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Measures to reduce road dust emissions from traffic

Nordic Council of Ministers

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Measures to reduce road dust emissions from traffic

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PHOTO: SCANPIX

Foreword

High concentrations of road dust have been identified as the major cause underlying violations of the EU daily PM_{10} limit value for the protection of human health in several locations in Sweden, Finland and Norway during the last decade. A science-policy dialogue between authorities and research organizations has been taking place for some time to support the development of measures and policies to reduce road dust emissions, improve air quality and to identify areas that require further research. Science based knowledge and information about road dust sources and mitigation opportunities is essential for evaluating the effectiveness of current measures as well as the development of further policies. Promising results have been observed in some Nordic cities.

This Policy Brief describes the current understanding of the road dust system and reviews several mitigation measures and policies in use in the Nordic countries. It has been compiled as part of the research project "NOn-exhaust Road TRaffic Induced Particle emissions (NORTRIP)" funded by the Climate and Air Pollution Group of the Nordic Council of Ministers, but reflects also the understanding developed over a decade of research into road dust and traffic induced non-exhaust emissions by researchers from 11 Nordic institutes.

Helsinki, October 2016

Kaarle Kupiainen,
Project coordinator of NORTRIP-2

Introduction

Nordic countries suffer from periodic worsening of the air quality during spring with high peak PM_{10} concentrations (airborne particulate matter with diameter less than 10 µm or 0.01 mm). Characteristic for the high springtime PM_{10} concentrations are high shares of coarse particles (with diameters between 10 and 2.5 µm), a signature of non-exhaust traffic dust formed via abrasion and wear of pavement, traction control materials, vehicle brakes and tyres. During the cold and wet weather conditions in winter, dust accumulates in snow and ice as well as in the humid road surface texture. In spring, as snow and ice melt and street surfaces dry up, high amounts of dust become available for suspension.

While PM exhaust emissions have decreased and will substantially decrease in the coming years due to more stringent regulation, the non-exhaust emissions are expected to stay at the same level or increase with traffic volume and will represent a dominating part of the total PM emissions.

Studies suggest that non-exhaust emissions from vehicular traffic cause significant health risks for the population. The high concentrations occurring during the spring period due to non-exhaust sources have been the major cause underlying violations of the EU daily PM_{10} limit value[1] for the protection of human health in several locations in Sweden, Finland and Norway during the last decade. Efforts have been taken to study the emissions, source contributions, air quality impacts and measures to reduce the burden of non-exhaust particles in the urban environment.

The understanding of road dust processes has improved significantly in recent years. The NORTRIP project has contributed to this development and declining trends of spring time PM_{10} concentrations have been observed in many cities in the Nordic countries.

This Policy Brief has been compiled as part of the NORTRIP project funded by the Climate and Air Pollution Group of the Nordic Council of Ministers. It summarizes the current understanding of the road dust system and presents the mitigation measures and policies currently in place in the Nordic countries.

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[1] According to the EU air quality directive (2008/EC/50), adopted in Denmark, Finland, Norway and Sweden, the PM_{10} daily mean value may not exceed 50 micrograms per cubic metre (µg/m3) more than 35 times in a year. As of 2015 Norway has a stricter limit where the PM_{10} daily mean value may not exceed more than 30 times.

Key messages

- **Non-exhaust particles are generated by traffic and are produced via wear of pavements, tyres and brakes. Non-exhaust particles become airborne directly after formation or they may be deposited on the road as road dust and be suspended by tyres, vehicle induced turbulence or wind from the road surface. Road dust may also originate from road sanding and salting as well as particles from other sources deposited on the road.**

- **Road dust is an important contributor to ambient PM concentrations in the Nordic countries where its main sources are pavement wear by studded tyres, and to a lesser degree traction sanding and salting as well as brake and tyre wear.**

- **Non-exhaust particles may cause significant health risks for the population living near intense traffic locations.**

- **Efficient ways to mitigate the emissions and ambient concentrations of road dust in Nordic cities exist. The mitigation measures can target (1) the formation of particles or (2) the emission of already produced particles (suspension):**

1. *In Nordic conditions, reducing the use of studded tyres, traffic speed and volume and improving the wear resistance of pavements have proven to be the most effective ways of reducing the production of PM_{10} containing road dust. Further research and development of studless winter tyres and less wearing studded tyres could also reduce emissions. Optimal designs for pavement and tyres that can account for safety issues, pollutant emissions and noise generation still need to be developed.*

2. *In Nordic conditions, dust binding with hygroscopic solutions has been demonstrated to be the most efficient short term method for reducing PM_{10} suspension emissions. If performed with efficient techniques at the right time, street cleaning with modern equipment can also reduce PM_{10}.*

Recommendations for further work

- **The understanding of road dust processes has improved significantly in recent years. Measurement and modelling methods exist that are able to study the dynamics of road dust emissions and efficiency of mitigation efforts. The NORTRIP project has contributed to this development. However, significant knowledge gaps still exist in many fundamental processes affecting the road dust emissions. Further measurements are needed concerning the movement of dust in vehicle flow, formation of PM_{10} from traction sanding and new generations of studded tyres.**

- **The NORTRIP model is a versatile tool for emission estimation in conditions where road dust is considered an important source for PM_{10} pollution as well as for follow-up and scenario analyses of abatement measures. Current and future model developments include modelling the emissions and air quality of multiple urban streets up to city level, coupling the model with air quality forecasting systems and improvement of model parameterizations through targeted measurement campaigns.**

Road Dust concepts

a) Airborne particles

Airborne particles or particulate matter (PM) are microscopic solid or liquid particles, small enough to remain airborne after emission.

b) Non-exhaust particles

The concept "non-exhaust" refers to road traffic generated particles produced during wear of pavement, brakes, tyres and other parts of the vehicle. It excludes particles emitted as exhaust from the incomplete combustion of fuel or motor oil in the engine as well as any secondary particles formed from precursors emitted during the combustion of fuels and motor oils.

c) Road dust

Road dust is often used synonymously to non-exhaust particles (see b) but generally refers to non-exhaust particles and dust from a range of other sources accumulated on the road surface, for example road sanding and salting.

d) Direct emissions

This includes both exhaust and mechanically generated non-exhaust particles that are emitted directly to the air without first being deposited onto the road surface. Both fuel and motor oil contribute to the exhaust particles, whereas wear of brakes, tyres and pavements contribute to the non-exhaust particles.

e) Suspension/Resuspension

Suspension refers to the action by wind or vehicles that makes dust on road surfaces become airborne. The term resuspension is often used synonymously to suspension, but it indicates that the suspended particles have originally been airborne before being deposited onto the road surface and being resuspended again. In practice it is not possible to distinguish between road dust particles that have first been airborne and those that are directly deposited on the road surface before any suspension takes place, e.g. during wet conditions. Under many conditions a large fraction of the particles suspended from the road surface have never been airborne so the term suspension is used in this document.

PHOTO: SCANPIX

PHOTO: ROOSA RITOLA

In practice it is not possible to distinguish between road dust particles that have first been airborne and those that are directly deposited on the road surface before any suspension takes place, e.g. during wet conditions.

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In addition to air pollution's role in the development of respiratory diseases, there is a strong link between air pollution exposure and cardiovascular diseases, such as strokes and ischemic heart disease, as well as between air pollution and cancer.

Impacts of road dust on human health

The World Health Organisation (WHO) estimates that seven million deaths are linked to air pollution every year.[1] This estimate is substantially higher than previous ones. In the case of outdoor air pollution, WHO has estimated that 3.7 million premature deaths in 2012 were caused by air pollution from urban and rural sources worldwide. Air pollution is therefore the world's largest single environmental health risk. In addition to air pollution's role in the development of respiratory diseases, there is a strong link between air pollution exposure and cardiovascular diseases, such as strokes and ischemic heart disease, as well as between air pollution and cancer. It has been estimated that the annual amount of premature deaths resulting from poor air quality in Europe ranges from approximately 600,000 to 700,000. Particulate matter is a major health risk most likely causing a significant part of the premature deaths.

Road transport emissions are a major contributor to ambient particulate matter concentrations and have been shown to cause severe adverse health effects. Studies suggest that non-exhaust emissions from vehicular traffic cause significant health risks for the population (WHO, 2013). Such risks are most substantial in urban areas, especially near intensively trafficked locations. This is understandable, as non-exhaust materials can be toxic; for instance, tyre and brake wear contains heavy metals, such as zinc and copper, but there may be many other reasons for the adverse effects.

Non-exhaust sources contribute significantly to concentrations of coarse particles (size range between $PM_{2.5}$ and PM_{10}). Although less studies about their association with health effects exist than for $PM_{2.5}$ and PM_{10}, WHO (2013) notes that there is evidence suggesting an association between exposure to coarse particles, including crustal material, with morbidity and mortality (WHO, 2013). A study in Stockholm demonstrated the strongest associations during the most intensive road dust period (Meister et al. 2012). Studies have also shown associations between adverse health effects and the exposure to Saharan dust or to coarse particles from arid areas of the United States.

Other impacts of road dust particles are reduced visibility, corrosion, and the nuisance caused by dust on surfaces, such as, for instance, windows and cars.

[1] www.who.int/mediacentre/news/releases/2014/air-pollution

PHOTO: NORDEN.ORG / KARIN BEATE NØSTERUD

PHOTO: ROOSA RITOLA

In the Nordic countries of Norway, Finland and Sweden, where snowy and icy winter conditions are common during the winter season, winter tyres are mandatory.

Formation and emission of non-exhaust particulate matter

Studded tyres and pavement wear

In the Nordic countries of Norway, Finland and Sweden, where snowy and icy winter conditions are common during the winter season, winter tyres are mandatory. Winter tyres are either studded or non-studded. Studded tyres have been, and are still, popular since they provide the best grip on ice. Although more wear resistant pavements and lighter studs have decreased road wear substantially in the past decades, still about 100,000 tons of road surface are worn each season in Sweden alone.

Tyre studs wear the road by impacting and scratching the pavement surface and form small particles. A fraction (~30%) of the total road wear caused by studded tyres is in the PM_{10} size range (diameters < 10 µm). This can be directly emitted into the air under dry conditions or accumulate on the road surface during wet conditions. Coarser fractions of wear (i.e. particles much larger than 10 µm) can also accumulate to later form PM_{10} by crushing or by abrasion of the road surface through traffic. Accumulated particles are suspended when the surface dries, intensifying emissions.

The factors influencing the generation of PM_{10} through road wear are many. First and foremost it is the traffic volume and studded tyre share that directly influence these emissions. Additional factors include stud weight, stud number, stud protrusion, vehicle weight, vehicle speed, cornering and acceleration and pavement wear characteristics.

Sanding

Winter sanding can also contribute to road dust PM_{10} emissions (Kupiainen et al. 2016). Compared to the constant wear from studded tyres, the emission from sanding is more sporadic and depends on the amount of sand applied, rock quality and size distribution. Sand grains easily migrate across the street surface and accumulate outside the wheel tracks as traffic moves them around. As long as cars keep to the clean wheel tracks little is emitted, but driving outside the wheel tracks might cause very high, but sporadic, emissions. Laboratory studies have shown that better rock quality and lower amounts of smaller size fractions in the sand can decrease the PM_{10} emissions (Kupiainen, 2007).


PHOTO: NORDEN.ORG / KARIN BEATE NØSTERUD

The use of winter salt can lead to PM_{10} emissions. A dried crust of de-icing salt can, through traffic abrasion and suspension, contribute to PM_{10} directly


PHOTO: ROOSA RITOLA

Salting

The use of winter salt can lead to PM_{10} emissions. A dried crust of de-icing salt can, through traffic abrasion and suspension, contribute to PM_{10} directly. Studies indicate that approximately 0.5% of the total salt distributed on the roads in Nordic countries can be emitted as PM_{10}. Though this may seem small, roughly 200,000 tons of salt are applied every year in each of the Nordic countries which makes national salt contributions to PM_{10} emissions as large as contributions from exhaust (Denby et al. 2016).

Dust load and suspension

Pavement wear, as well as traction sand and dust from other traffic and non-traffic sources, accumulates in the street environment forming road dust. Especially during winter, when the weather is wet and cold, dust accumulates in snow and ice as well as in the humid road surface texture. Winter salting also helps to keep the road surface humid and prone to accumulating dust.

In spring, as snow and ice melt and the increased sunshine dries up the streets, high amounts of dust become available for suspension. Suspension is induced by vehicle tyres moving over the surfaces as well as the turbulence around the vehicles. Higher speed and larger vehicles increase the suspension. A truck may suspend tens of times more dust than a personal car at the same speed. Strong winds can also lift particles airborne. Suspension is directly dependent on the surface conditions (Johansson et al. 2007). The suspension rate will also depend on the surface roughness. A smooth road surface will quickly loose the accumulated dust whilst rough surfaces retain the dust.

Modelling studies (Denby et al., 2013a) indicate that despite the obvious emission of dust through suspension, the continuous direct emission of dust through road wear under dry conditions is the largest contributor to long term average PM_{10} concentrations in Nordic urban conditions.

Meteorology

Meteorological conditions have a strong impact on the road dust emissions. Wet conditions reduce suspension whilst at the same time allowing the removal of road dust by drainage and vehicle spray. Particularly on high speed roads, vehicle spray is an effective method for removing road dust from the surface.

Fig. 1 shows the NORTRIP model calculated source contribution to PM_{10} emissions, based on 23 annual datasets from 7 locations of the four Nordic countries. The associated road wear from studded tyres accounts for more than half of the total PM_{10} emissions. However, even without studded tyres non-exhaust emissions of PM_{10} are still twice as large as exhaust emissions.

FIGURE 1

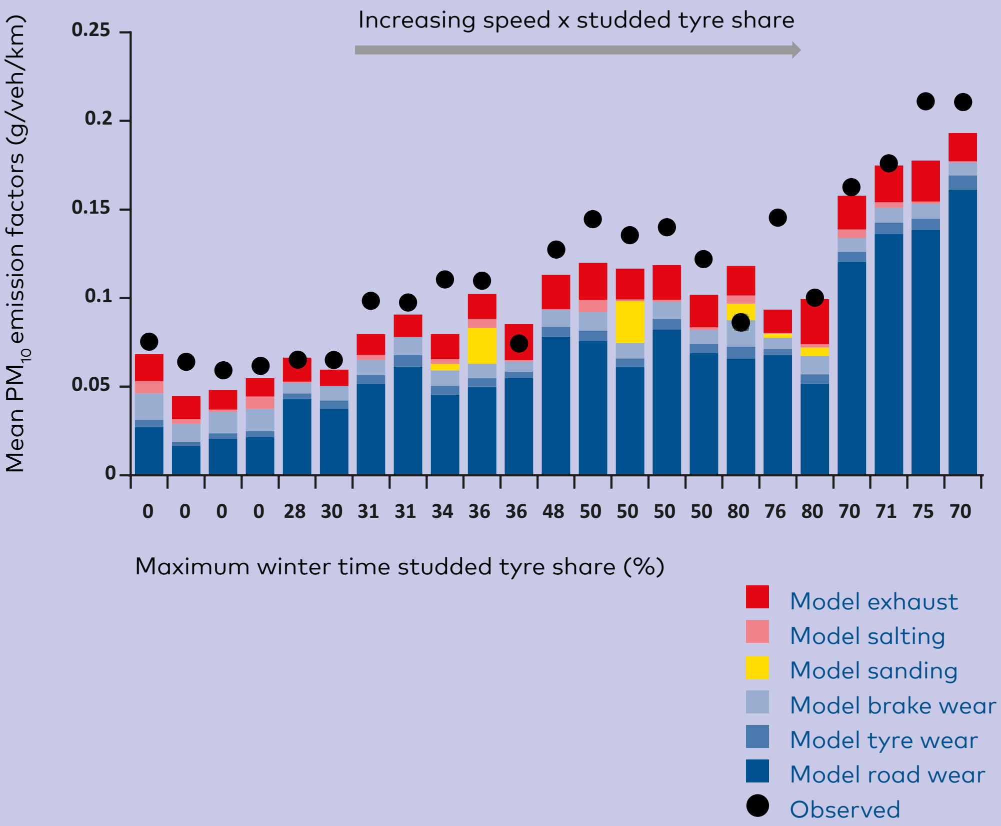
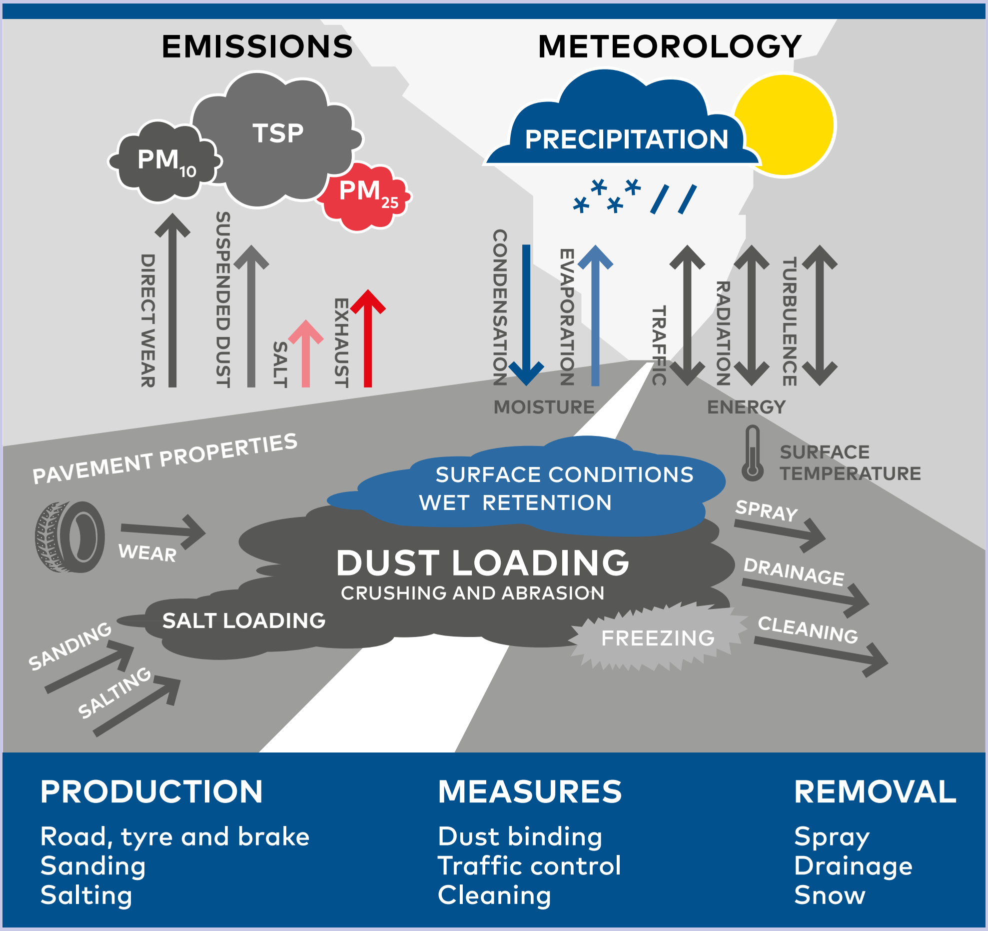


Figure 1

NORTRIP model calculated source contribution to PM_{10} emission factors, based on 23 annual datasets from 7 locations in the four Nordic countries. Results are sorted according to increasing maximum studded tyre share multiplied with average vehicle speed. This reflects the fact that both these factors lead to higher emissions. Variations in the emission factors are also due to meteorological and road pavement conditions.

FIGURE 2 – NORTRIP – Road dust and moisture processes



The NORTRIP model

Understanding and quantifying the processes affecting road dust emissions is an essential step in developing effective abatement measures. To aid this computer models are used that can predict the outcome of measures prior to their implementation. The NORTRIP emission model has been developed to achieve this by describing the processes that govern road dust and salt emissions, the accumulation of dust on the surface and the processes that determine surface road conditions (water/ice/snow and temperature) (Fig. 2). The model has been successfully applied to predict PM_{10} concentrations for a wide range of sites in the Nordic countries, including Denmark (Fig. 1, Fig. 3). It can be used to predict the impact of traffic reductions, studded tyre reductions, speed reductions, fleet changes, changes in pavement characteristics and the impact of salt and dust binding.

FIGURE 3

NORTRIP builds upon, and significantly extends, previous models developed by Omstedt et al. (2005), Kauhaniemi et al. (2011) and Berger and Denby (2011). The model is described and assessed in more detail in Denby et al. (2013a, 2013b) and Kauhaniemi et al. (2014), and is under continuous development and application. Included in NORTRIP is another Nordic model, the street canyon dispersion model OSPM (Berkowicz, 2000), which allows direct estimation of curbside concentrations from the emission calculations as presented in Fig. 3.

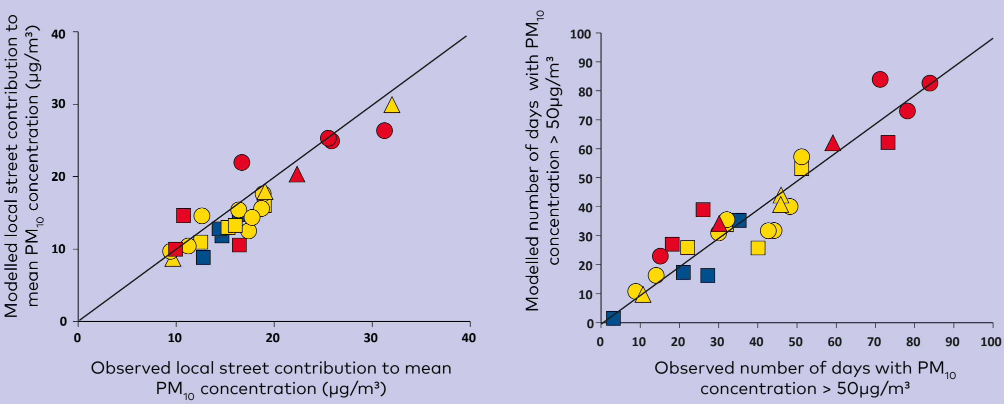


Figure 3

Validation of the NORTRIP model showing comparison of modelled and observed PM_{10} concentrations for 10 sites (28 annual datasets) in the Nordic countries. The model correctly predicts both the mean local contribution to PM_{10} (left) as well as the number of days in exceedance of the legislative limits (right). Results are shown grouped into studded tyre share and vehicle speed ranges.

■ 0–20% studs, 20–40 km/hr
■ 20–50% studs, 20–40 km/hr
● 20–50% studs, 40–60 km/hr
▲ 20–50% studs, 60–90 km/hr
■ 50–80% studs, 20–40 km/hr
● 50–80% studs, 40–60 km/hr
▲ 50–80% studs, 60–90 km/hr

Sampling of road dust in the Nordic countries in the urban street network

1

Mobile measurement vehicles SNIFFER, EMMA and Vectra have been designed to measure street dust emissions from the street surface in urban street network (see Pirjola et al. 2010).

2

The VTI road simulator generates wear particles from the interaction between road pavement and tyres under controlled laboratory conditions (Gustafsson et al. 2008).

3

The VTI wet dust sampler (WDS) is a road dust sampling device. Sample analysis may include dust load amount on the street surface as well as the composition and size distribution of dust.

Overview and efficiency of current policy measures and mitigation practices in the Nordic countries

Studded tyre restrictions

The use of studded tyres has been identified as one of the largest sources for traffic non-exhaust particles in the Nordic countries and policy measures to reduce their impact have been introduced in Norway and Sweden. Studded tyre charges were introduced in Norway, first in the city of Oslo in 1999 and later in the cities of Trondheim and Bergen. The share of cars equipped with studded tyres decreased significantly in Oslo and Bergen from the original 50% down to 15% after the introduction of the charging system. The PM_{10} concentrations in all three cities have shown a downward trend that is largely due to the reductions in studded tyre use.

In Sweden studded tyre bans have been introduced for individual streets in Stockholm, Uppsala and Gothenburg from 2010 onwards. In 2016, the ban is in effect on two streets in Stockholm. On Hornsgatan, Stockholm, the maximum share of vehicles using studded tyres reduced from 70% to 36% immediately after the ban and further to 30% in later years. The combined effect of all emission sources and meteorological factors showed a reduction of around 50% in the street increment PM_{10} concentration averaged over the period 2011–2014 with the ban in place (Norman et al. 2016).

Vehicle speed

Road dust emissions from both direct and suspended emissions increase with increasing vehicle speed. For example on an arterial road, outside of Oslo, Norway, the speed limit was changed from one year to the next from 80 to 60 km/h, which resulted in a real world driving speed reduction of just 10 km/h, from 75 to 65 km/h. This speed change was also accompanied by a 4% reduction in traffic volume and a slight reduction in studded tyre share from 27% to 24%. As a result of all these changes the measured PM_{10} concentrations reduced by 36%. The NORTRIP model was applied to this case where it was able to reproduce the observed PM_{10} concentrations and to show that approximately half of the observed reduction in PM_{10} concentrations was due to the speed reduction (Norman et al., 2016). A winter time environmental speed limit (60km/h) is now implemented on major ring and arterial roads in Oslo.

Traffic measures

There are many different measures to affect general traffic characteristics, which will also have important consequences to non-exhaust particle emissions. It is beyond the scope of this policy brief to discuss all possible actions, but different types of urban vehicle access restrictions such as congestion taxes and low emission zones can be considered as important. In addition parking restrictions, promotion of public transport or other alternative means of commuting will reduce vehicle traffic and potentially also road dust formation, emissions and concentrations. Given the complex nature of the road dust system, the NORTRIP model is a useful tool to study the impacts of such measures on the generation and suspension of PM.

Given the complex nature of the road dust system, the NORTRIP model is a useful tool to study the impacts of such measures on the generation and suspension of PM.

Dust binding

Dust binding refers to the spreading of liquid, often hygroscopic, solution on paved streets to prevent street dust emissions by keeping the road surface moist. Individual cities in the Nordic countries have chosen to use different solutions; calcium magnesium acetate (CMA), magnesium chloride ($MgCl_2$) and Calcium Chloride ($CaCl_2$) are examples. The doses used have been reduced from several tens of grams per m^2 in early tests to the current about 10–20 g/m^2, due to a risk for reduced friction. Dust binders are normally spread using rotating disc spreader or by spray nozzle ramp. Several measurement studies show dust binding to result in the most significant and reliable short term reduction of suspended dust and the NORTRIP model has been able to reproduce and explain the observed impacts. Based on studies, dust binding may reduce daily mean PM_{10} concentrations by up to 40%. In the period of 2012 to 2014 in Hornsgatan, Stockholm, dust binding with CMA reduced on average the contribution of local street sources to annual mean PM_{10} concentrations by 8%. On days when dust binding took place this reduction was 24%. In Helsinki the average springtime PM_{10} concentrations decreased by 10–20% for the years 2006–2009 due to dust binding with $CaCl_2$. Of course, the effect of dust binding on ambient PM_{10} highly depends on the size of road dust load and its actual contribution to PM_{10}. In environments or situations where road dust load and its contribution to PM_{10} is small then dust binding will have little impact on ambient PM_{10}.

Street cleaning

The efficiency of today's street sweepers to pick up and contain particles as small as PM_{10} is generally low. Some modern sweeper techniques have been shown to reduce road dust loads containing PM_{10} and also ambient PM_{10} on the short term. Dry vacuum cleaning with very high vacuum has been shown to reduce the local contribution to PM_{10} by approximately 20%. In Finland a "street scrubber" that combines high pressure flushing of the pavement surface with immediate vacuuming of the washing liquids was shown to be effective in reducing PM_{10} suspension in conditions with high road surface dust loads. Tests in Norway show that high pressure water washing in combination with strong vacuum cleaning (both in separate and combined vehicles) is efficient to remove road dust load. The same tests showed that a lower cleaning speed enhanced the reduction in dust load.

Some modern sweeper techniques have been shown to reduce road dust loads containing PM_{10} and also ambient PM_{10} on the short term.

The efficiency of street cleaning depends on the road surface macro texture and maintenance state. A rough surface with ruts and damages is more difficult to get clean than a more even surface. Dry vacuum cleaning is most efficient when street surfaces are dry. As with dust binding, a pre-condition for the street cleaning to be effective in reducing ambient PM_{10} is that road dust actually is a major contributor to the current PM_{10} concentrations, which might not be the case in all street environments. Efficient continuous cleaning will not result in day-to-day PM_{10} reduction, but will mitigate the build-up of road dust load and its subsequent suspension.

Traction sanding and salting

Studies in a suburban street environment in Helsinki demonstrated that traction sand can contribute to average spring time PM_{10} suspension and concentrations by up to 25% (Kupiainen et al. 2016). Options to reduce road dust formation and impacts of traction sanding exist. An obvious solution is to use alternative less dust producing traction control methods like road salt. However, if alternatives cannot be used, for example due to weather conditions, only sieved material with the finest fractions removed, preferably by wet sieving, should be used and the material should have a high fragmentation resistance. Sand grains and dust migrate across and along the street surfaces due to traffic, precipitation and wind. Thus also traction sand applied to the cycle lanes and sidewalks can contribute to road dust suspension and PM_{10} concentrations.

Measurements of salt in ambient air at 10 kerbside sites in Norway, Finland, Denmark and Sweden were compared with NORTRIP model calculations (Denby et al. 2016). The average salt concentration in both measurements and modelling was found to be up to 10% of the PM_{10} concentration. Salt can be a significant part of the total PM_{10} levels and contribute to the number of exceedances of the EU air quality limit values.

Pavements

Pavement wear by studded tyres is an important source of PM_{10}, thus improving the wear resistance of pavements is a potential measure. Pan-Nordic pavement construction guidelines are relatively strict in this respect, and have already been in place for several decades. Therefore the Nordic pavements have in general relatively high wear resistance, especially on high trafficked roads. Research indicates that reduced total wear of asphalt pavements also results in lower PM_{10} emissions. Stone mastic asphalt pavements (SMA) with coarse and wear resistant rocks should be chosen to reduce pavement wear and PM_{10} emission (Gustafsson et al. 2009). Initially, a new pavement will result in lower PM_{10} concentrations as an effect of the bitumen cover, reducing the formation and emission of dust. Alternative materials for use in asphalts as well as alternative constructions to asphalt may reduce PM_{10} emission further.

Pan-Nordic pavement construction guidelines are relatively strict in this respect, and have already been in place for several decades.

Catalogue of measures to abate road dust emissions

Action	Process affected by the action	Methods of implementation and examples from Nordic countries	Evaluation* of efficiency/ comment
Studded tyre restrictions	Decreases PM_{10} from road wear	Fee or tax implemented in several cities in Norway (Oslo, Bergen, Trondheim).	+++ (Norman et al., 2016)
		Ban on single streets or in broader zones in some Swedish cities (Stockholm, Uppsala and Gothenburg).	+ to ++ (generally) +++ (on street with ban) (Norman et al., 2016)
		Seasonal restrictions in all of the Nordic countries.	+++ (using seasonal restrictions) + to ++ (for prolonging restriction period) (Johansson et al., 2011)
		Information campaigns implemented in Norway, Sweden and Finland.	+
Dust binding	Decreases suspension	Several Nordic cities use different dust binding solutions spread on the street surface. Commonly used are water solutions with Calcium Magnesium Acetate (CMA), Calcium Chloride ($CaCl_2$) and Magnesium Chloride ($MgCl_2$).	+++ Short term effect (hours) that depends on ambient relative humidity
Vehicle speed regulations	Decreases road wear and suspension	Lower signposted speed limits on major ring and arterial roads in Oslo and on highway and city streets in Stockholm.	++ Speed regulations may also affect amount of traffic. (Norman et al., 2016)

* Qualitative evaluation of the effectiveness of an action conducted by the authors. The scale is from + (less effective or effectiveness has not been confirmed by studies) to +++ (very efficient action, confirmed by studies)

Action	Process affected by the action	Methods of implementation and examples from Nordic countries	Evaluation* of efficiency/ comment
Street cleaning/ sweeping	Decreases suspension and wear of road and sand	Several different methods (dry vacuuming and wet sweeping) are used in Nordic countries. Dry vacuum sweeping implemented in Stockholm and Uppsala. Street scrubber implemented in Helsinki.	From - to ++ Depends on method used. Some sweeping methods can emit PM_{10} in the short term, whereas some are able to reduce suspendable PM_{10}
Decrease/ optimise sanding/ salting	Decreases wear and suspension	Restricted use of sand or replacement with salt in several cities in the Nordic countries. Use washed and sieved sand in several cities. Use of wear resistant rocks tested in Finland, but not extensively used so far.	+ to ++ Need for improvements in modelling and source apportionment capabilities to assess efficiency in different conditions
Optimized pavement properties	Construction, large stone size and durable rock aggregates increase wear resistance.	Pan-Nordic pavement standards exist that require the use of wear resistant rocks and coarse aggregates to give less wear and PM_{10}. In Norrköping, a wear resistant pavement was used to reduce PM_{10} emissions. In Copenhagen new pavements reduced PM_{10}	From + to +++ (depends on state of current pavement)
Different traffic measures	Reduced traffic decreases wear and suspension (if other factors are the same).	Several methods exist, e.g. congestion charging or other vehicle access regulations, restricted parking in the city centre, promoting public transport, park and ride Stockholm and Göteborg has a congestion charge/ tax. In Oslo and several other Norwegian cities there is a toll for entering the city.	From + to +++ (depends on traffic measure) (Norman et al., 2016)

* Qualitative evaluation of the effectiveness of an action conducted by the authors. The scale is from + (less effective or effectiveness has not been confirmed by studies) to +++ (very efficient action, confirmed by studies)

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Road dust and PM_{10} in the Nordic countries

Nordic countries suffer from periodic worsening of the air quality during spring with high peak PM_{10} concentrations (airborne particulate matter with diameter less than 10 µm or 0.01 mm). Characteristic for the high springtime PM_{10} concentrations are high shares of coarse particles (with diameters between 2.5 and 10µm), a signature of non-exhaust traffic dust formed via abrasion and wear of pavement, traction control materials, vehicle brakes and tyres. This Policy Brief summarizes the current understanding of the road dust system and presents the mitigation measures and policies currently in place in the Nordic countries. It has been compiled as part of the NORTRIP project funded by the Climate and air pollution working group of the Nordic Council of Ministers by researchers from 11 Nordic institutes studying different aspects of traffic non-exhaust emissions and road dust.

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