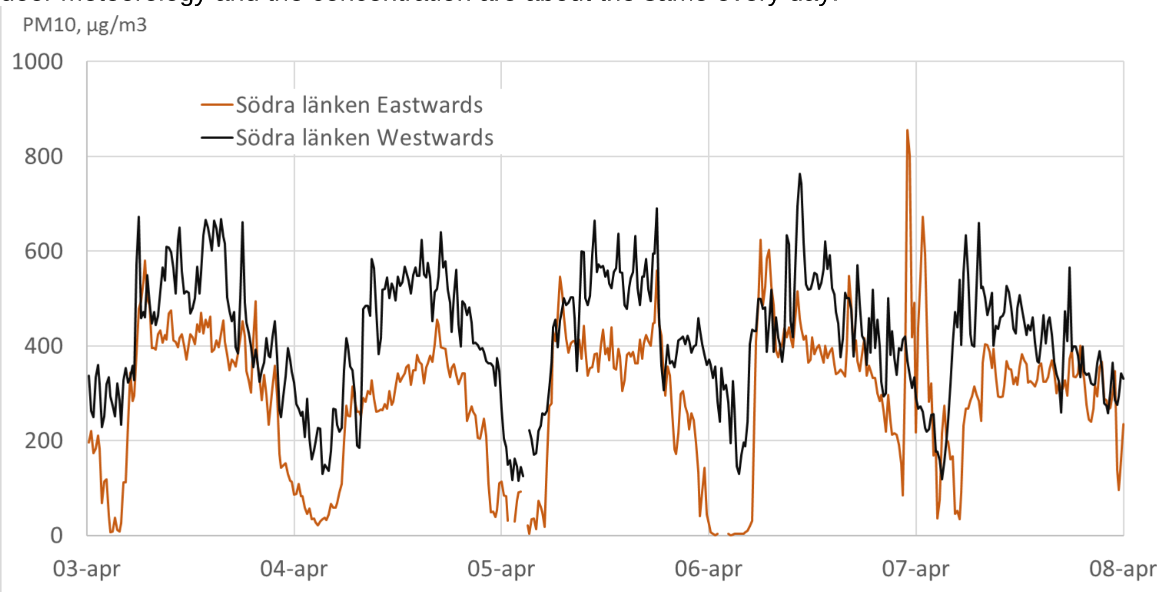


Figure 78. The PM10-concentration in Södra länken tunnels during the Stockholm campaign.

E18 measurements

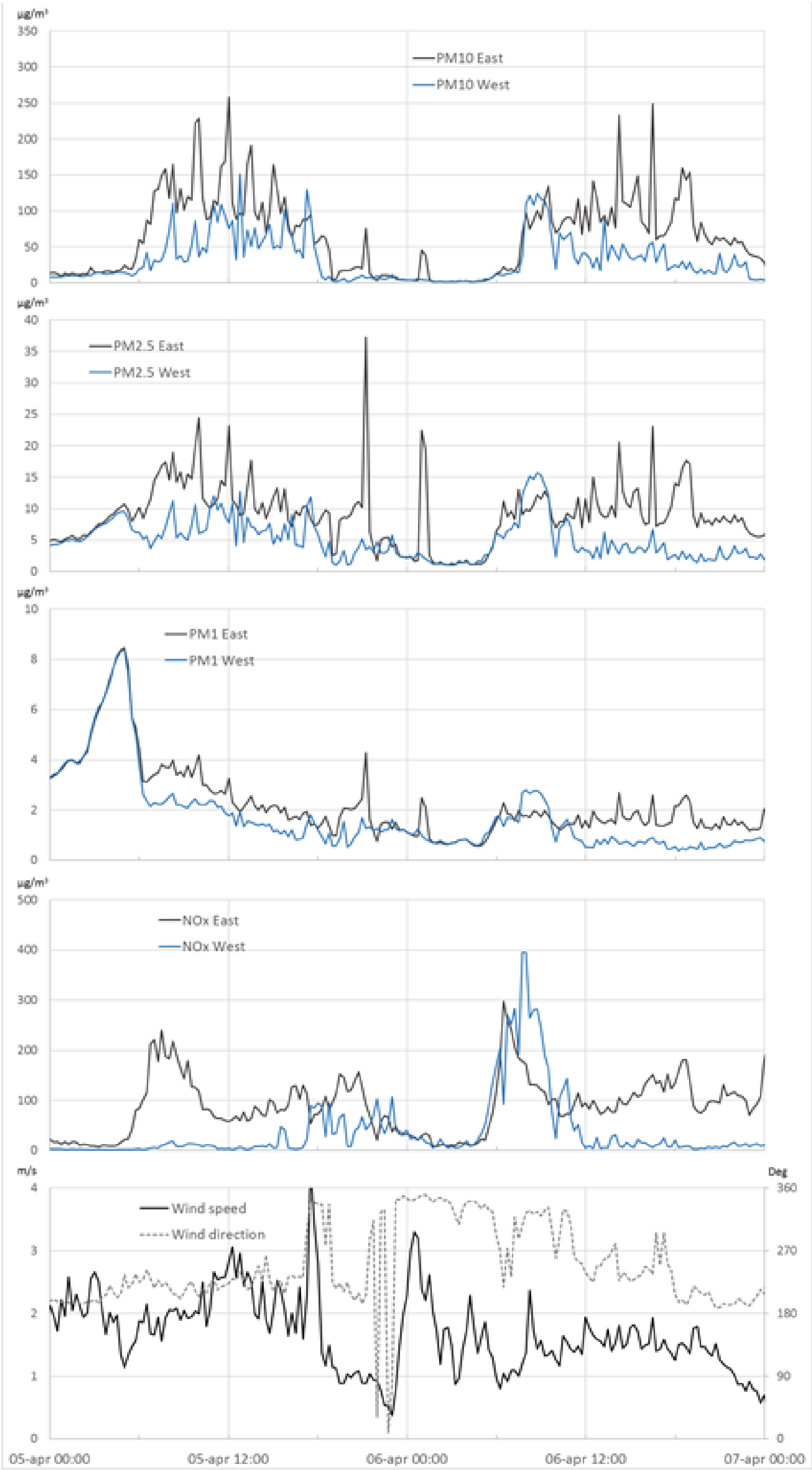


Figure 79. PM10, PM2.5, PM_1, NOx and wind parameters during two days at the E18 site.

Sweeping test on Fleminggatan

The results of the vacuum sweeping test show a general increase in dust load after sweeping, across the whole of the transect (Figure 80). This implies that dust is not just redistributed across the driving lane, but also added from upstream of the transect, or from adjacent surfaces, like the sidewalk.

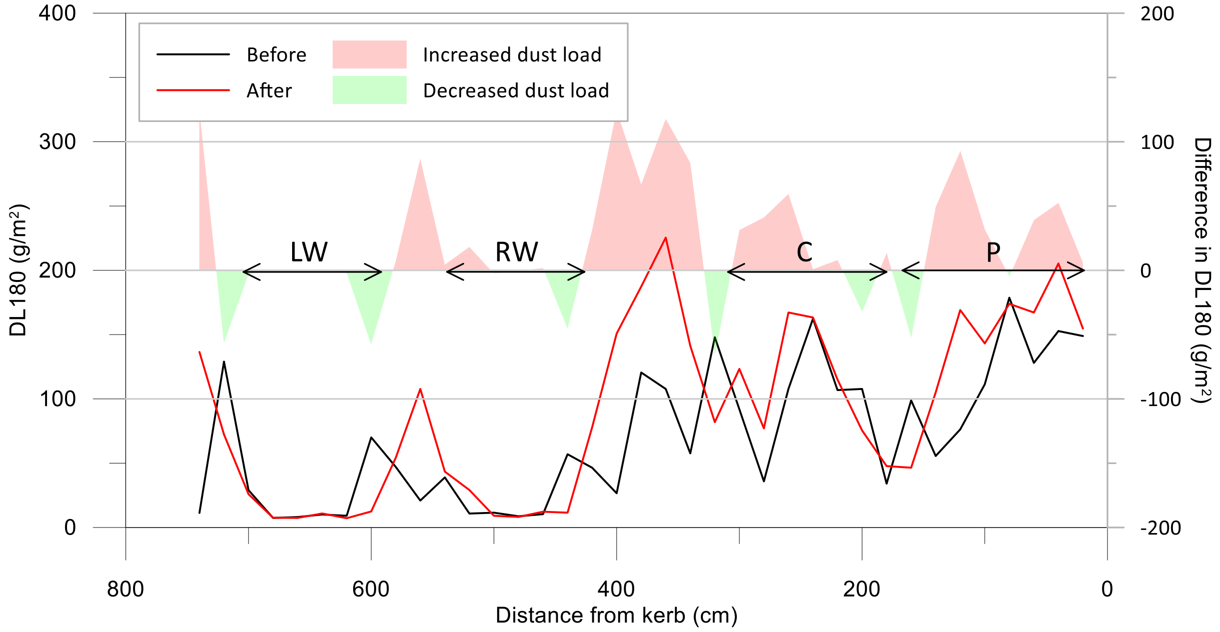


Figure 80. Turbidity profiles representing dust load before (red) and after (black) dry sweeping with DisaClean vacuum sweeper.

Flushing and vacuum sweeping test on Hornsgatan

The water flushing followed by vacuum sweeping managed to remove dust especially from the area between wheel tracks (Figure 81). Only minor increases in dust load is noted, especially in left wheel track and in the biking lane.

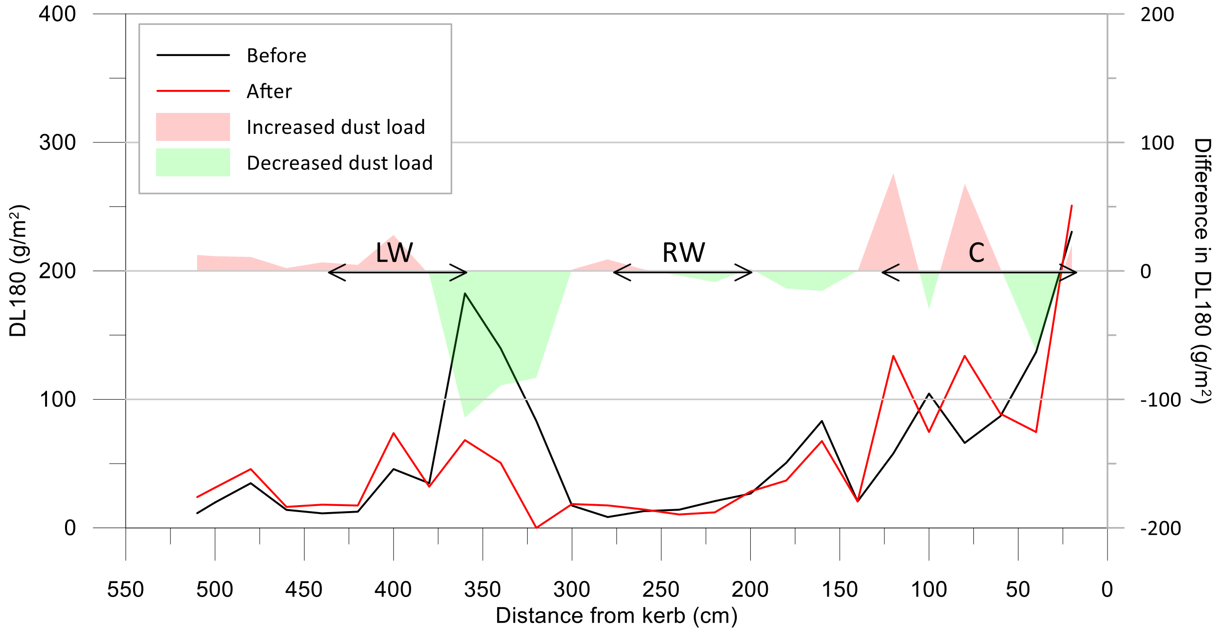


Figure 81. Turbidity profiles representing dust load before (red) and after (black) high pressure water flushing combined with sweeping with DisaClean vacuum sweeper.

Traffic dislocation test on Hornsgatan

The traffic dislocation test showed that the area between wheel tracks seem to be eroded by the dislocation of the traffic and is reduced by about 50 g/m^2 during the test.

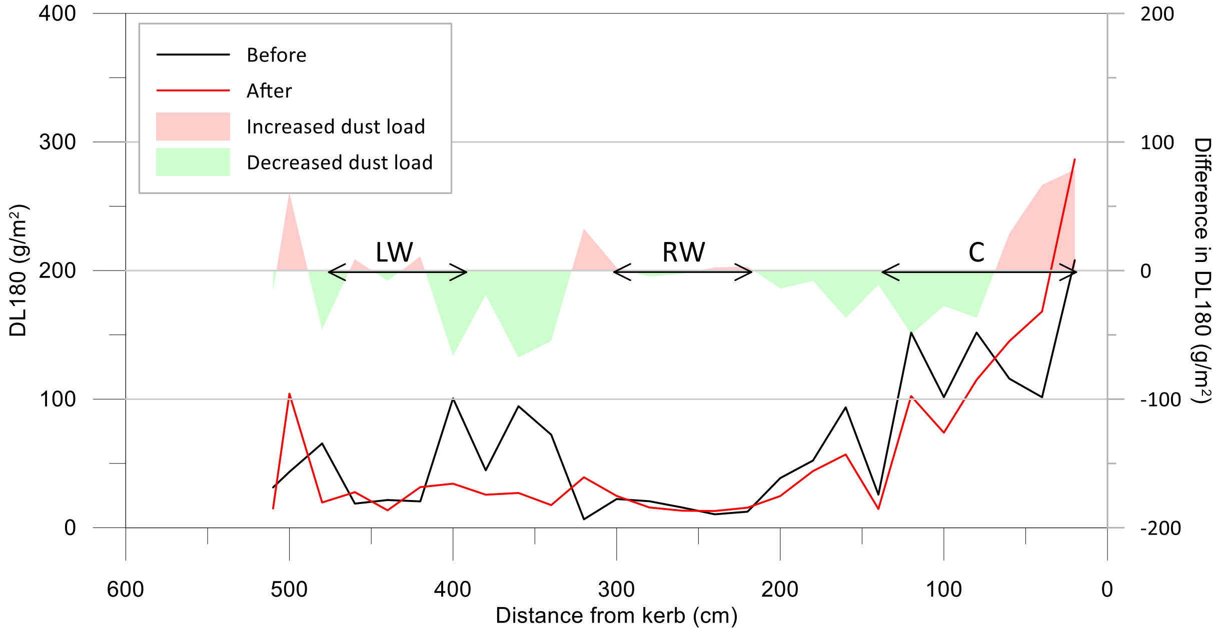


Figure 82. Turbidity profiles representing dust load before (red) and after (black) the traffic dislocation test.

Comparison between dust load and Sniffer signal

In Hornsgatan, two lanes are used in each direction and traffic can move across these. The dust amount in wheel tracks increase after sweeping, likely due to redistribution of dust from surfaces outside the wheel tracks. The dust load is high in between wheel tracks but is reduced after flushing and vacuum sweeping (still rather high, though). The Sniffer signal increase after flushing and vacuum sweeping reflecting the higher dust amounts in wheel tracks.

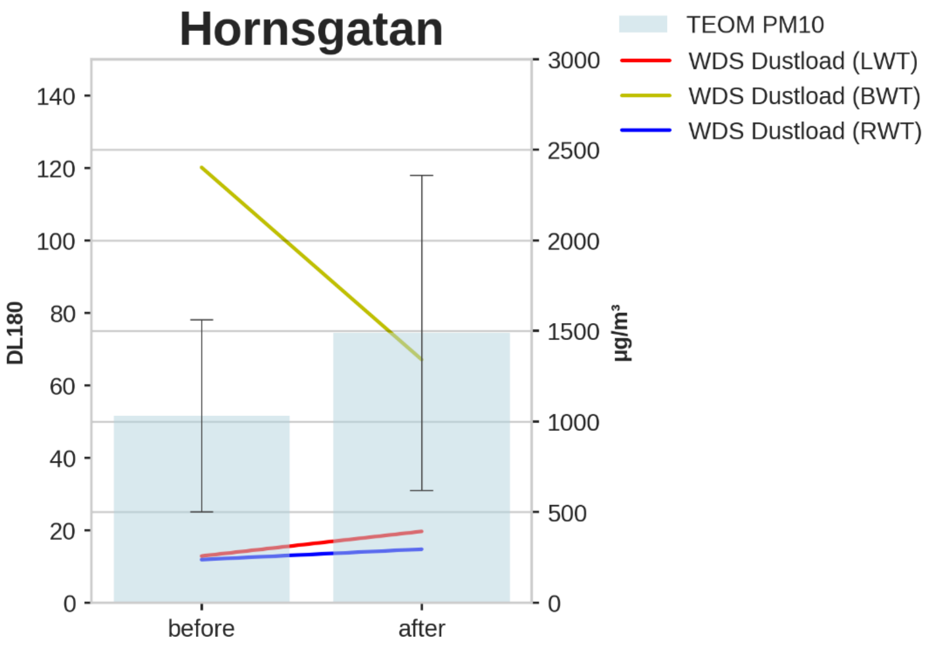


Figure 83. Comparison between Sniffer PM10 signal and WDS dust load on Hornsgatan.

At Fleminggatan, the traffic is confined to one lane and the wheel tracks especially well defined and narrower than on Hornsgatan. This also results in very clean wheel tracks, since they are constantly exposed to suspension to traffic. The dust load is equally low after the sweeping, while the dust load in between wheel tracks have increased. The Sniffer has a rather wide wheelbase, which will likely also suspend dust from the outer verges of the wheel tracks.

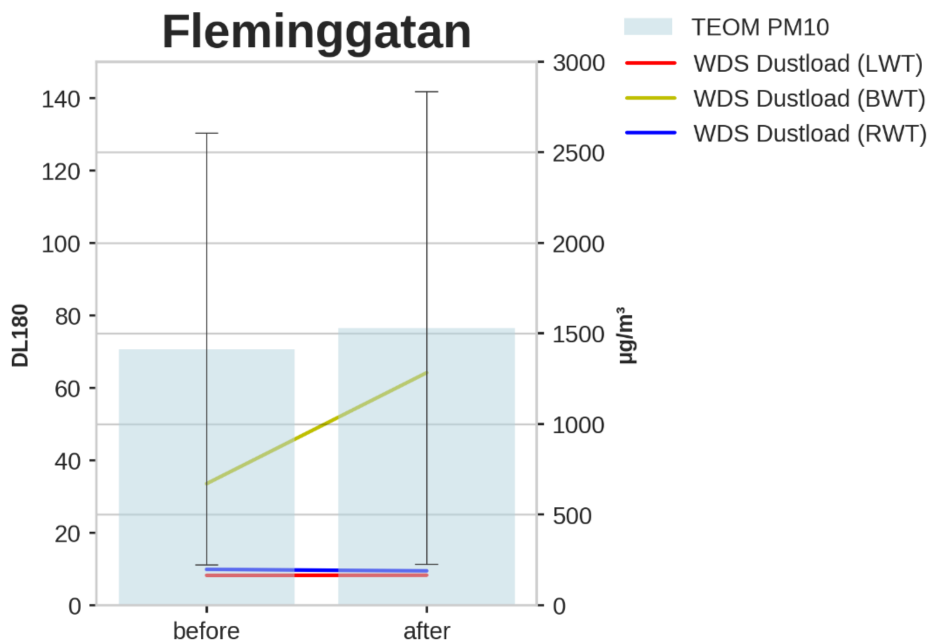


Figure 84. Comparison between Sniffer PM10 signal and WDS dust load on Fleminggatan.

WP2 Laboratory studies

Studded tyre tests in road simulator

Mass and number concentrations and particle size distributions

In Figure 85, the PM10-concetrations during the five days of testing are shown. When the simulator starts, the PM10 concentration rises and then level out on a quasi-stable level, where the production of PM10 is balanced by deposition in the simulator hall. During the test, temperatures in tyre, pavement and air rise due to friction heat. After each hour-long run, as the simulator stops, PM10 rapidly decreases due to running of the large filtering fan installed in the room. Simultaneously, the cooling system is run to lower the temperatures back to the initial starting temperatures as close as possible. The first and last runs each day are done using the same tyre set. Often, they end up on similar levels, but the inevitable drift in temperatures during the day as well as the wearing of tyres, studs and pavement, will result in slightly differing levels.

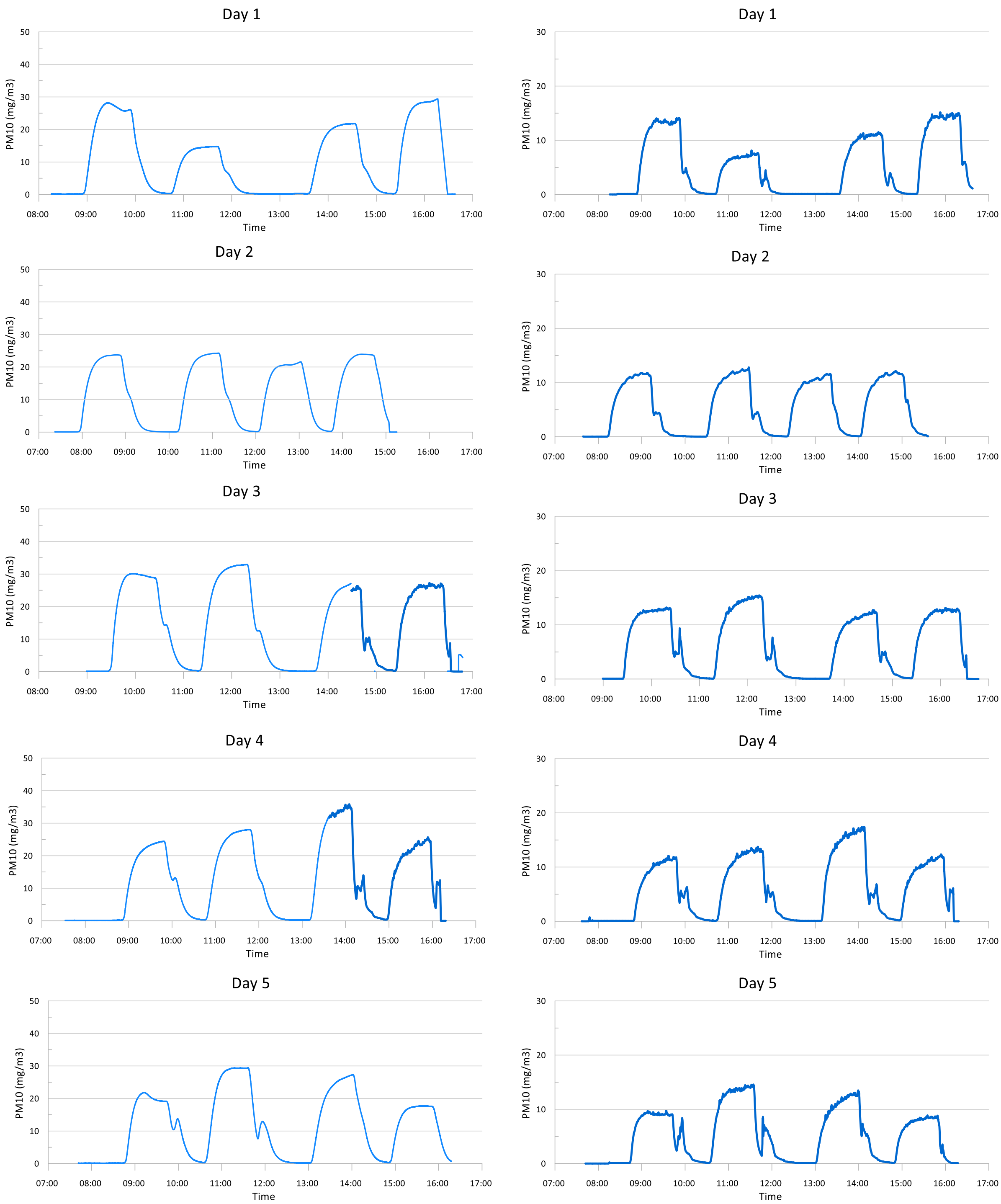


Figure 85. PM10 from TEOM (left) and DustTrak (right) instruments all test days. Some of TEOM-data day 3 and 4 is re-constructed from the correlation with DustTrak, due to TEOM instrument failures.

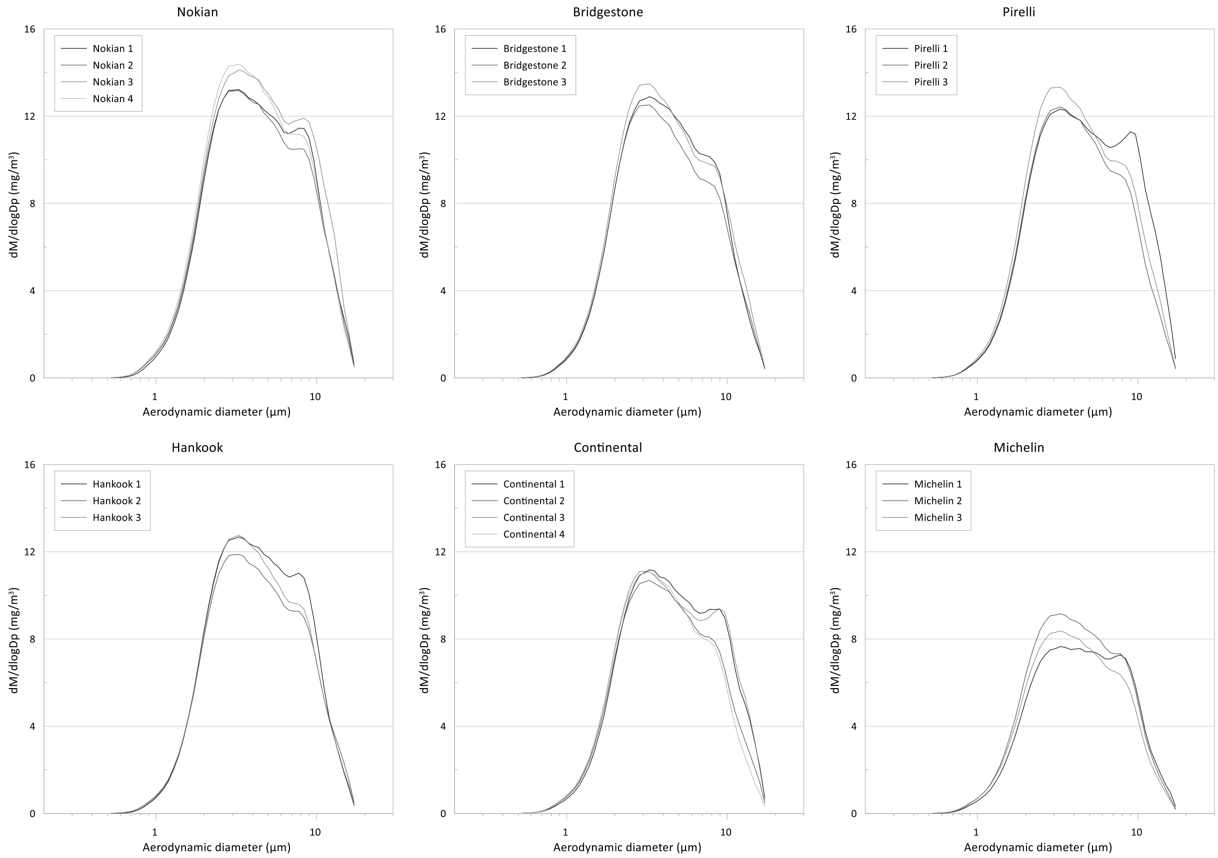


Figure 86. Mass size distributions of PM10 for all runs with the six tyre models tested. Mean values for the last 15 minutes before the end of each run.

Statistical analyses

The main focus of this paragraph is to use the results and initial observations in order to investigate statistical relations between tyres and PM10 concentration. The studied tyres were:

Label	Tyre
1	Nokian
2	Hankook
3	Bridgestone
4	Continental
5	Michelin
6	Pirelli

Since PM10 is measured using both TEOM and DustTrak, analyses are made on data for both instruments. Also analysed and presented are PM2.5 from DustTrak and particle number concentration (PNC) derived from the SMPS instrument.

PM10 (TEOM)

The data are shown in Figure 87, one subplot for each day. The bullets show the observations. The circles show the fitted values and the lines show the general behaviour estimated with the main analysis. The vertical distances between circles and bullets are estimates of the random variation. The plus-signs show the fitted values for the second analysis.

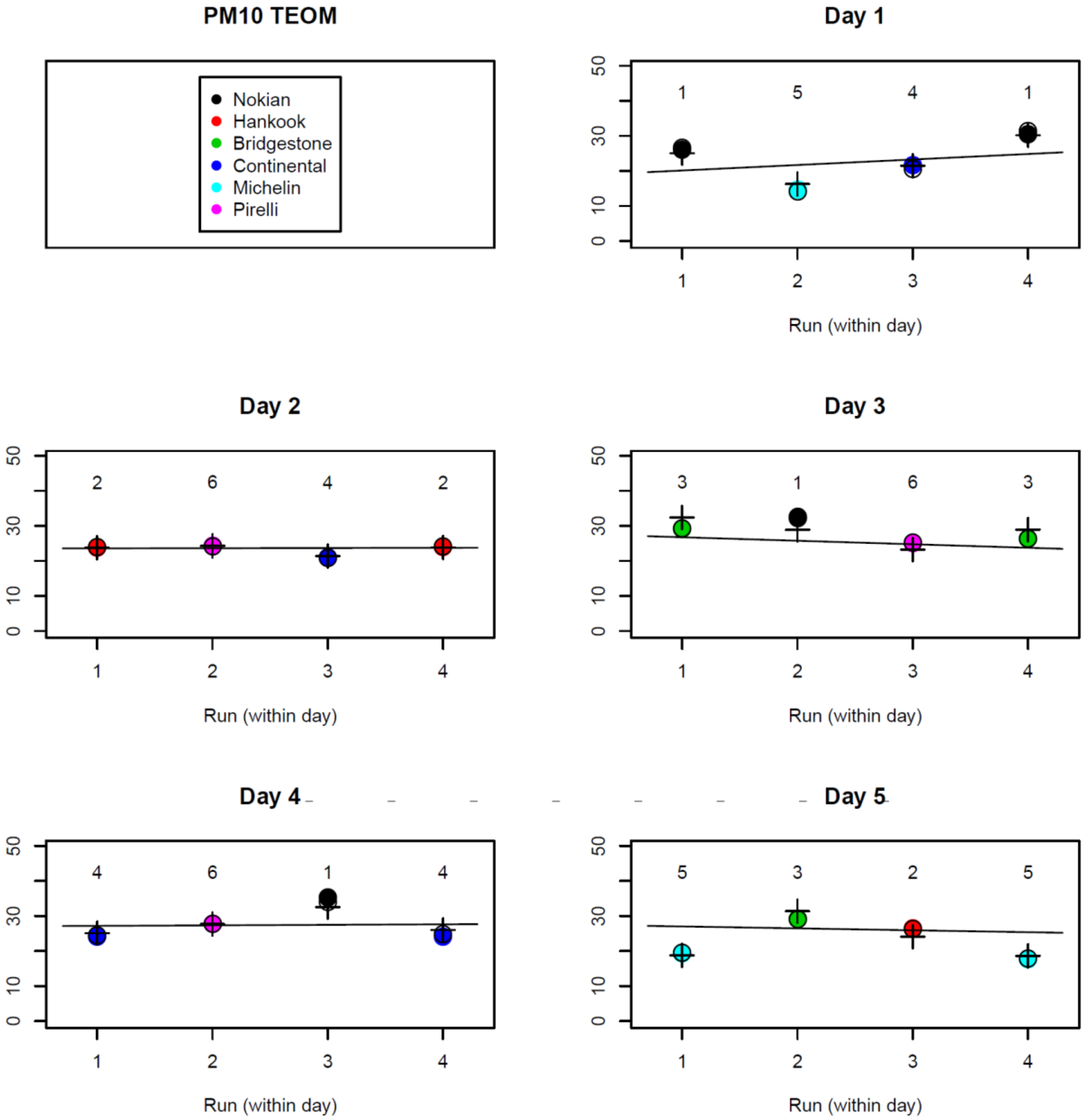


Figure 87

The coefficients are shown in Table 15. All 6 tyre effects are not estimated in the same analysis. The table combines results from two analyses. The levels estimate represent the middle of the day. The slope estimates the difference between two consecutive runs. The tyre effects compare each tyre with the mean of all tested tyres.

Table 15. Results of regression analysis for PM10 (TEOM).

	Estimate	Std. Error
Level day 1	22.46	0.62
Slope day 1	1.57	0.48
Level day 2	23.67	0.64
Slope day 2	0.05	0.48
Level day 3	25.26	0.63
Slope day 3	-1.00	0.48
Level day 4	27.40	0.63
Slope day 4	0.15	0.48
Level day 5	26.19	0.64
Slope day 5	-0.54	0.48
Tyre 1	6.59	0.59
Tyre 2	0.41	0.69
Tyre 3	2.65	0.69
Tyre 4	-2.70	0.60
Tyre 5	-7.47	0.69
Tyre 6	0.52	0.62

It is estimated that Tyre 1 results in 6.59 mg/m^3 higher concentration than the average of the tyres included in the study while tyre 2 results in 0.41 mg/m^3 higher than the average etc. The average overall level is about 25 varying at most about 5 units between days. The background level increase during day one, decrease during day 3 and 5 and is about constant day 2 and 4.

The analysis forces the estimates to be levelled out for the different number of observations for each tyre. The average of the 5 level estimates above is not exactly the same as the sample mean of all PM10 TEOM values.

When statistically testing the hypothesis that all tyres have equal PM10 concentrations against the alternative that there is at least some difference, P=0.0002198, meaning that the hypothesis that all tyres results in equal PM10 concentrations is rejected. All pairwise comparisons are shown in Table 16. Note that the p-values are not adjusted for multiple comparisons.

Table 16. Pairwise comparisons.

Comparison no.	Contrast	Estimate	P-value
1	1 - 2	6.18	0.002
2	1 - 3	3.95	0.010
3	1 - 4	9.29	0.000
4	1 - 5	14.06	0.000
5	1 - 6	6.08	0.001
6	2 - 3	-2.23	0.099
7	2 - 4	3.11	0.025
8	2 - 5	7.88	0.001
9	2 - 6	-0.10	0.920
10	3 - 4	5.34	0.004
11	3 - 5	10.11	0.000
12	3 - 6	2.13	0.087
13	4 - 5	4.77	0.006
14	4 - 6	-3.21	0.015
15	5 - 6	-7.98	0.001

As an example, tyre 1 results in 6.18 mg/m³ higher concentration than tyre 2, and the unadjusted p-value is 0.002.

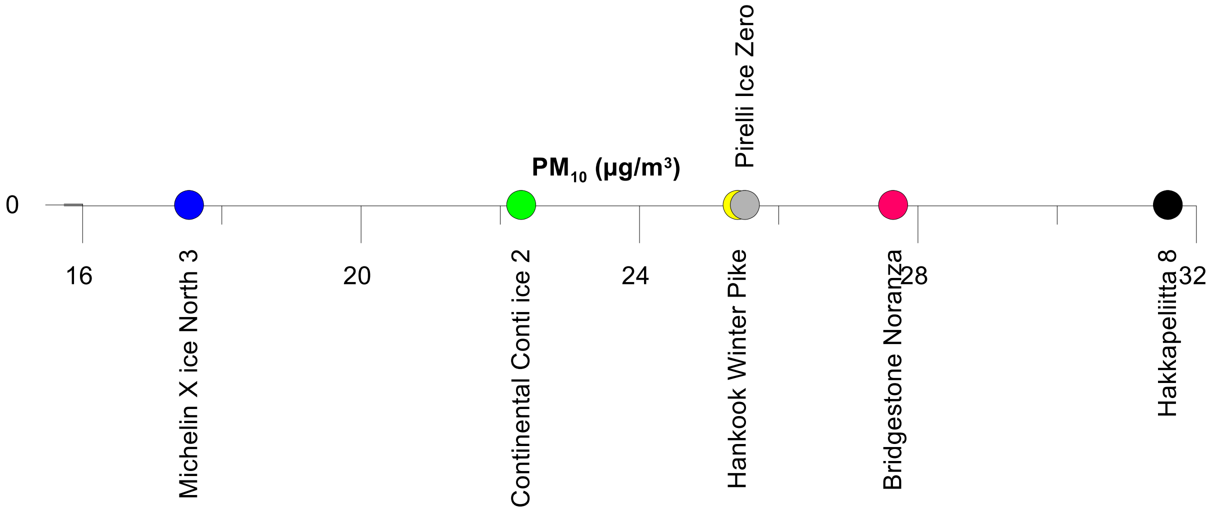


Figure 88. Ranking of adjusted mean PM10 concentration (TEOM).

PM10 (DustTrak)

The results are summarized for PM10 DustTrak and shown with the same format as for PM10 TEOM. Explanations how to read the results are only present in the previous section.

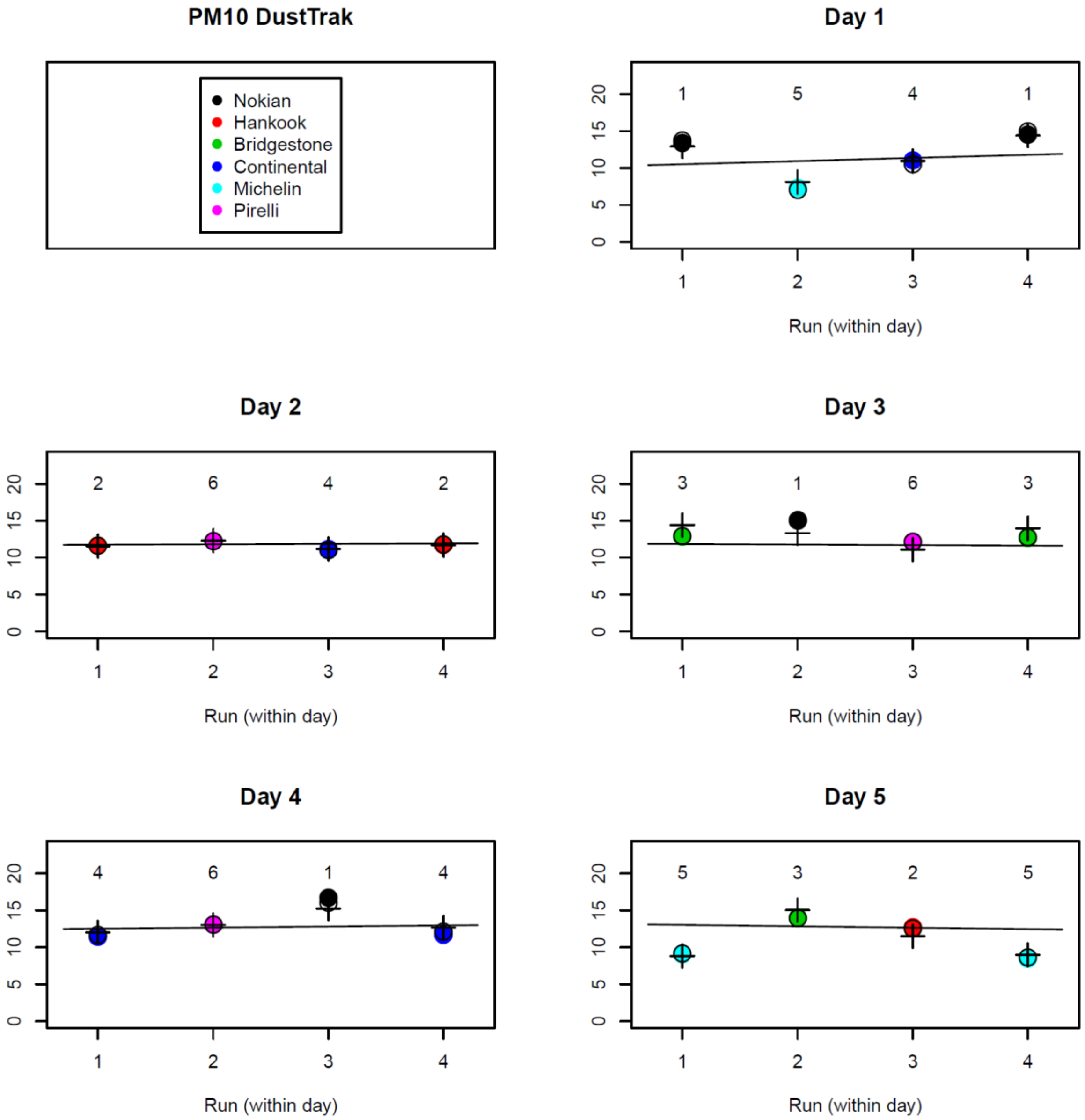


Figure 89

Table 17. Results of regression analysis for PM10 (DustTrak).

	Estimate	Std. Error
Level day 1	11.15	0.33
Slope day 1	0.43	0.26
Level day 2	11.83	0.34
Slope day 2	0.05	0.26
Level day 3	11.74	0.34
Slope day 3	-0.07	0.26
Level day 4	12.74	0.34
Slope day 4	0.14	0.26
Level day 5	12.75	0.34
Slope day 5	-0.19	0.26
Tyre 1	3.22	0.32
Tyre 2	-0.09	0.37
Tyre 3	1.10	0.37
Tyre 4	-0.83	0.32
Tyre 5	-3.84	0.37
Tyre 6	0.43	0.33

When testing the hypothesis that all tyres results in equal PM10 concentrations, the P value is 0.000387 and hypothesis is rejected.

Table 18. Pairwise comparisons.

Comparison no.	Contrast	Estimate	P-value
1	1 - 2	3.32	0.002
2	1 - 3	2.12	0.010
3	1 - 4	4.05	0.000
4	1 - 5	7.07	0.000
5	1 - 6	2.80	0.003
6	2 - 3	-1.19	0.098
7	2 - 4	0.73	0.220
8	2 - 5	3.75	0.001
9	2 - 6	-0.52	0.370
10	3 - 4	1.93	0.020
11	3 - 5	4.95	0.000
12	3 - 6	0.67	0.264
13	4 - 5	3.02	0.003
14	4 - 6	-1.25	0.046
15	5 - 6	-4.27	0.001

PM2.5 (DustTrak)

The results are summarized for PM2.5 DustTrak and shown with the same format as for PM10 TEOM. Explanations how to read the results are only present in the previous section.

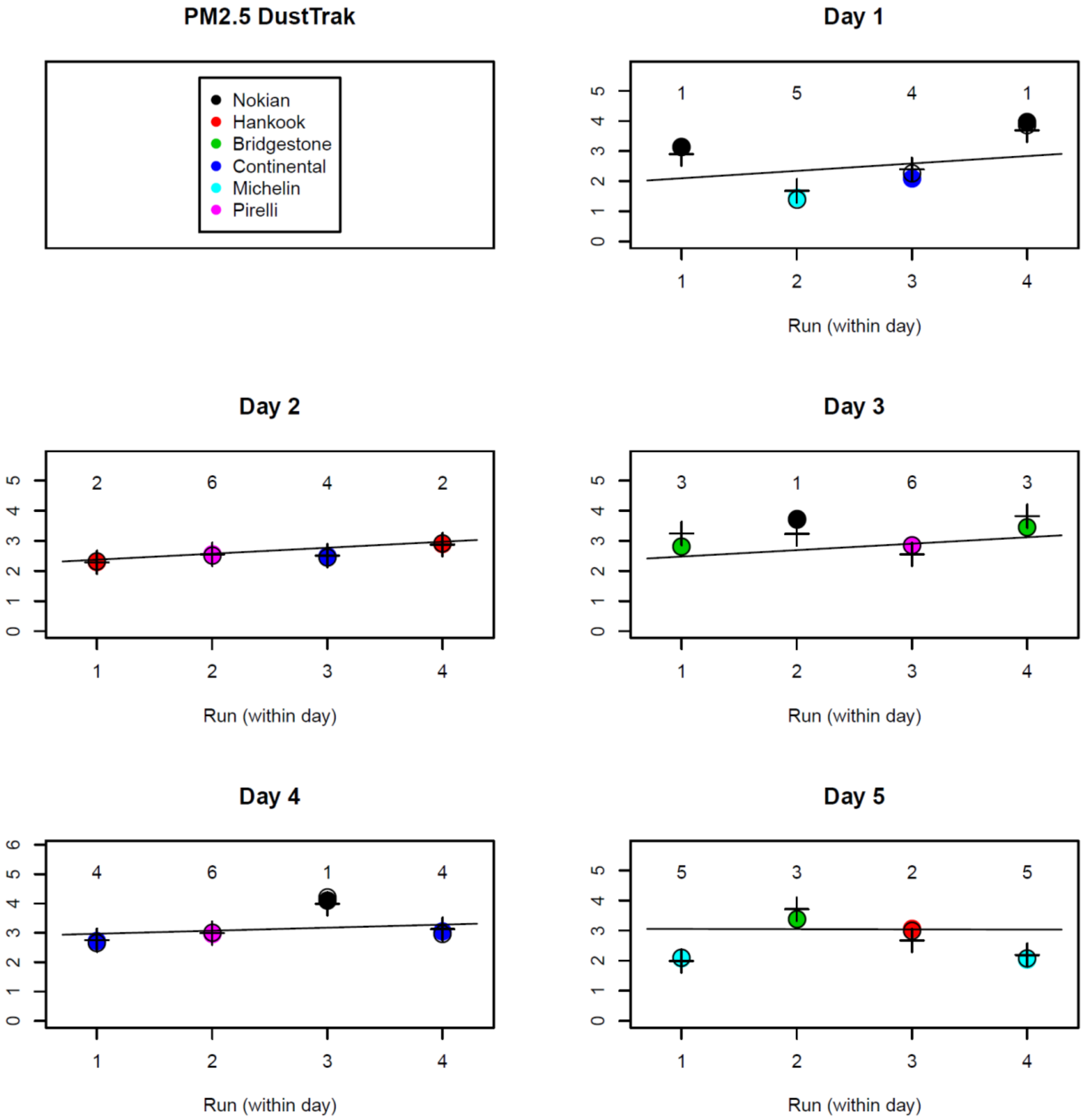


Figure 90

Table 19. Results of regression analysis for PM2.5 (DustTrak).

	Estimate	Std. Error
Level day 1	2.465	0.075
Slope day 1	0.246	0.058
Level day 2	2.671	0.077
Slope day 2	0.198	0.057
Level day 3	2.798	0.076
Slope day 3	0.214	0.058
Level day 4	3.123	0.076
Slope day 4	0.104	0.058
Level day 5	3.044	0.077
Slope day 5	-0.007	0.058
Tyre 1	1.035	0.071
Tyre 2	-0.046	0.083
Tyre 3	0.336	0.083
Tyre 4	-0.313	0.072
Tyre 5	-0.954	0.083
Tyre 6	-0.058	0.075

When testing the hypothesis that all tyres emit PM2.5 equally, the P value is 0.0001045 and hypothesis is rejected.

Table 20. Pairwise comparisons.

	Contrast	Estimate	P-value
1	1 - 2	1.081	0.000
2	1 - 3	0.699	0.002
3	1 - 4	1.348	0.000
4	1 - 5	1.988	0.000
5	1 - 6	1.092	0.000
6	2 - 3	-0.382	0.034
7	2 - 4	0.267	0.073
8	2 - 5	0.907	0.001
9	2 - 6	0.011	0.927
10	3 - 4	0.649	0.004
11	3 - 5	1.290	0.000
12	3 - 6	0.394	0.022
13	4 - 5	0.641	0.004
14	4 - 6	-0.255	0.062
15	5 - 6	-0.896	0.001

Particle number concentration

The results are summarized for particle number concentration and shown with the same format as for PM10 TEOM. Explanations how to read the results are only present in the previous section.

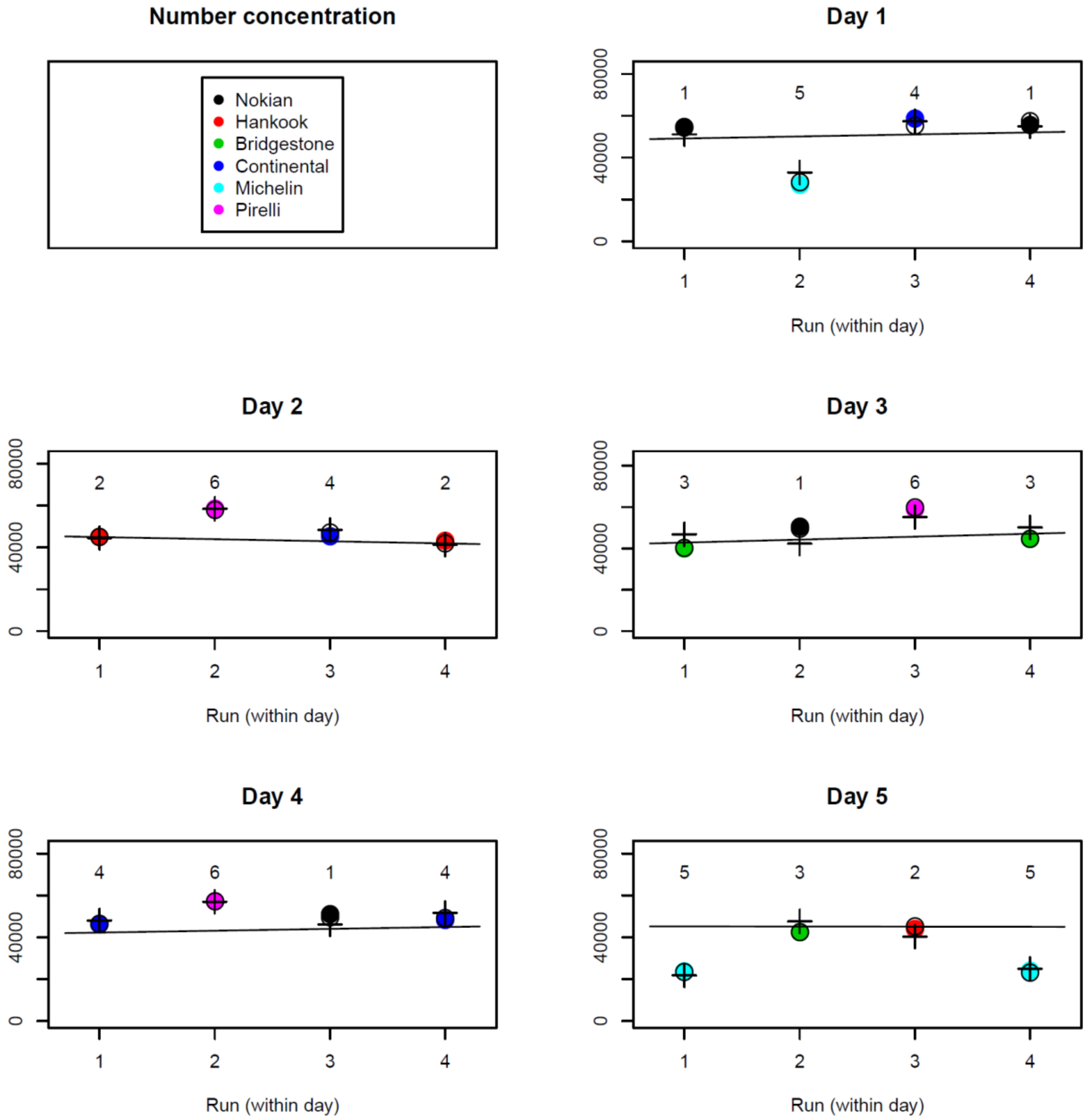


Figure 91

Table 21. Results of regression analysis for particle number concentration.

	Estimate	Std. Error
Level day 1	50584	1421
Slope day 1	966	1104
Level day 2	43443	1463
Slope day 2	-1007	1096
Level day 3	44985	1445
Slope day 3	1425	1098
Level day 4	43581	1451
Slope day 4	876	1098
Level day 5	45104	1468
Slope day 5	-57	1106
Tyre 1	5547	1352
Tyre 2	130	1574
Tyre 3	-2506	1575
Tyre 4	4403	1371
Tyre 5	-21689	1579
Tyre 6	14115	1427

When testing the hypothesis that the number concentration is equal for all tyres, the P value is 0.0003704 and hypothesis is rejected.

Table 22. Pairwise comparisons.

	Contrast	Estimate	P-value
1	1 - 2	5416	0.077
2	1 - 3	8053	0.015
3	1 - 4	1144	0.573
4	1 - 5	27236	0.000
5	1 - 6	-8568	0.010
6	2 - 3	2637	0.344
7	2 - 4	-4272	0.115
8	2 - 5	21820	0.000
9	2 - 6	-13985	0.002
10	3 - 4	-6909	0.037
11	3 - 5	19183	0.000
12	3 - 6	-16622	0.001
13	4 - 5	26092	0.000
14	4 - 6	-9713	0.005
15	5 - 6	-35805	0.000

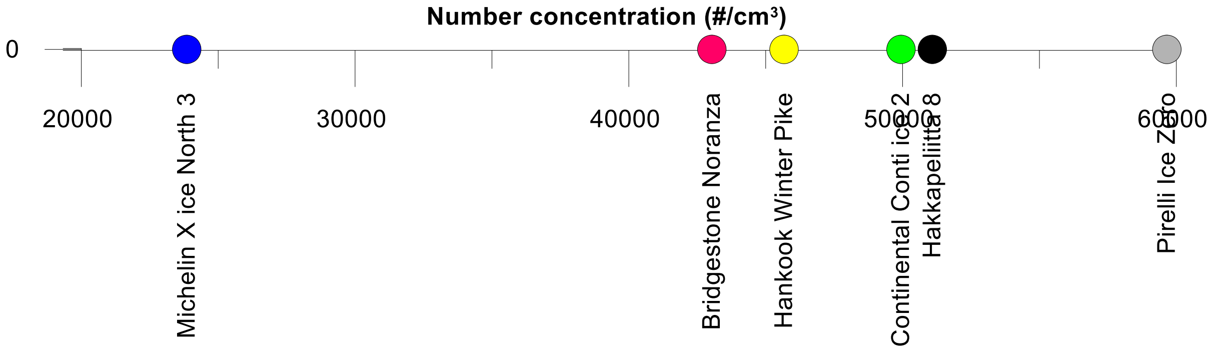


Figure 92. Ranking of adjusted mean particle number concentration

Influence of tyre properties and experimental environment

The second analysis aimed at replacing the simple tyre effects with a function of number of studs etc. The 4th analysis made the same replacement and to that made a similar replacement for the back-ground. The results for tyre properties with these two analyses were:

Table 23. Results of regression analysis for influence of tyre properties and experimental environment

	Analysis 2			Analysis 4		
	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
teom						
Number of studs	0.11	0.04	0.023	0.06	0.03	0.068
Stud protrusion	-10.73	8.39	0.248	-5.03	5.61	0.389
Stud force	-0.10	0.07	0.230	0.21	0.08	0.029
Stud mass	52.27	24.23	0.074	-42.18	25.46	0.126
dusttrak1						
Number of studs	0.06	0.02	0.022	0.03	0.01	0.035
Stud protrusion	-6.19	4.15	0.186	-1.95	2.16	0.386
Stud force	-0.03	0.04	0.426	0.11	0.03	0.006
Stud mass	18.77	11.97	0.168	-23.23	9.79	0.037
dusttrak2						
Number of studs	0.013	0.005	0.045	0.005	0.004	0.162
Stud protrusion	-1.899	1.177	0.158	-0.718	0.643	0.288
Stud force	-0.017	0.010	0.148	0.024	0.009	0.025
Stud mass	6.007	3.402	0.128	-6.745	2.921	0.041
Number concentration						
Number of studs	329	80	0.006	161	54	0.013
Stud protrusion	-22734	18153	0.257	-8040	9720	0.426
Stud force	478	160	0.024	880	142	0.000
Stud mass	-23144	52440	0.674	-166609	44129	0.003

It could be noticed that:

- Protrusion has negative coefficient, which is unexpected
- Results for number of studs are about the same for both analyses and the coefficients have the expected sign
- otherwise, the size of the coefficients and p-value when testing the hypothesis that the effect is zero changes between analyses 2 and 4 in such a way that general statements is unreacha-ble

Analysis of the test environment

Table 24. Results of regression analysis for test environment influence

	Analysis 3			Analysis 4		
	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
teom						
roadtemp	0.55	2.38	0.821	3.31	1.77	0.088
humidity	-1.15	2.23	0.619	-4.24	1.24	0.006
tyretemp	-0.26	0.14	0.103	-0.15	0.14	0.293
rpm	-0.40	1.53	0.798	-0.60	1.66	0.726
dusttrak1						
roadtemp	0.13	0.79	0.876	1.66	0.68	0.033
humidity	-0.33	0.74	0.669	-2.03	0.48	0.001
tyretemp	-0.10	0.05	0.062	-0.04	0.05	0.507
rpm	-0.38	0.51	0.476	-0.47	0.64	0.476
dusttrak2						
roadtemp	0.303	0.247	0.248	0.691	0.203	0.006
humidity	-0.176	0.231	0.463	-0.614	0.142	0.001
tyretemp	-0.041	0.015	0.020	-0.026	0.016	0.128
rpm	-0.106	0.158	0.516	-0.135	0.190	0.491
Number concentration						
roadtemp	221	2834	0.939	8874	3065	0.015
humidity	1197	2656	0.662	-8384	2144	0.002
tyretemp	395	171	0.044	773	237	0.007
rpm	-967	1816	0.606	-1438	2870	0.626

With analysis 4, PM10 and PM2.5 show similar results (similar p-values, similar pattern of coefficients but with different size). That does not hold equally good for analysis 3. The results for the environment variables changes depending on which approach is used for the tyres.

Model selection

Table 25. R2 with different response variables for the 4 analyses

	Main analysis	Analysis 2	Analysis 3	Analysis 4
teom	0.988	0.762	0.906	0.847
dusttrak1	0.983	0.765	0.947	0.860
dusttrak2	0.991	0.784	0.946	0.871
Number concentration	0.987	0.863	0.972	0.822

Generally, R2 is lower when changing from simple tyre effects to tyre properties, but that is a simple fact. It is more difficult to judge, from above, the explained approach seems to give results that cannot be summarized. The combined view is that the main analysis is the one that should primarily be used. The design was not by any means chosen to be optimal for the environment part of analysis 3 and 4 and has failed for the tyre part of analysis 2 and 4.

The results in Table 25 only focus on the part of the models that has been changed compared to the main analysis. The simple tyre effects in the main analysis will not have the same estimated values in analysis 3. An extended model comparison could also include how the tyre coefficients change be-tween analyses 1 and 3 and how background behaviour changes between analysis 1 and 2.

Comparison of road simulator results with field results from Vectra tests

The tyres used in the road simulator is a subset of the tyre models used in the test site experiments using the instrumented car Vectra. To investigate if the laboratory and field results was comparable, data on mean PM10 concentrations together with data on stud protrusion and number were analysed. In Figure 93, PM10, PM10/protrusion and PM10/protrusion x number of studs in Vectra tests are plotted to the same parameters in the road simulator (PVM) tests. PM10 does not correlate well in itself (R^2=0,17), but dividing by stud protrusion and, finally, stud protrusion multiplied with number of studs increases the correlation to R^2=0,86. While tyres with many studs cause higher PM10 concentrations, the tyres with fewer studs have higher PM10 concentrations per mm protrusion and per stud, probably reflecting higher stud mass.

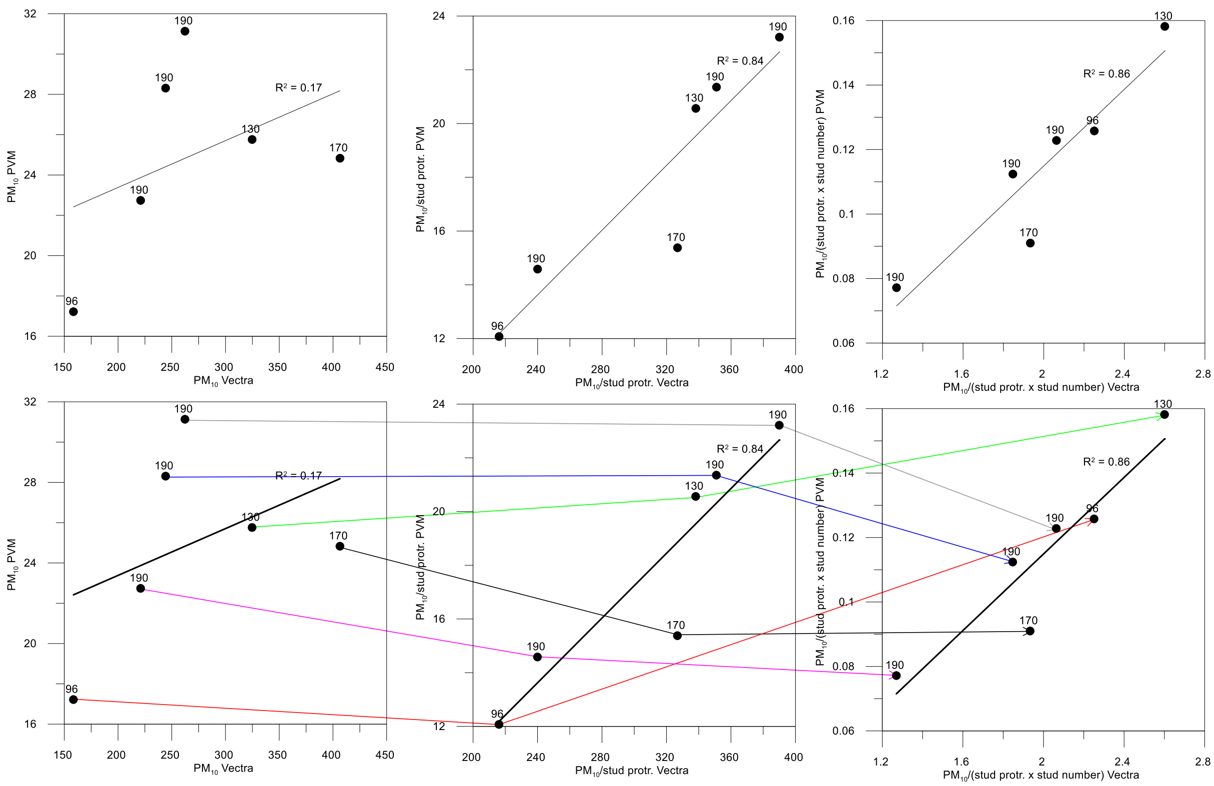


Figure 93. PM10, PM10/protrusion and PM10/protrusion x number in Vectra tests plotted to the same parameters in road simulator (PVM) tests. Numbers at symbols are number of studs per tyre. Lower figure links the same tyres through the adding the parameters protrusion and stud number from left to right.

NORTRIP model development

Relating mobile measurement data to dust loading and emissions

During the Stockholm campaign near simultaneous measurements by Sniffer and wet dust sampling were carried out on Hornsgatan and Fleminggatan. These are summarized in Table 26 below. It is unlikely that Sniffer drives exactly in the wheel tracks in real traffic situations, but the frequency of deviation is not known. The available data is also too little for a proper statistical assessment, so we simply take the average of the four measurements.

In the Vantaa experiment Vectra was used and the signals varied greatly during the start of the campaign whilst the road dust levels did not vary very much. If we take the second half of the Vectra period, which would better represent real traffic conditions, we find an average Vectra signal of 900 µg/m^3 and an average dust loading in the wheel tracks, over the three regions, of around 40 g/m^2 and an average dust loading between wheel tracks of 50 g/m^2. (NOTE: These have been estimated from the graphs in Figure 37 and Figure 38.)

During the meandering experiment in Vantaa, where the vehicle drove in and out of the wheel tracks, the Vectra signal increased by a factor of 3.4 on average. In addition, the Vectra signal at the start of the experiment, when suspendible dust was available in the wheel tracks, was roughly 5 times higher than later in the measurement period (Figure 38). The road dust measurements are not conclusive as to how much dust was removed during this first period, due to the spatial variation in the measurements, but it may be estimated that the reduction in road dust in the wheel tracks was around 30 g/m^2 after the passage of 400 vehicles or 800 tyres, after which most of the directly suspendible dust had been removed from the wheel tracks. This is in agreement with the estimated e-folding tyre number of 400 tyres.

The positions of the passages were measured during the Vantaa campaign and these indicate a medium deviation of +/- 10 cm. There is no clear delineation in regard to the edge of the wheel track as this is best represented by a Gaussian distribution with a standard deviation indicated by the mean deviation of the traffic. This indicates that the meandering term f_{BWT} may be quite small for Vantaa (< 0.1).

Using the method of analysis outlined previously we find the coefficients for the two campaigns in Stockholm (Sniffer) and at Vantaa (Vectra) to be:

$$C_{sniffer} / DL_{sus} = k_{sniffer}\, f_{sus}\, f_{BWT}\, W_{tyre} = 0.045\ m^{-1}$$
$$C_{vectra} / DL_{sus} = k_{vectra}\, f_{sus}\, f_{BWT}\, W_{tyre} = 0.011\ m^{-1}$$

If Sniffer signals are 3.6 times higher than Vectra, as indicated by the E18 results (Figure 64), then these two coefficients would be quite similar.

In other words, a Sniffer signal of 100 µg/m^3 is equivalent to 4.5 g/m^2 of suspendible road dust < 180 µm and a Vectra signal of 100 µg/m^3 is equivalent to 1.1 g/m^2 of suspendible road dust < 180 µm.

If we assume values for $W_{tyre} = 0.1\ m$, $f_{sus} = 0.0025$ and $f_{BWT} = 0.05$ then we can derive the factor $k_{sniffer}$ that relates the sniffer signal to the actual suspended emissions from that tyre. If we do this then we find $k_{sniffer} = 3600\ m^{-2}$ for one tyre. The total emission factor in g/km/veh is then given for 4 tyres by

$$EF_{sus} = 4\ f_{sus}\, f_{BWT}\, DL_{sus}\, 1000\, W_{tyre}$$

Combining with equation 3 we can derive an emission factor based on the sniffer signal

$$EF_{sus} = C_{sniffer}\, 4000 / k_{sniffer}$$

Given the above parameters this becomes

$$EF_{sus} = 1.1\, C_{sniffer}$$

This factor 1.1 should be comparable with that derived in Pirjola et al. (2012) from ambient air measurements. The value given there was 0.6093 for $C_{sniffer} < 2000\ ug/m^3$. Given the uncertainties in the f_{sus} and f_{BWT} factors then this derivation is quite uncertain but does indicate that information concerning the surface dust loading is contained in the sniffer signal and can be used to help define both emission factors and suspendible dust loading.

More data would still be required to further refine this relationship and also to determine its dependence on vehicle speed, tyre type, surface texture, traffic meandering and measurement method.

Table 26. Wet dust sampling and Sniffer/Vectra signals for the Vantaa and Stockholm campaigns used to derive the emission factors for Sniffer and Vectra

	Before Hornsgatan	After Hornsgatan	Before Flemmingsgatan	After Flemmingsgatan	Vantaa (Vectra)
WDS WT (DL_{WT})	14	18	10	10	40
WDS BWT (DL_{BWT})	120	68	33	62	50
Suspendable (DL_{sus})	106	50	23	52	10
Sniffer signal ($C_{sniffer}$)	850	1400	1350	1450	900

Cleaning efficiencies and cleanable dust load

Data from road cleaning from Trondheim in Norway (Snilsberg and Gryteselv, 2017) and from Koisotie in Finland (Kulovuori et al., 2019) have been analysed. In Trondheim six road sections were cleaned with different types of sweeper techniques and WDS road samples were taken in and between the wheel tracks at these sections. These samples were also analysed for mass and size distribution.

In Figure 94 we show the absolute size distribution for one of these sections (Field 2), with before (F) and after (E) for both in wheel tracks (H) and between wheel tracks (M). There is a substantial reduction in the amount of dust on the surface as a result of the cleaning.

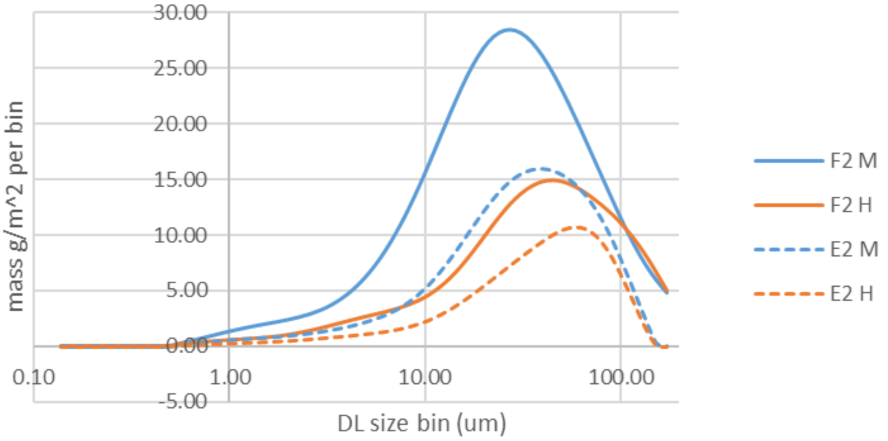


Figure 94. Absolute mass in g/m² per size bin from Trondheim field 2 for the between (M) and in (H) wheel track measurements. Both before (F) and after (E) are shown.

In Figure 95 we show the same results but presented as the percentage reduction in road dust as a function of size distribution. From this, the road dust reduction appears to be fairly independent of size for sizes < 20 µm but to be most inefficient for sizes of around 80 µm. The efficiency then increases for larger sizes, though interpretation of sizes above 100 µm are complicated by cut-off effects in the filtering of 180 µm and that these values are mostly quite low. The other section measurements show similar behaviour below 100 µm but can show both positive and negative values above this value.

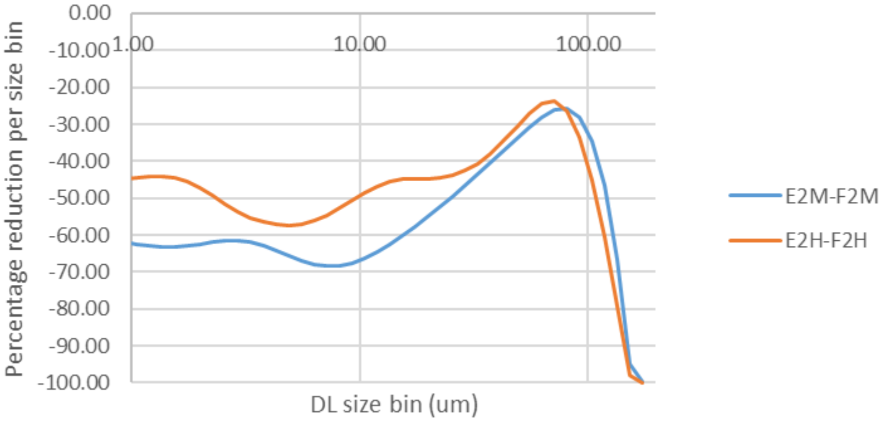


Figure 95. Percentage reduction due to cleaning measured in Trondheim field 2 for the between (M) and in (H) wheel track measurements.

Use is now made of all 'before and after' measurements to plot the relative reduction of DL180 as a function of road dust loading DL180. In this figure both a linear fit and an asymptotic fit are provided. The asymptotic fit does not allow a reduction of more than 100% and has a zero-cleaning efficiency at 20 g/m². The equation for the fitted cleaning efficiency ($E_{cleaning}$) is given below where $f_{cleaning}$ is the factor defining the shape of the curve

$$E_{cleaning} = 100\left(1 - exp\left(-\frac{(DL_{180} - 20)}{f_{cleaning}}\right)\right)$$

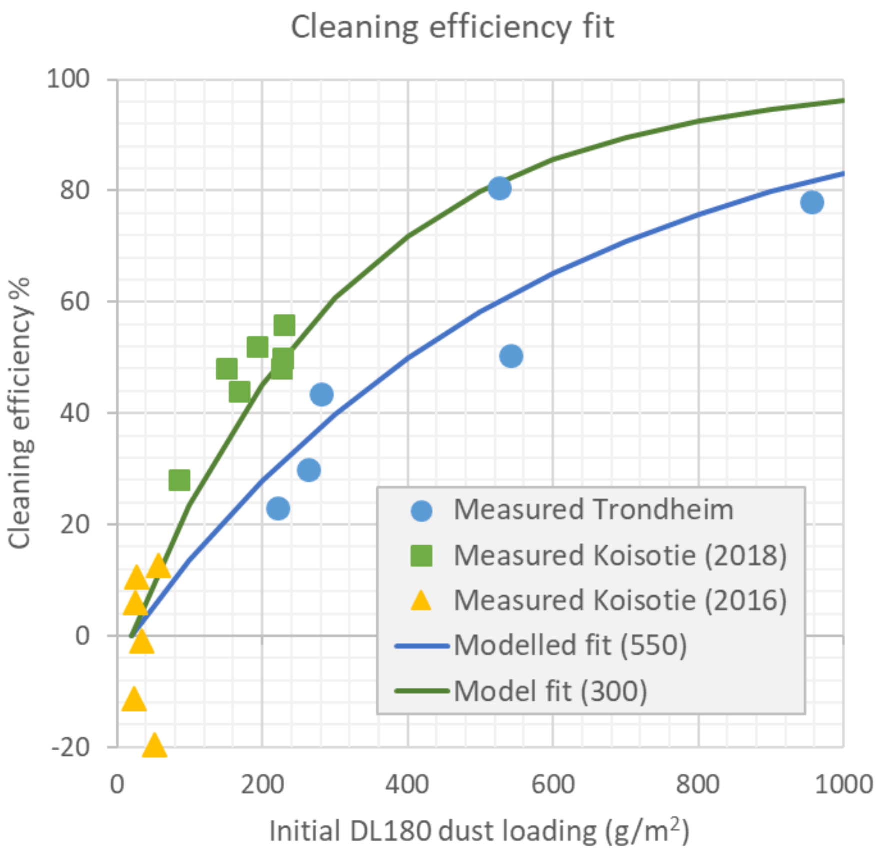


Figure 96. Measured and fitted relationship for cleaning efficiency and DL180 loading for Trondheim cleaning activities. The parameterisation is shown for two values of $f_{cleaning}$.

More data can be added from different cleaning machines and different measurements to improve the robustness and applicability of the relationship. The above relationship can be implemented in the model after further assessment at other sites and with other machines.

Sand crushing

The experiment involved running a car backwards and forwards over a confined sand sample, up to 360 times, and resampling the surface first by dry sampling of the larger particles and then wet sampling the remaining particles with the WDS. These samples, one of the original sand and 3 samples after 120, 240 and 360 passages, were analysed for their size distribution. The results are shown in Figure 97. There is an expected shift from large sizes to smaller, compared to the initial sample, but this is not monotonic, i.e. the shift is less for the 240 passages than for the 120 and 360 passages. With further assessment of the data and the sampling method it became clear that the shift seen was not necessarily a result of crushing but the fact that the initial sample was not made from the surface where the experiment took place, but from the sand pile. Even though a clean area was chosen for the experiment there was still a significant amount of finer particles on the surface. The apparent shift in size distribution was then most likely related to the additional sampling of already existing finer material on the surface and not due to the crushing itself. This experiment then gave us little reliable information to base parameters on.

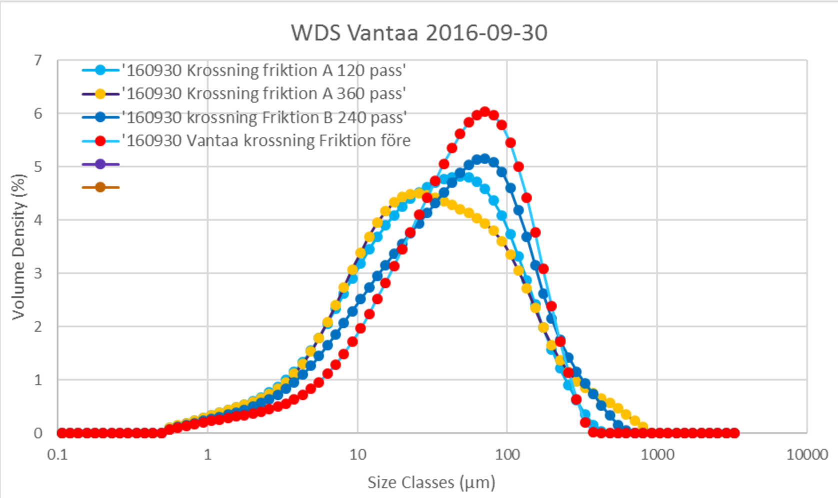


Figure 97. Size distribution of WDS samples taken during the crushing experiment.

Despite the lack of consistency in the crushing results we can still do a model calculation to assess its possible impact. From the data acquired we estimate an order of magnitude transfer of mass from DL_{200-10} to DL_{10} to be around $1x10^{-6}$ to $1x10^{-5}$ veh^{-1}. In other words, roughly 1 millionth of the mass in bin size DL_{200-10} is transferred to DL_{10} for each vehicle pass. We set the crushing transfer parameter from DL_{200-10} to DL_{10} to be $5x10^{-5}$ and the crushing parameter for $DL_{10-2.5}$ to $DL_{2.5}$ to be $5x10^{-6}$. The results showing the model calculated ratios of the different sizes are shown in Figure 98 with no crushing, and Figure 99 with crushing applied to a data set from Hornsgatan during 2007–2008. The result is a steadily increasing DL_{10} / DL_{200} fraction during the winter season as the larger fractions are crushed to the smaller. In this particular case the average concentrations of PM10 increased by 10% due to an almost doubling of the suspension contribution. In this modelling experiment, measurements do not reflect the surface DL_{10} / DL_{200} fractions, which at the end of the season are up to 60%. These are usually around 20 % – 30%. Much more detailed work would be required to properly quantify the crushing contribution to road dust and it is still not known if it has a significant contribution or not.

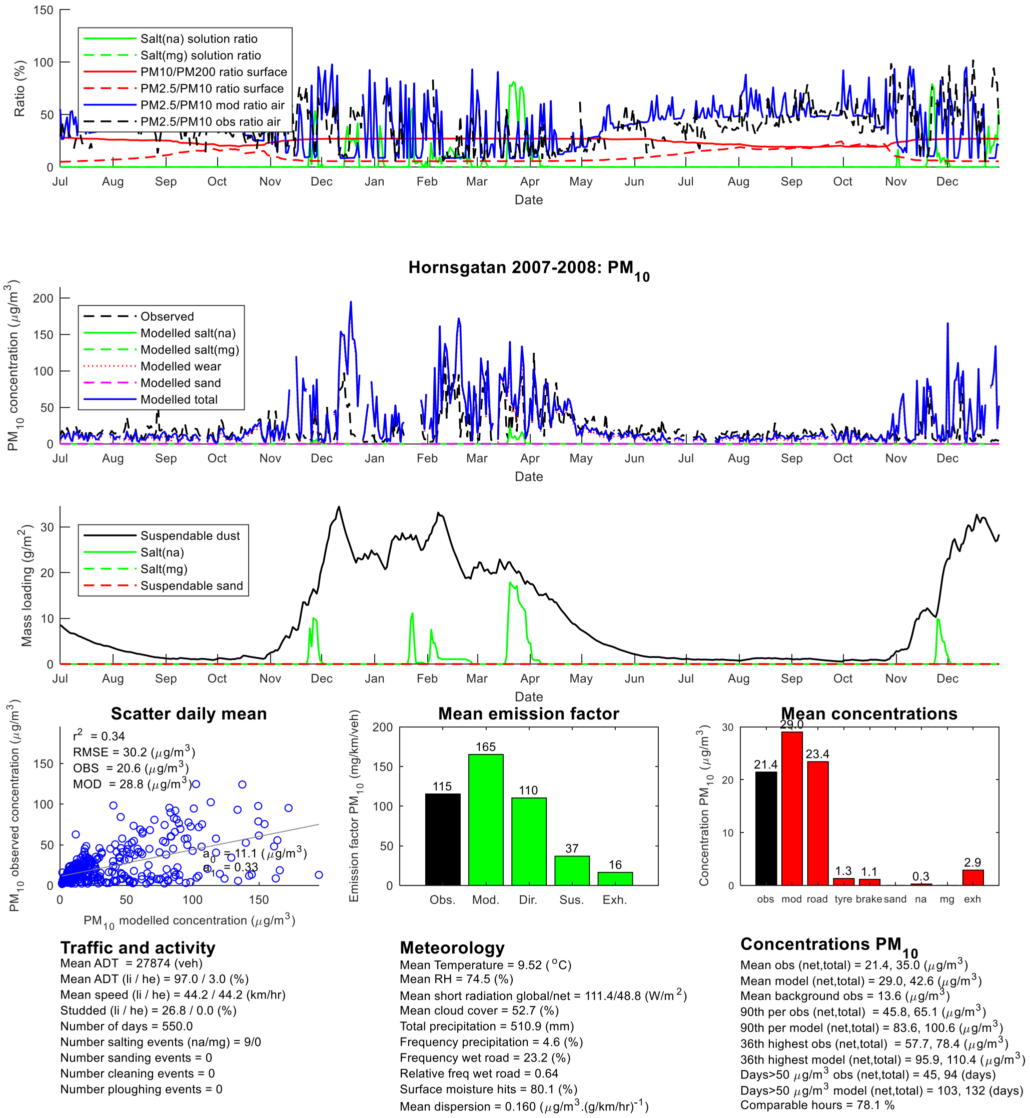


Figure 98. NORTRIP model results with no crushing

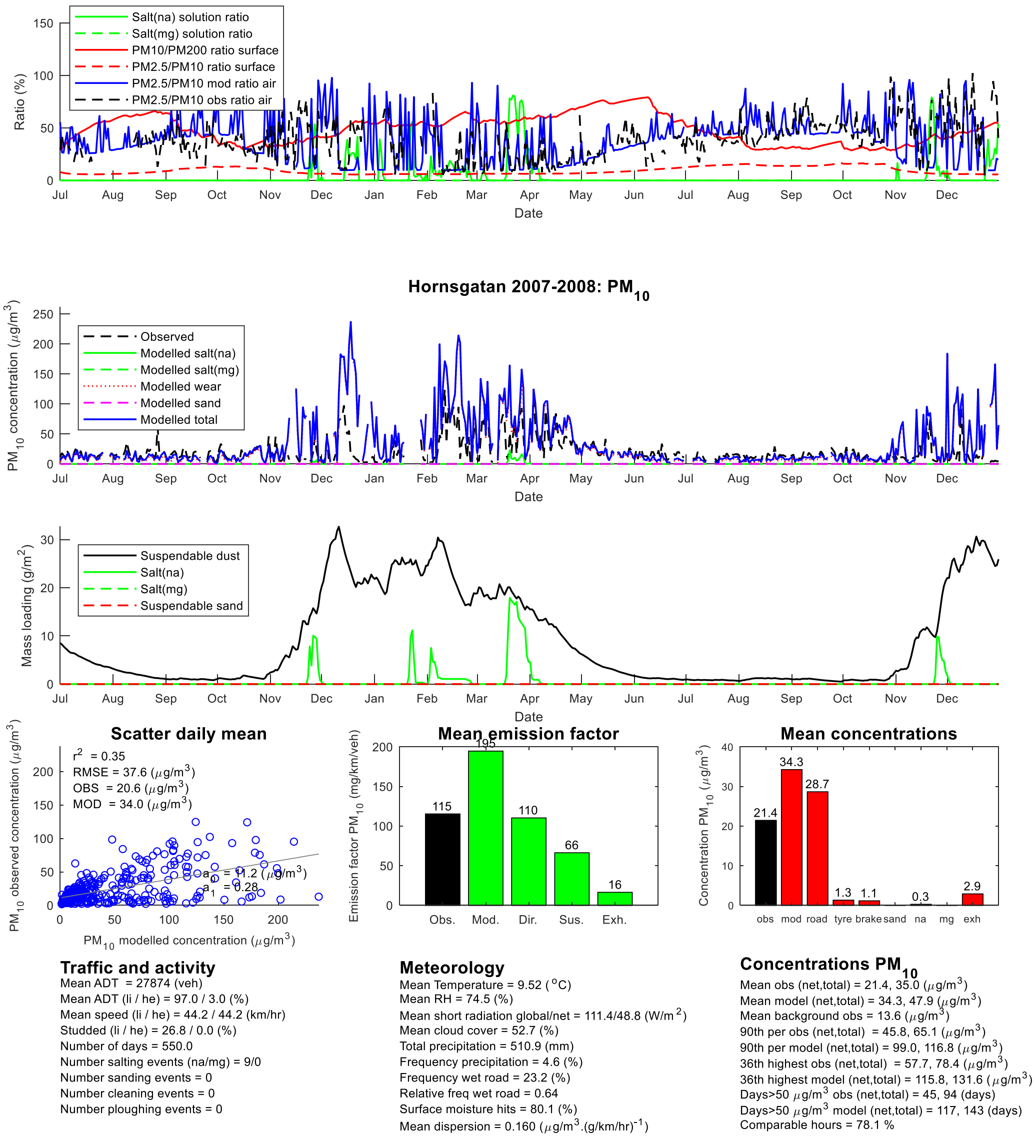


Figure 99. NORTRIP model results with crushing

PM2.5/PM10 ratio of surface and ambient air road dust emissions

The following data were available on size fraction:

Sniffer sampling: Sniffer sampling should provide a PM ratio uncontaminated by exhaust, though background concentrations may affect the results. Sniffer sampling indicate a range of PM2.5/PM10 fractions from 6% to 19% with an average of 8%.

Ambient air sampling: Samples in ambient air at E18 Hornsgatan and Sveavägen give a range of PM2.5/PM10 ratios of from 9% to 16% with an average of around 11%. This is, as expected, larger than the Sniffer values since the ambient air measurements also contain exhaust emissions.

Road simulator data: Road simulator data where road wear is sampled in the ambient air give consistent PM2.5/PM10 ratios of 25%.

Road dust sampling: The ratio DL10/DL180 varies significantly from 2% to 44%. The DL10/DL180 ratio is generally highest when road dust samples are highest. In recent years, since 2014, this ratio is also less than in the previous years due most likely to a change in sampling analysis technique. Maximum values in recent years are around 35% with an average of 18%, generally with a peak in the middle of the dust season. The ratio DL2.5/DL10 for the latest measurements (2017-2018) have been assessed and an average and consistent ratio of 22% has been found, similar to the Road simulator data of 25%.

Earlier studies: Snilsberg (2008) found, by sampling directly behind the tyre in the road simulator, PM10/PM200 ratios of 28% and PM2.5/PM10 ratios of 29%.

There is thus an inconsistency when comparing the PM2.5/PM10 size distribution generated by the road simulator and from surface measurements with the road dust suspension measured by Sniffer and ambient air samples. The surface and laboratory measurements indicate PM2.5/PM10 ~24% (on average) whereas the Sniffer measurements indicate a PM2.5/PM10 ratio=8%, which is around 3 times smaller.

The first explanation would be that the efficiency of suspension removal is lower for PM2.5 than it is for PM10, by around a factor of 3. However, the ambient air measurements would also include direct emissions from studded tyres and these generally dominate the emissions, particularly on cleaner pavements such as E18. Also, with lower efficiency then the ratio of DL2.5/DL10 would increase during the winter season, which it is not seen to do in the measurements.

Another possible explanation is that dust can aggregate into larger particles on the road surface, reducing the ratio of PM2.5/PM10 during suspension. The wet dust sampler, due to the force of the water pressure, disaggregates these back to their original sizes. This process is not described in the NORTRIP model.

An example of a NORTRIP calculation with standard output and default parameters for Hornsgatan 2008–2009 is shown in Figure 100, including the various ratios discussed in the text. The ambient air PM2.5/PM10 ratio is well modelled compared to measurements (obs ratio air). The Surface PM2.5/PM10 ratio has a maximum of 20% before the start of the winter season and a minimum of 5% during the winter season. The PM10/PM200 surface ratio varies from 18% before the start to 28% during the season. This variation is due to the differing contributions of brake and tyre wear compared to road dust which have different size distributions.

In Figure 101 we show the results of the model with reduction of PM2.5 suspension efficiency by 1/3 and an increase in the road wear PM2.5/PM10 ratio to 24%, as suggested by the available data. The results reflect the previous discussion and do not provide a good comparison with measurements any longer. This is because the increased road wear PM2.5/PM10 ratio to 24% is mostly directly emitted, rather than suspended, and the surface ratio increases dramatically because the suspension of PM2.5 is lower.

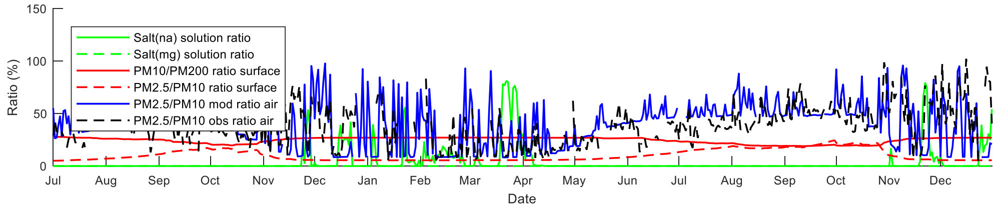


Figure 100. NORTRIP model results with standard output and default parameters for Hornsgatan 2008–2009.

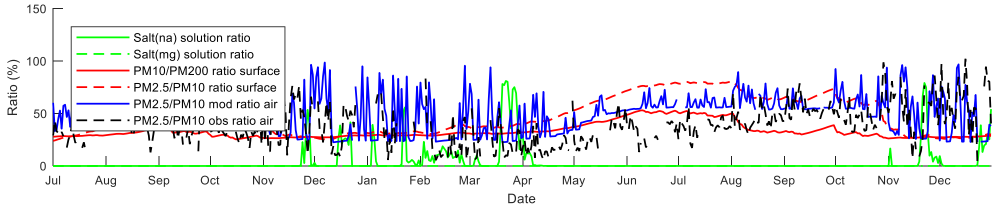


Figure 101. NORTRIP model results for Hornsgatan 2008–2009 with reduction of PM2.5 suspension efficiency by 1/3 and an increase in the road wear PM2.5/PM10 ratio to 24%.

NORTRIP implementation in Iceland

The collected data refer to the years 2012 and 2016 and several periods were modelled, from the whole year to single months according to the availability of the data. Table 27 shows a summary of the ability of the model to calculate the PM emissions compared to the observed measurements at GRE for different background stations and time periods.

Table 27. Summary of the daily mean correlation, the modelled and observed mean PM10 concentrations and exceedance days for the modelled periods 2012 and 2016.

Period	Daily mean correlation R^2	Mean PM10 observed	Mean PM10 modelled	Exceedance days observed (days > 50 µg/m³)	Exceedance days modelled (days > 50 µg/m³)
2012 - all year (FHG*)	0.03	11	8.8	3	7
2012 - April - May (FHG)	0.29	12.2	8.8	0	0
2012 - June-July (FHG)	0.03	12.8	5.1	1	0
2012 - Nov. - Dec. (FHG)	0.07	12.5	9.7	2	0
2016 - all year (FHG)	0.06	12.0	5.1	0	0
2016 - all year (KOP*)	0.00	14.0	6.7	2	3

* background stations: FHG - Fjölskyldu-og Husdyragardurinn / KOP - Kopavogur Dalsmari

The daily mean correlation gives an information about the correct representation of the temporal variability. In case of the non-exhaust emission it depends on the surface moisture which influences the emission variability and on the meteorological and dispersion conditions (Denby & Sundvor, 2013). The following subchapters give an overview of the different analysed periods.

The 2012 dataset

Even though the 2012 dataset is not complete regarding the air quality measurements of the main station (GRE) and the background station (FHG), the first model run was applied to the whole year. In case of missing data NORTRIP interpolates them from the previous values. This could explain the very low R^2 of 0.03. Table 28 reports the main model output data.

Table 28. Background station FHG using the 2012 dataset, modelled through the whole year - output data overview.

Total surface mass budget (g/m²)

Wear retention	Other production	Suspension	Drainage	Spray	Cleaning	Ploughing	Windblown
292.92	0	-40.85	-72.44	-171.11	0	-7.61	0

Energy budget (W/m²)

Net shortwave	Net longwave	Net radiation	Sensible heat	Latent heat	Traffic heat	Surface heat	Sub-surface heat
33.37	-15.23	18.14	-4.04	-6.7	0.18	6.76	-6.45

Moisture budget (mm/day)

Rain	Drainage	Rain-drainage	Evaporation	Melt	Freezing	Spray	Wetting
2.3004	-2.0375	0.263	-0.2395	0.2153	-0.0275	-0.1635	0

Traffic and activity data

Number of days	Mean ADT	HDV (%)	Mean speed (km/h)	Mean studded (%LDV)	Max studded (%LDV)	Total salt (ton/km)	Salting (1) events	Salting (2) events	Sanding events	Cleaning events	Ploughing events
365.96	45707	3	82.5	12.84	35	26.97	108	0	0	0	52

Meteorological data

Mean Temp (C)	Mean RH (%)	Mean global (W/m^2)	Mean cloud cover (%)	Total precip. (mm)	Frequency precip (%)	Frequency wet (%)	Mean dispersion
5.97	78.5	39.42	84.34	1366.5	19	48.56	0.036

Source contribution (µg/m³).

Observed total	Model total	Model road	Model tyre	Model brake	Model sand	Model salt (na)	Model salt (mg)	Model exhaust
10.99	8.77	5.47	0.48	0.7	0	0.4	0	1.73

Table 28 continued

Net concentration results (μg/m³).

Obs_ mean	Mod_ mean	Obs_90_per	Mod_90_per	Obs_36_high	Mod_36_high	Obs_ex_50	Mod_ex_50	R_sq	RMSE	NRMSE(%)	FB(%)
10.99	8.77	16.1	17.89	15.31	15.26	6	9	0.03	15.32	145.03	-24.44

With background concentration results (μg/m³).

Obs_ mean	Mod_ mean	Obs_90_per	Mod_90_per	Obs_36_high	Mod_36_high	Obs_ex_50	Mod_ex_50	R_sq	RMSE	NRMSE(%)	FB(%)
17.94	15.73	32.41	31.59	30.44	29.87	7	10	0.34	15.32	85.85	-13.78

Figure 102 shows the summary output with the PM10 concentrations, modelled and observed, the mass loading due to suspendible dust, sand and salt, the scatter daily mean, the mean emission factor and the mean concentrations. It also gives a summary of the traffic and activity and the meteorological conditions. The model underestimates the mean PM10 concentrations (8.8 μg/m³ vs. the 11.0 μg/m³ observed) and gives an overview of their origin; road wear (5.5 μg/m³), tyre wear (0.5 μg/m³), brake wear (0.7 μg/m³), Na- salt (0.4 μg/m³), and from the exhaust (1.7 μg/m³).

During 2012 there were 7 days with PM10 concentrations of more of 50 μg/m³, while the model calculated 10 days.

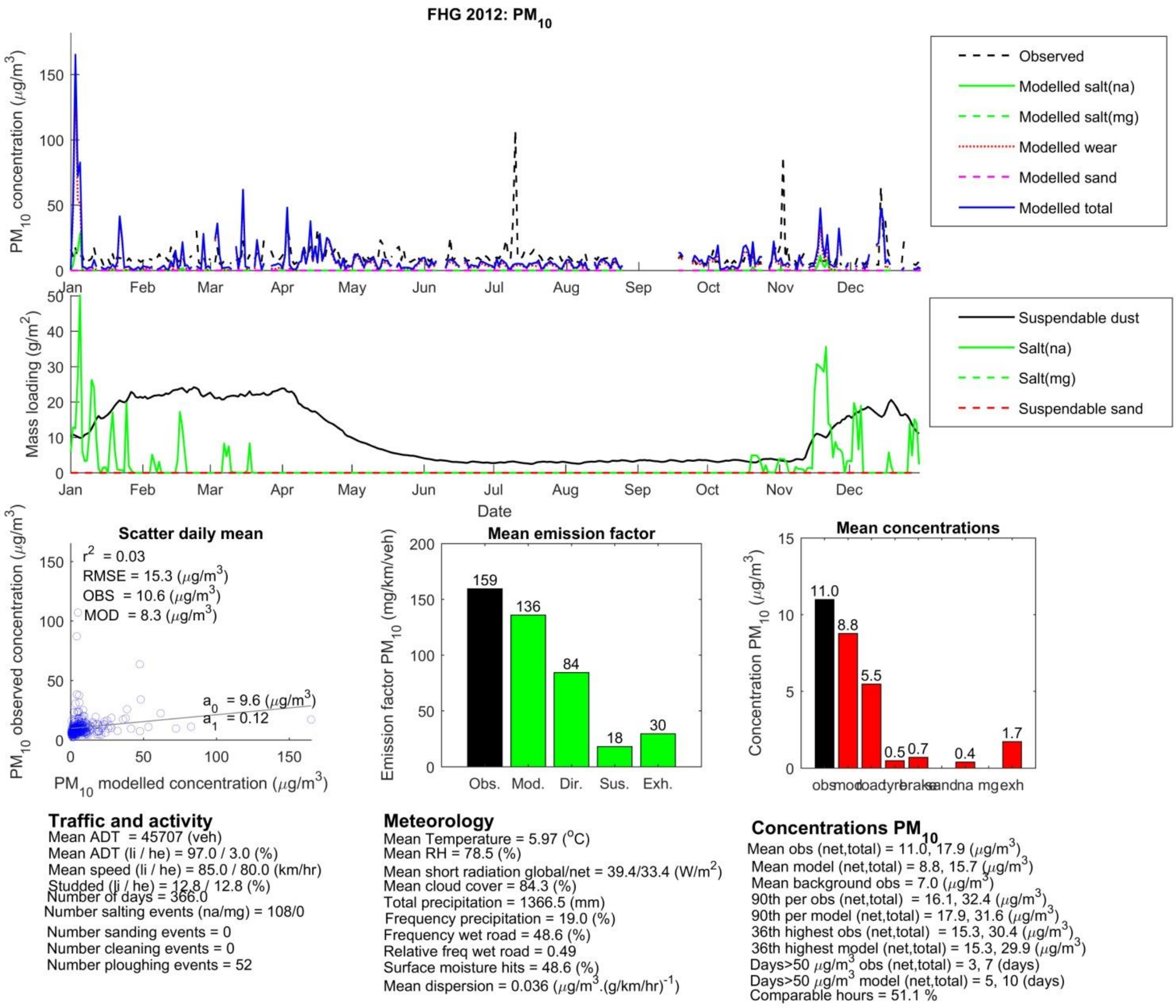


Figure 102. FHG 2012 dataset - summary output.

Due to the missing air quality data, the period April to May 2012 was modelled to see if the correlation R² depends on the availability of the input data. In April studded tyres are still allowed and their influence on the air quality and the model calculations are interesting to see. The summary output (Figure 103) shows that the correlation R² is higher and reaches 0.29 which still is lower than the lowest correlation found in the other test sites across the Nordic countries (e.g. Oslo, Nordby Sletta). The model catches some of the peaks of the PM10 concentration in April but fails to reproduce them in May. In general, the modelled concentrations are underestimated compared to the observed ones.

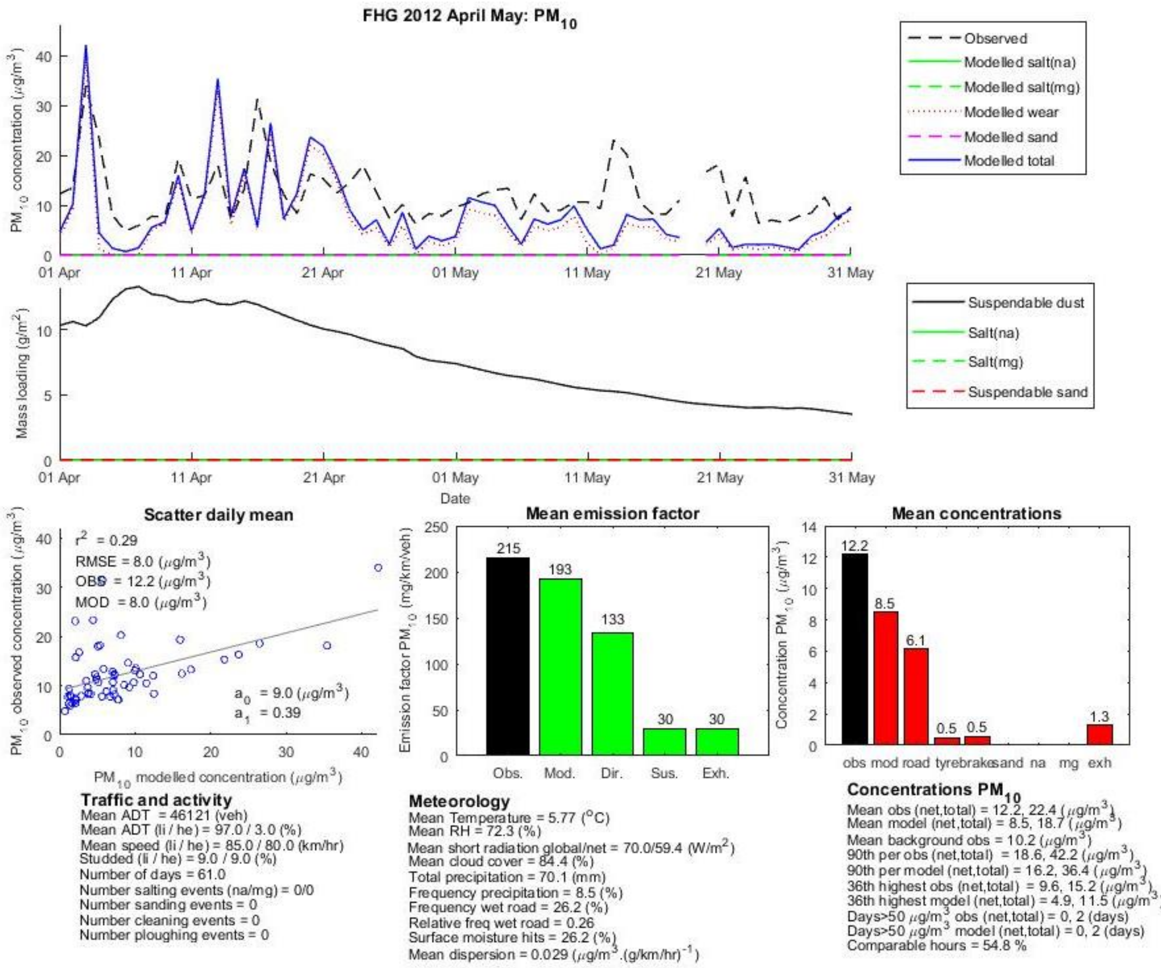


Figure 103. FHG 2012 April to May summary output.

The sources of PM in Reykjavik are not exclusively due to road traffic, but often dust particles can be blown in from green areas, construction sites or even from the dustier areas outside the capital region in case of sand storms. A method to discriminate an external contribution of dust is to check if PM and NO_x show the same pattern. When NO_x and PM follow the same pattern, the PM10, most likely, derives from traffic. Plotting NO_x and PM10 from GRE-station together with the wind speeds it is possible to infer likely origin of dust (Figure 104 and Table 29).

Table 29. Comparison of the input data and the model for the period April-May 2012.

Date	NO_x	PM10	Wind	Presumable Origin	Model*
3-5 April	high	high	low (<5m/s)	traffic	+
11-12 April	low	high	high (>5m/s)	not traffic	+ but overestimation PM10
16-17 April	low	high	high (>5m/s)	not traffic	+ but lower than observed
14 May	low	high	high (>5m/s)	not traffic	-
20-22 May	high	high	medium-high	dust storm	-

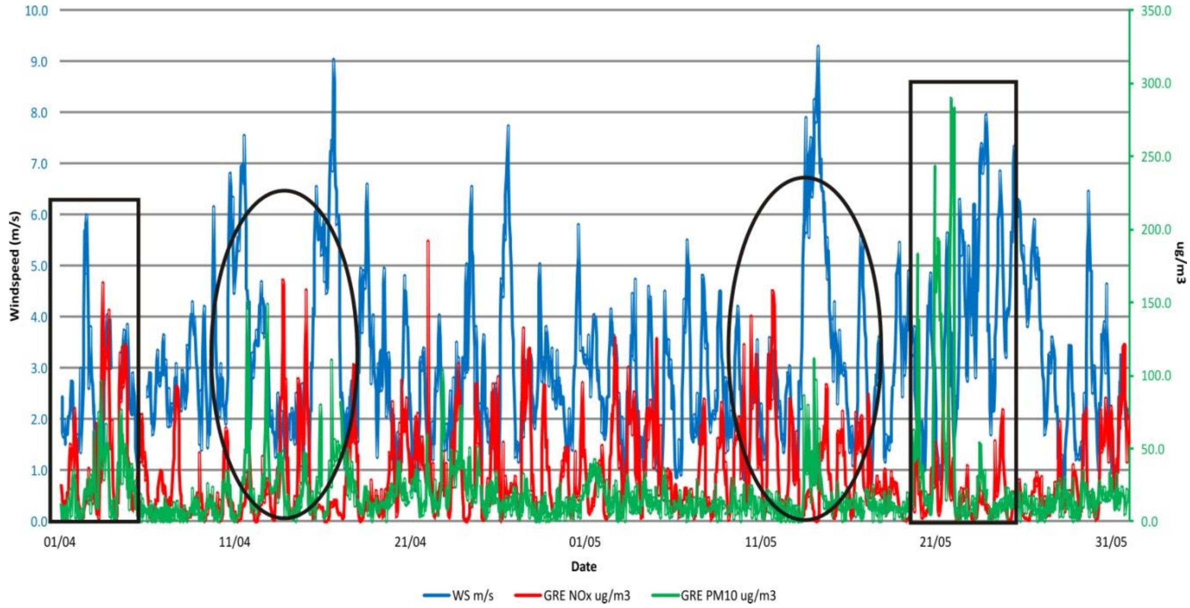


Figure 104. PM10 (green) and NO_x (red) at GRE and wind speeds (blue) for April-May 2012. The box evidences most likely PM origin from traffic, the circle from another source.

Comparing the input data (Figure 104) with the net concentrations and the modelled output from NORTRIP (Figure 105) it is possible to see that in three cases the model can reproduce the observed concentrations, once it overestimates and once underestimates the PM10 concentrations and other two times it does not reproduce the peak (Table 29).

The importance of the road surface conditions has been shown by the previous applications of NORTRIP in Scandinavia. The surface wetness is a precursor to higher modelled emissions. Is the surface wet, the particles will be found in droplets and cannot be easily suspended, only with the passing of a vehicle (spray) (Denby & Sundvor, 2012). This means that particles accumulate on the surface and are released once the surface dries.

Figure 106 shows the results for the same period using a simple model developed by Throstur Torsteinsson at University of Iceland (UoI model), which accounts for traffic and wind resuspension. The measured data looks a little different, which needs to be examined. The peak around 21 May is probably due to a dust storm, since the concentration increases towards midnight. This model run does not get the 3 April peak as well, but some others are well captured.

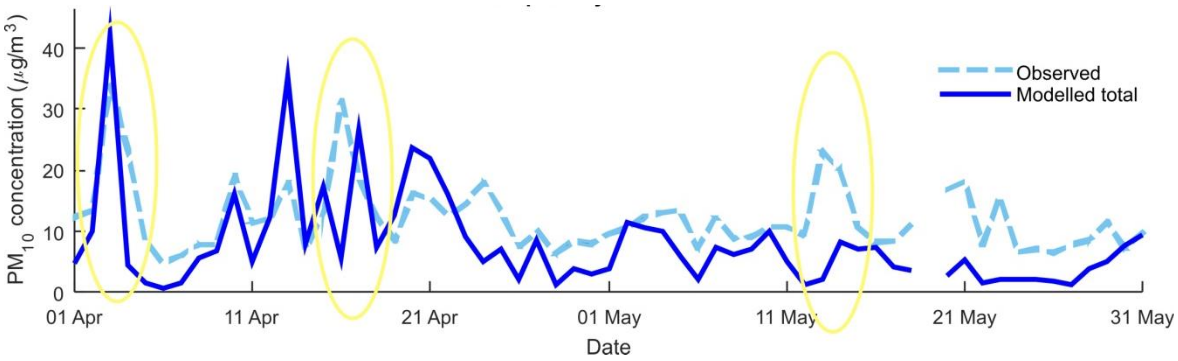


Figure 105. Net concentrations for the period April-May 2012 from NORTRIP.

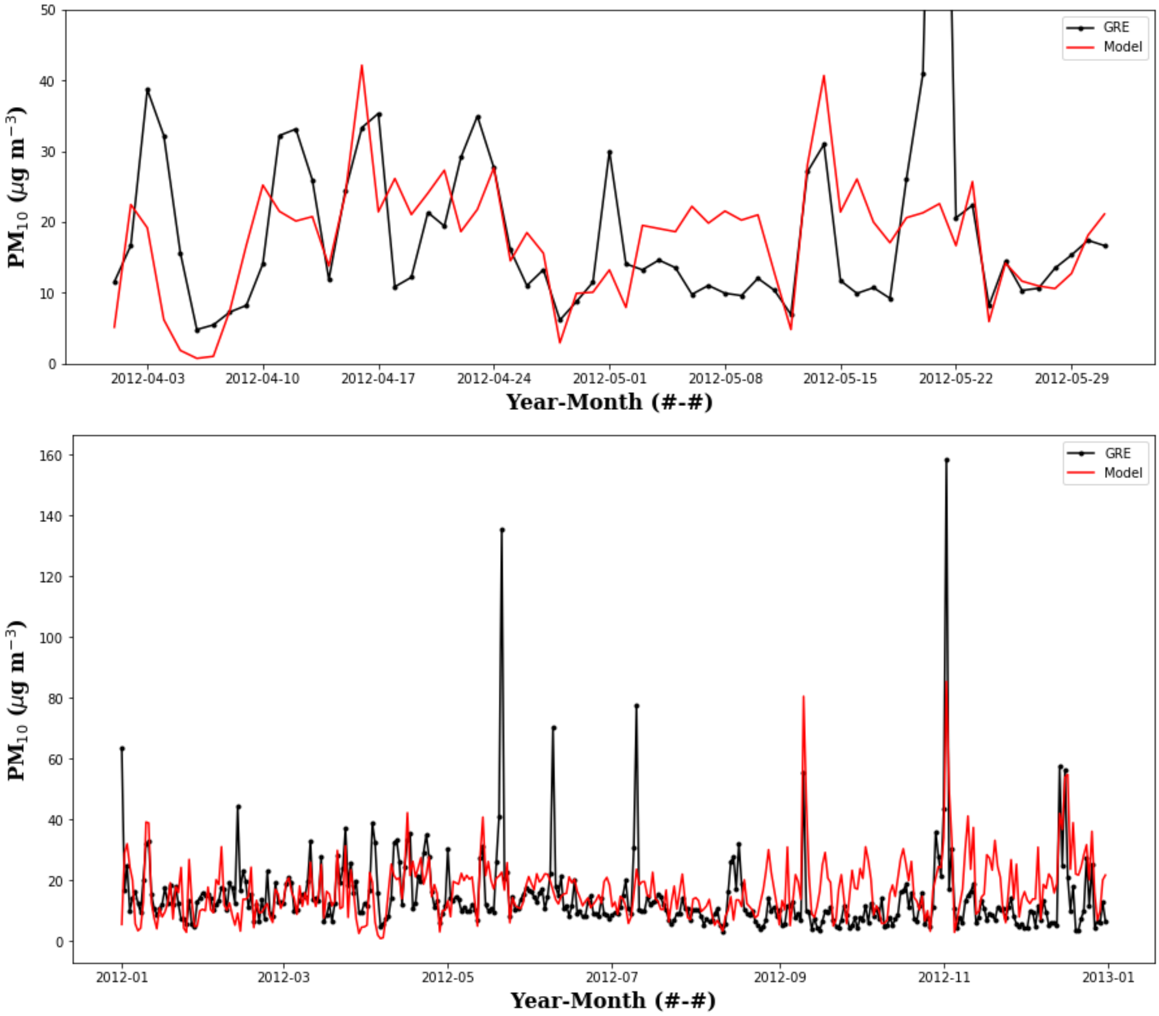


Figure 106. Measured (black line) and modelled (red line) PM10 concentration at GRE station in April and May 2012 (upper plot) and for all of 2012 (lower plot). The peak around 21 – 22 May is due to a dust storm and local resuspension and reaches almost 140 µg/m^3 on 22 May.

Figure 107 reports the surface conditions for the April-May 2012 period as modelled by NORTRIP. The modelled surface moisture influences the availability of road dust which can be resuspended. A completely dry surface is non-retentive, that means no dust can be deposited while a wet or moist surface is completely retentive. The dust particles (from various sources, including the mechanical wear sources) are trapped in the water film formed on the surface of the road due to the moisture and can be released when the road dries up. It has been shown in previous model applications that the road moisture parameter is very important to obtain a correct modelling of the PM concentrations. Comparing the modelled surface wetness from Figure 107 with the modelled PM10 concentrations from Figure 105 it can be seen, that there is not a clear response of higher PM10 concentrations during a "dry" period (when the surface wetness is 0 mm). This of course is due to the fact, that multiple factors influence the calculation of the PM10 concentrations. Water on the road surface can also act as a sink, by draining away the particles or by letting them exit the road area due to the water splash created by the car traffic itself.

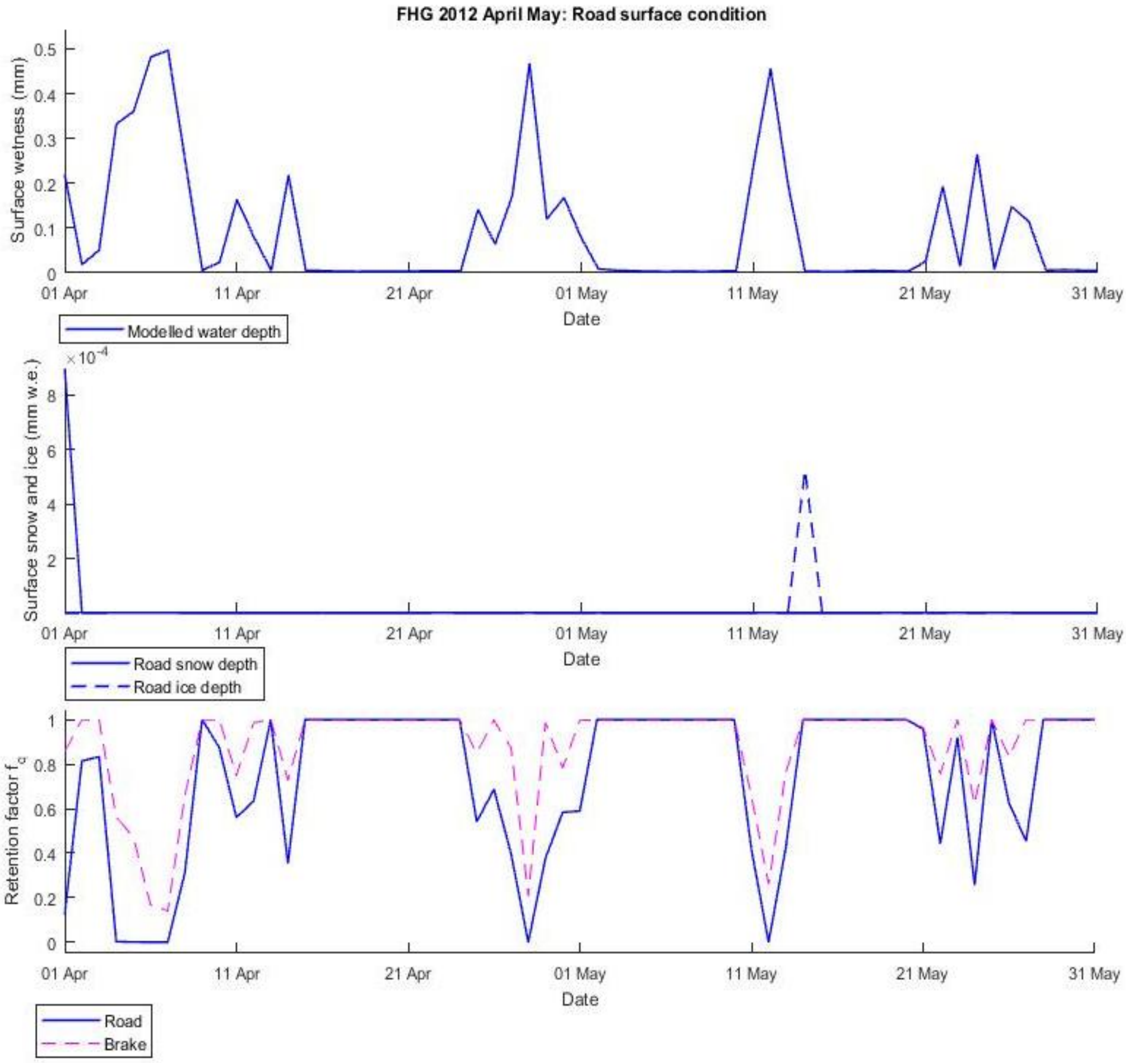


Figure 107. FHG 2012 - April-May, road surface conditions.

The 2016 dataset

The 2016 dataset presents some major air quality data gaps, as the PM2.5 data from FHG are totally missing and neither air quality station (observation GRE and background FHG) had any data entries after 16 November.

To have anyway the whole year modelled, it was decided to use a very small number (0.1 µg/m³) as a value for the PM2.5 background values. The results are still not satisfactory with several data gaps in the representation of the concentrations, an underestimation of the modelled emissions and a correlation factor R^2 of 0.06 (Figure 108).

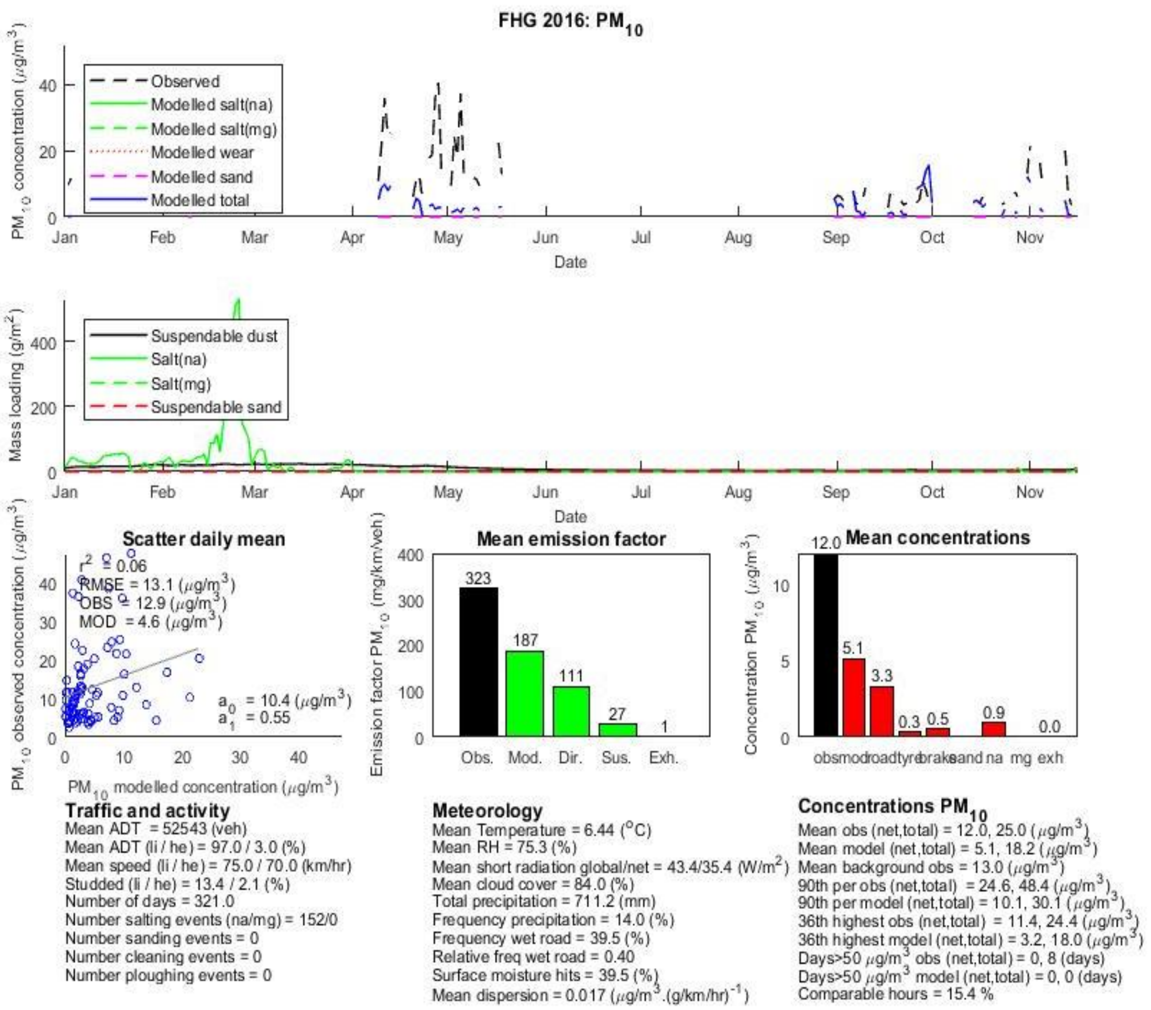


Figure 108. FHG 2016 summary output.

Changing the background station to Kopavogur- Dalsmari doesn't produce satisfactory results with even a lower correlation of R^2=0.00 and underestimated modelled concentrations (Figure 109). This is probably because this air quality station is far away from the Grensasvegur station, is itself located close a road, influenced by traffic and other sources there and therefore is not able to reproduce the background atmosphere for Grensasvegur.

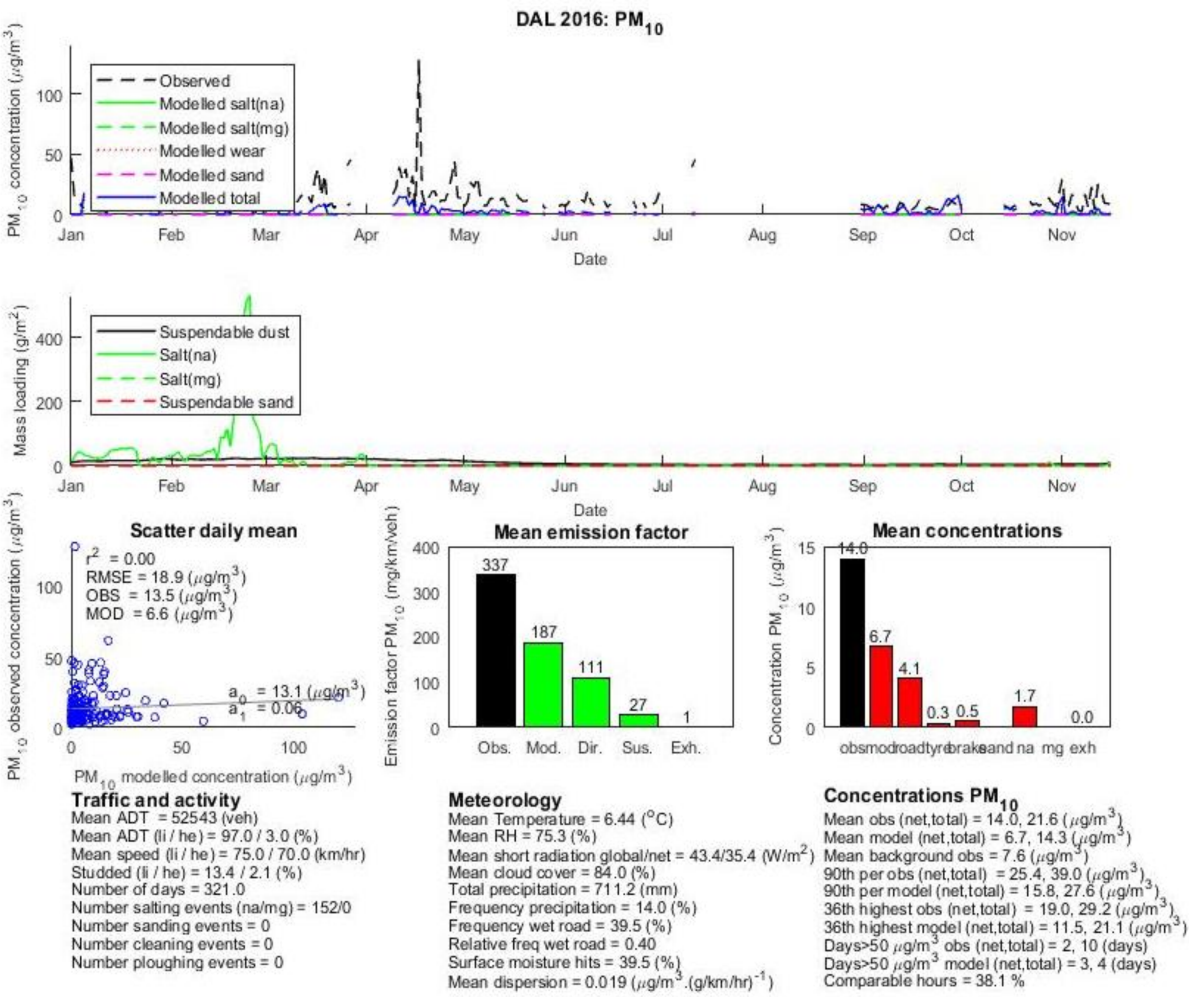


Figure 109. DAL-2016, summary output.

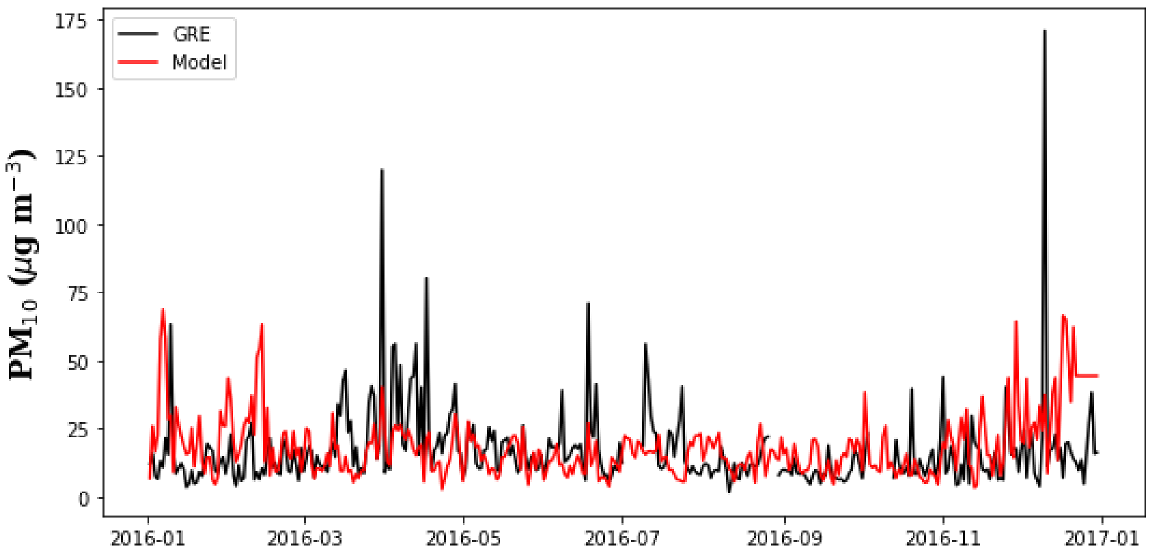


Figure 110. Measured (black line) and modelled (red line) PM10 concentration at GRE station for all of 2012.

A quick calculation with the UoI model, without any calibration, for the year 2016 is shown in Figure 110. The benefit of that model is that it only requires meteorological data and NO_x (or NO_2) values. There are issues with snow cover and a need to calibrate due to possible changes in the NO_x – traffic volume relationship; changes in diesel cars, heavy duty vehicles, and more can cause

Discussion

The suspension tests with controlled traffic during the Vantaa campaign is a unique experiment were the traffic effect on dust load, suspension and particle concentration in air close to the track were evaluated simultaneously. The expected depletion of road dust load with increasing vehicle passages could be observed in one of the test surfaces, holding an initially higher dust load, while the dust load on the two surfaces with initial low loads did not decrease during the tests. This is in line with previous observations regarding low dust loads and WDS-sampling, where small differences in low loads before and after sweeping is not discernible in data (Gustafsson et al., 2011, Gustafsson et al., 2019c, Janhäll et al., 2016, Järlskog et al., 2017, Männikkö et al., 2014). From the suspension measurements using the Vectra vehicle, it is also clear that the suspendible dust fraction is depleted after 200–250 passages and after that the suspension is low but rather stable.

How a stable suspension should be interpreted is not obvious. Either the suspendible dust load is replaced by deposition of dust suspended from the surfaces in or between wheel tracks and/or crushing of larger fractions is supplying new dust contributing to the PM10 fraction. The depletion of dust load has been observed in similar studies, e.g. Langston et al. (2009), where the silt load (sL) was seen to decrease to about a third of the initial load after just 20 passages. The Traker II vehicle used is a van, which would be more efficient in suspending dust than the Vectra used in the Vantaa field tests (Figure 111).

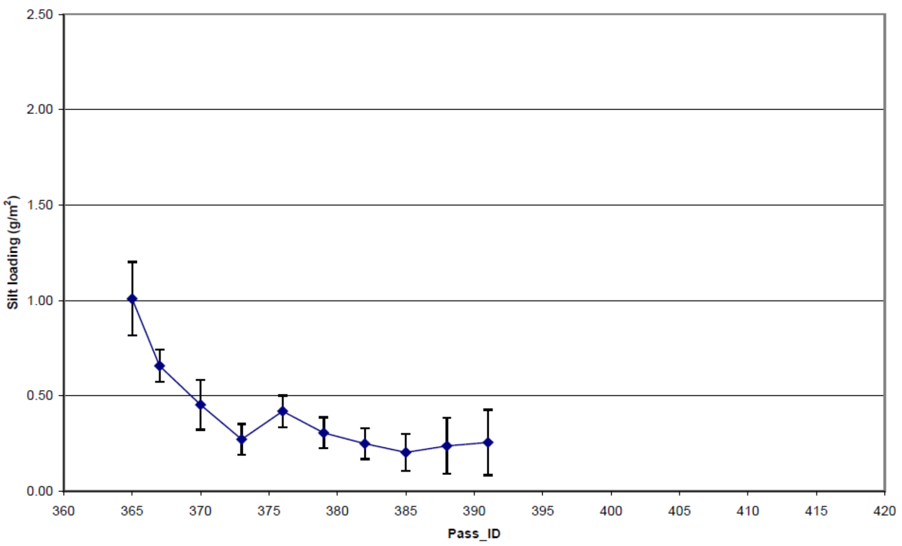


Figure 111. Silt depletion with increasing vehicle passes. Nominal applied silt loading 0.6 g/m^2, varying vehicle speed (Langston et al., 2009).

The measured PM10 at the side of the O-track reflects the development in dust load and suspension, with decreasing concentrations after initially high values. But even though the dust load is depleted, each car passages generates a peak in PM10. This, together with the rather constant Vectra signal, shows, that at given conditions, there is a PM10 reservoir, that is will deplete very slowly. The suspension losses are small and might be compensated by deposition, crushing and lateral movement of dust.

The demonstration of the effect of meandering driving, with a fourfold increase in the suspension signal and a much higher increase in PM10 concentration, shows that while the dust load is quickly depleted in wheel tracks, the dust load between and outside of the tracks is more or less undisturbed and will emit high PM10 concentration when if trafficked. The difference in dust load in and between wheel tracks as sampled with WDS is not that pronounced and sometimes even higher in wheel track. A possible explanation to this is that the coarser fractions (10–180 µm), that dominate the WDS samples, do not contribute to PM10 directly. The fraction below 10 µm constitutes about 10–25 % of DL180.

Ideally in a controlled experiment looking at road dust suspension it should be possible to measure and follow the mass balance of the dust loading, i.e. measure the amount of suspension, the amount of depletion on the road surface, the transport of dust across and along the road. Though Vantaa was intended as such a controlled experiment it was not entirely suitable for estimating the mass balance. This was chiefly because there was no control over the initial dust distribution. This had a high spatial variability over the surface and there was a significant part of the dust that was cemented into the pores of the surface. This meant that a large fraction of the WDS measurements were measuring non-suspendible dust so the signal of the suspendible removal was small in relation to the total amount of dust. In addition, since the WDS cannot be made in exactly the same spot each time, large spatial variations in the road dust load created significant noise, making it difficult to extract the depletion signal in the data.

In the section Relating mobile measurement data to dust loading and emissions” a method for integrating the Sniffer signal, the suspended road dust and the road dust loading is described and applied to derive estimated emission factors and road dust loadings based on Sniffer measurements. Such a methodology would require more assessment under more controlled conditions to further determine its applicability.

Importantly it has become clear that the suspendible dust load can be significantly less than the total dust load. The difference between these two will be dependent on the history of the road surface in terms of traffic, meteorology and salting, as well as the surface texture. This has consequences for modelling which assumes the entire dust load is available for suspension. It also indicates the need for a dry dust sampling measurement methodology, that can provide information on the suspendible part of the dust load.

The sanding experiment showed that sand is quickly reduced in wheel tracks but reduced slower in between. In wheel tracks, the reduction after almost 600 passages of cars running at about 50 km/h is about 70 %. Kuhns et al. (2003) reported that the direct impacts of road sanding on PM10 emissions are short lived lasting no more than 8 h or 2500 vehicle passes

The crushing test did not result in easily interpreted data. Initial results showed a tendency towards crushing, but as the test progressed, a reversion could be seen, where the material became coarser. It is most likely that there are too many influencing factors not accounted for to interpret these results.

In Stockholm, tests were performed to evaluate the effects on dust load and suspension from cleaning and flushing the streets. As in previous studies (e.g. Järlskog et al. (2017)), high pressure washing followed by strong vacuuming, seems to reduce the dust load most. The reduction is most obvious in between and outside wheel tracks. When comparing the results from the Sniffer vehicle to the dust loads the relation between the changes in dust load in wheel tracks is in the same direction for both methods. On Hornsgatan, dust load increases in wheel tracks after sweeping, inducing an increased suspension by the Sniffer. On Fleminggatan, the dust load in wheel tracks is practically unchanged after the flushing. The Sniffer signal is slightly higher after, but the difference is not significant.

PM10 concentration is obviously reduced when flushing and vacuuming Hornsgatan, but the effect is short-lived (1 hour) under the prevailing meteorological situation. The dip in concentration well resembles experimental results in the CMA+ project (Hafner, 2012). The concentrations went below the inner-city average concentration which is a mean value of three other inner-city streets (Sveavägen, Norrlandsgatan and Folkungagatan) where PM10 is also measured with TEOM. These streets generally have lower concentrations than Hornsgatan, which makes the result even clearer since Hornsgatan drops well below the inner city mean concentration during the cleaning. Maybe the concentrations of PM10 would have been even higher in the afternoon if no street cleaning had been made. However short-lived, the effect looks like it still manages to decrease the daily average concentration with about 2 µg/m^3 and without adding salts or chemicals. A small and visible ‘clean’ cleaning.

The size distribution analyses in AQ data from Stockholm reveals some interesting features, that might relate to road operation. When comparing the Stockholm data with data from a similar street in Uppsala, the abundance of coarser particles is higher in Uppsala, which might be related to intense vacuum cleaning in Stockholm during 2017. When the vacuum cleaning was abandoned in Stockholm, in 2018, the coarse fraction increased as compared to 2017.

Since studded tyres have been able to be approved using the overrun method, several manufacturers have increased the number of studs compared to what is allowed using the 2015 regulations, for better friction in winter conditions. To compensate for the expected higher wear, studs are smaller and lighter, and developments have been made concerning their shape, material and how they are fitted into the tyre rubber.

The statistical methods used in the road simulator to compare the different studded tyres has been used both for non-studded (Grigoratos et al., 2018, Gustafsson and Eriksson, 2015)and studded tyres (Grigoratos et al., 2018, Gustafsson and Eriksson, 2015). The differences between tyres rank as

Nokian > Bridgestone > Pirelli = Hankook > Continental > Michelin;

when it comes to PM10 emission. Compared to previous tests in the road simulator in Gustafsson and Eriksson (2015), Nokian, Pirelli, Continental and Michelin rank in the same order, even though the difference between Pirelli and Continental was smaller in the previous work..

An interesting result, which also have been seen before, is that when studying the number concentration, the rank is changed between tyres. The rank for number concentration is:

Pirelli > Nokian = Continental > Hankook > Bridgestone >> Michelin.

Also here, the rank in Gustafsson and Eriksson (2015) is the same between Nokian, Pirelli, Nokian, Continental and Michelin, but with Pirelli and Nokian being almost similar with a gap down to Continental.

The number concentration is totally dominated by ultrafine particles, which form in different ways than the coarse, mineral-dominated PM10. It is therefore not surprising that other material and construction properties than stud properties have a high influence. A hypothesis is that these particles are formed when studs move vigorously in their attachments and cause heating of the rubber resulting in evaporation of softening oils, which then condensate into ultrafine particles.

Initial comparison between only PM10 results show low correlation between the road simulator and Vectra test methods, but by adding stud protrusion to the analyses, the correlation improves markedly. At this stage it is clear that two of the 190 stud tyres are the highest PM10 emitting tyres and that the 96 studs tyre is the lowest emitting, but also that the 130 studs tyre is close as high emitter as the two highest and that one 190-studs tyre is the second lowest PM10 emitter. This indicates how well manufacturers have managed to reduce PM10 emissions by tyre, despite the increased number of studs.

By also adding stud number per tyre, improves correlation between the test methods slightly. Now the results reflect the performance per stud and shows that the studs of the 130-stud tyre are the highest PM10 emitters followed by the studs of the 96-stud tyre. All studs from tyres with 170-190 studs per tyre, perform better and the lowest emission comes from the same 190-stud tyre as the one that performed second best when comparing the whole tyre. This implies that the manufacturers working with lighter, but more, studs, have succeeded in reducing PM10 emission per stud. Still, this do not always compensate enough for the increases number of studs.

A number of experiments were carried out in NORDUST with the intention of improving parameterisations used in the NORTRIP model. Not all of these were successful, but much has been learnt about how to develop measurement campaigns to provide quantifiable results for use in the model. As seen in this report the amount of data collected is large and diverse. One of the main challenges has been to integrate these diverse measurements together to produce quantifiable results for modelling. Some measurements were ambiguous, for example the crushing experiment and the PM2.5/PM10 ratios found with different measurement techniques, and for some measurements there was not enough control of the experimental situation, for example the initial road dust loading in Vantaa. Even though controlled experiments are useful for model development it is also important to carry out experiments in real world conditions, for example in the real-world sanding is only carried out under cold and icy conditions and not on warm dry surfaces as done during the Vantaa campaign. Despite this useful conceptual and quantifiable information for modelling has been obtained.
Based on the results from the campaigns the following updates have been made in the NORTRIP model:

1. Fraction PM2.5/PM10 has been increased from 5% to 8%
2. No change in PM2.5 suspension efficiency has been implemented due to the ambiguity of the measurement results
3. The crushing process description has been tested and first estimates of parameters have been included in the model. These will be further applied and tested but relevant measurement data is still needed to confine the parameterisations
4. The cleaning efficiency parameterisation has been implemented in the model and will be further tested

5. New water spray parameters based on MORS2 data have been implemented

The following questions remain open concerning the processes addressed in this study

1. The impact of surface texture on the various wet and dry processes
2. Inconsistencies in road surface, ambient air and Sniffer data do not indicate a consistent and explainable size dependence on the suspension of PM. More light may be cast on this through a dry dust sampling technique that will provide information on the suspendible fraction of road dust. It is also a question as to whether dust load size characterisation is the same as aerodynamic size characterisation
3. The fate of sand, both in crushing and suspension, was only partially successfully tested in the field studies as the results were ambiguous and not representative for real traffic conditions. A well-planned field campaign where this is further explored is still needed.

The application of the NORTRIP model with the Icelandic datasets presents some problems connected mainly to the availability and quality of the input data.

The **traffic data** are extrapolated from seasonal or monthly averages and therefore do not reflect day to day variations in the hourly traffic passing the investigated road stretch. Vehicle speed, which importance in generating PM from non-exhaust emissions is underlined by the applications of NORTRIP in Oslo (Norman et al., 2016), is only inferred from the existing speed limits. It must be highlighted that the investigated road stretch is located at a road crossing and traffic lights are present, which are not accounted for. Lower speed would produce less road wear but braking due to the traffic lights produces more brake wear. Traffic lights could also induce speeding, especially during non- rush hour times.

NORTRIP does not calculate dispersion so NOx is often used as a tracer to provide an estimate of dispersion in order to calculate dispersion. For this reason, reliable air quality monitoring data is required, both from an observation station, that is close to the investigated road stretch, and from a background station, located within the urban context but not directly affected by traffic variations. The best dataset, available from Stockholm – Hornsgatan, uses the air quality at the road level inside the street canyon and the background data at the rooftop level (around 24 m high houses). The closest background station to GRE is FHG, located within a green area around 1.1 km NNE from the test site. It can’t be excluded that this air quality station is affected by the traffic at the test site, and it can be influenced by other sources such as dust from soil and non-vegetated areas within the park. FHG data are very often not available for the investigated time periods.

According to the developers, an important parameter is the **surface moisture**, which influences greatly the performance of the model for PM concentration. There are no direct measurements available regarding the surface moisture in Iceland for comparison of the road surface moisture sub-model performance.

In addition to the missing input data, or input data of poor quality because extrapolated from averages, the **test location** in Reykjavik might not be suitable. The main traffic roads leading into the town centre cannot be described as street canyons and the investigated road stretch is very open (Figure 112). The distance between the relatively low buildings (maximal three-storey) amounts around 120 m. The road stretch presents also a slight slope in direction WSW. The location was mainly chosen because of the location of the air quality station and because of the availability of traffic counts along the main road (Miklabraut). The presence of the crossroad (Grensasvegur) is contributing to the openness of the area.

The model was run with the default parameters and no adjustments to Icelandic conditions were made. Improvements to the overall performance of the model could be achieved by adjusting or re-defining the used parameters, related to the road wear and the tyre wear for example.

Figure 112. Map of the test area in Reykjavik. Green shows open, green spaces, blue the existing buildings.

The application of NORTRIP in Oslo for the years 2008, 2009 and 2010 has shown an model error in predicting the number of exceedance days and an error in the calculation of the mean concentrations, with the first being higher than the latter (Denby & Sundvor, 2013). The days with higher than allowed PM10 concentration are over-predicted, while the annual mean concentrations are under-predicted. This trend can be seen also with the used datasets from 2012 and 2016, where for 2012, all year and background station FHG the exceedance days are over-predicted, while the mean concentrations are always under-predicted.

In general, the model requires a considerable amount of data, some of which are not available now in Iceland. Besides the road surface measurements, which are not easily realized, it would be helpful to have the real measurements of the hourly traffic data together with the vehicle speed data. The continuity of air quality measurements at the roadside (GRE) and the background stations (FHG) is also not always given, making it difficult to model a longer time period.

The use of the model can help to understand the impact of mitigation strategies which could be realized in Reykjavik to abate the air pollution from particulate matter, deriving especially from road traffic. There are different mitigation strategies which can act either to minimize the sources or minimize the suspension (Amato et al., 2014). The first category includes the improvement of the wear properties of tyres, brakes and road pavement and the reduction of wear due to traffic, especially from studded tyres. The second category includes the removal of the suspendible dust from the road surface, for example through cleaning, the dust binding to the road surface and measures regarding the management of traffic (reduction, lower speed, lower heavy vehicles) (Amato et al., 2014).

In Norway, the abatement strategies comprise the reduction of studded tyres, the reduction of vehicle speed using environmental speed limits, the use of dust binding salts (MgCl2), and cleaning (Denby & Sundvor, 2013). In the NORTRIP model road wear and suspension rates are linearly dependent on vehicle speed and it has been shown that the reduction of vehicle speed in Oslo follows a reduction of PM non-exhaust emission (Denby & Sundvor, 2013).

Conclusions

At an overall level the NorDust project has resulted in:

- The first common Nordic road dust research collaboration
- Increased knowledge on
  - road dust formation and dynamics
  - influence on PM10 emissions of new studded tyre types
  - road dust abatement efficiency and influencing factors
  - road dust sampling technique and methodology
- Improved NORTRIP emission modelling and extended model implementation and evaluation

At a more detailed level, the NorDust project has resulted in a large number of conclusions, of which the most important ones are listed below.

Field tests Vantaa

- On a previously un-trafficked surface, road dust suspension is reduced to a constant level after about 200-300 passages at about 50 km/h. On site 1 on O-track, the dust load reduced in a similar manner, while the dust load on site 2 and 3 did not show an obvious decrease.
- Meandering (off-track driving) resulted in markedly higher suspension emission and PM10 concentration peaks, revealing the high lateral variability of suspendible road dust load caused by traffic depleting the wheel track dust load. WDS data did not show a marked lateral variability connected to wheel tracks.
- Based on the conclusions above it is clear that, at the Vantaa site, there is a dominant dust load portion, sampled with WDS, that is either larger than PM10 and/or not available for suspension.
- During the sanding experiment, approximately 600 passages removes about 2/3 of the initial amount in wheel tracks and 1/3 in between.
- Estimated increase in the suspension on the sanded segment was 180% after one hour and 100 vehicle passages, and 250% after 3 hours and additional 50 vehicle passages.
- The crushing experiment was not conclusive. A tendency that studded tyres promotes production of finer fractions than friction tyres could be seen.
- Cleaning effects was not discernible in the dust load at Vantaa, but an effect could be seen in the suspension measurements, probably because only a small fraction of the dust load contributes to PM10. The small-scale variation in texture and dust load was also high and not typical for a street, which complicated the analyses.
- In suspension tests with Vectra, the cleaning effect was 35 and 54 % for CityCat 5006 and PIMU, respectively on the same day as the treatment. Effect remained a day after for PIMU, but was lost for the CityCat.

Field tests Stockholm

- WDS sampling on E18 showed a high variability across the three lanes with marked low dust load in wheel tracks and high in between and on shoulders.
- Vectra tests on E18, showed that a bus lane had significantly higher emissions than the car lanes due to accumulated dust on shoulders.
- Road dust load is reduced mainly between wheel tracks, but increased slightly in wheel tracks by flushing followed by vacuuming, while only vacuuming had no obvious effect.
- The PM10 suspension increased after flushing and vacuuming.

Tyre tests with Vectra and in road simulator

- The large range of stud number among today's studded tyres influences the PM10 emission. Higher number of studs per tyre is generally causing higher PM10 emissions, but exceptions show that there are ways of designing studs and stud attachments in the tyre rubber, that will decrease PM10 emission.
- Particle number emission do not follow the rank for PM10 emission concerning the high-number studded tyres, but low-number studded tyres still emit the lowest amounts of ultrafine particles.

NORTRIP development

Three new parameterisations have been implemented in the NORTRIP model as a result of NORDUST. These are the cleaning, the sand crushing and the vehicle spray parameterisations. In addition, a number of parameters in existing parameterisations have been updated. These parameterisations will be applied in NORTRIP and their use in real world modelling situations will be continually assessed.

An important part of model development is building a conceptual model. During NORDUST the need to separate suspendible and non-suspendible road dust in the model formulation has become clear. In addition, an alternative description of the model that treats in and between wheel tracks separately is required if this concept, and others such as meandering, are to be included. Though the crushing parameterisation has been implemented the correct parameters for its application are still not well defined and an improved experimental setup is required to better define these.

NORTRIP in Iceland

- The NORTRIP model did not perform well in Iceland, mainly due to lack of, and/or poor quality of, input data for the model, but also on a complex site used for modelling.
- Reliable PM10 emission modelling in Iceland using NORTRIP, there is therefore a need for increased monitoring and data collection as well.

Future work

The NorDust project has answered some of the initial research questions. Some remain and new questions have arisen during the project.

Results from NorDust indicate that cleaning might be a suitable abatement method for road dust, but only depends on methods and on what particle fraction the cleaning aim to reduce. Several projects before NorDust has also contributed to information regarding cleaning as well as dust binding and other street operational measures. The knowledgebase should therefore be used to identify the most promising technologies or technology combinations for road dust abatement. Still, there is also a need to evaluate promising new techniques and strategies using methodologies based on NorDust evaluation experiences.

Regarding knowledge on parameters influencing on road dust emissions, the surface macro texture remains important, but is still not quantified. Quantification of macro texture influence on both dust load and dust suspension, but also on sweeping efficiency, drainage and spraying, is therefore of interest. Very little is also known about how heavy-duty vehicles influence the production and suspension of road dust. Dedicated experiments are needed to assess how they compare to light duty vehicles.

The NORTRIP model would benefit from further input regarding a number of parameters. Dust binding effect depends on chemicals used and their dose and concentration, but these are factors not yet parametrised in the model. Laboratory and/or field experiments could add knowledge to improve the model regarding this. A dust transport process, that remains unclear is the removal in water as run-off or splash and spray. Further studies would be beneficial for further development and evaluation of the NORTRIP model. Due to the high lateral variability of road dust load, the NORTRIP model also needs to be able to handle that different processes and conditions prevail in different parts of the road surface, i.e. be developed into a multitrack model for better description of the dust suspension. This would also improve model description of surface wetness and interaction with salt. Even though NorDust, together with some previous projects, has produced information about the influence of sand and grit on road dust load and emission, this is still a complex research area in need of more elaborate tests and test methods.

There are no standards for road dust sampling, and the sampler used in NorDust, the WDS, uses the concept of estimating the total amount of dust on the road surface. This is important information, but to investigate a more direct connection to dust emission, a complement is needed, that can sample or estimate the suspendible fraction. The development of a road dust sampling equipment to also quantify the suspendible fraction as a complement to the total load is of high interest to the research field.

A research area that has high priority since some years is microplastics from road traffic. Since TRWP (tyre and road wear particles) have been identified as a main source, there is an obvious connection to road dust research, like the NorDust project. Including microplastics in the road dust concept would be possible through adapting road dust sampling techniques for microplastics, study the contributions to road dust from tyre wear, road markings and bitumen and through data analysis to establish the dependencies and implementation in NORTRIP.

The main data on road dust in Nordic countries are from Norway, Finland and Sweden. Even though Iceland is experiencing high air pollution levels related to road wear and suspension, almost no data, except for air quality, is available to support NORTRIP modelling during Icelandic conditions. Iceland has a different climate, different road surfaces and different non-traffic sources compared to other

Nordic countries, why data collection and measurements are needed. Especially, there is a need for data on dust loads and road operation measures to be able to model emissions also in the special Icelandic conditions.

An issue related to activity data is how the data can be registered in a correct and precise way, preferable as independent as possible of operators. Activity precision in time and space is vital to be able to model the influence of the activities on emissions. Therefore, it would be of high interest to further investigate and test how road operation activity data can be automatically registered for comprehensive and more correct activity data as input to NORTRIP model and follow-up of dust mitigation strategies.

The knowledge produced in NorDust, is intended to improve the NORTRIP model, which in turn can be used to optimize mitigation scenarios and strategies and quantify the benefits of mitigation strategies for health benefits and lower societal costs. Further improving the model through implementing results from above mentioned activities and research would further improve the results of NORTRIP modelling.

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Havnegade 27

1058 København K