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Studies of some measures to reduce road dust emissions from paved roads in Scandinavia

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Abstract

In this paper we present quantitative assessments of different measures to reduce the PM10 levels along streets in Scandinavian cities based on tests in Stockholm. The effect of the use of studded tyres on concentrations in a street canyon has been quantitatively assessed using monitoring data. A 10% decrease in the fraction of studded tyres was estimated to reduce the weekly average street canyon PM10 levels (due to local road abrasion) by about 10 $\mu g\,m^{-3}$ if only daytime and dry street conditions were considered. These results are obtained by correlating the increase in PM10 levels during autumn with the increased use of studded tyres. Since the share of studded tyres is around 75% in Stockholm during wintertime, the peak springtime PM10 levels that occur during dry road conditions would be substantially lower if the use of studded tyres were regulated. Intense sweeping or washing of the pavements resulted in marginal reductions (<10%) and will have no important influence on the PM10 levels with the methodologies and working machineries tested here. Application of calcium magnesium acetate (CMA, Ice Away, as 25% water solution) on the road surface of a highway during dry conditions resulted in an average reduction of around 35% in the daily PM10 averages. The most efficient way to reduce PM10 levels in the long-term and for a large area is to reduce the use of studded tyres, while application of CMA may be efficient to reduce peak levels, which frequently occur during dry road conditions in spring.

Keywords: PM10; Studded tyres; Sweeping of roads; Dust binding; Road wear

1. Introduction

Long-term measurements have shown high levels of PM10 in Stockholm City and along busy roads and highways in Sweden during winter- and spring-time. The monthly averages in Stockholm has been observed to be above 80 $\mu g\,m^{-3}$ for March and April during 1999–2004 and daily averages extending above 200 $\mu g\,m^{-3}$ for several days during each year (Johansson et al., 2004). The annual averages have been between 30 and 50 $\mu g\,m^{-3}$ for three busy streets, shown in Table 1, which is close to the European Union (EU) environmental quality standards of 40 $\mu g\,m^{-3}$ for PM10. According to the EU directive (1999/30/EG) the daily averages of PM10 should not exceed 50 $\mu g\,m^{-3}$ for more than 35 days during each year. As shown in Table 1 this limit has been exceeded at all three streets during the years 1999–2004. The main reason for the exceeding values is the local road dust generation from the

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Table 1
Annual mean PM10 levels and number of days exceeding 50 $\mu g\,m^{-3}$ each year at three street canyon measuring sites in Stockholm

Year	Hornsgatan		Norrlandsgatan		Sveavägen	
	Annual average $\mu g\,m^{-3}$	Number of days $>50\,\mu g\,m^{-3}$	Annual average $\mu g\,m^{-3}$	Number of days $>50\,\mu g\,m^{-3}$	Annual average $\mu g\,m^{-3}$	Number of days $>50\,\mu g\,m^{-3}$
2000	46.2	103				
2001	47.1	84				
2002	47.5	101	36.8	66	41.3	74
2003	45.5	73	36.8	80	39.3	75
2004	41.4	80	33.1	63	33.0	59

Annual mean EU limit value is 40 $\mu g\,m^{-3}$ and the number of days allowed to exceed 50 $\mu g\,m^{-3}$ is 35.

roads (Omstedt et al., 2005). Long-range transport is of some importance for the annual mean levels but of marginal importance for the springtime levels. Likewise vehicle exhaust emissions have been found to contribute only marginally to the observed PM10 levels (Omstedt et al., 2005) in contrast to many European cities outside Scandinavia where it may account for 50% or more of the local PM10 levels (Querol et al., 2004). Other important factors are meteorological parameters such as dry road surface and wind speed but also traction sanding of the streets (Kupiainen et al., 2005). Similar problems with elevated PM10 levels as in Stockholm have been reported from several other Scandinavian cities like Helsinki (Pohjola et al., 2002; Laakso et al., 2003), Oslo (Lützenkirchen and Lutnaes, 2005), Trondheim and Bergen (Laupsa et al., 2005) as well as Gothenburg and Lycksele (Areskoug et al., 2004).

No significant decreasing trend has been observed in the PM10 levels during the last 5 years in Stockholm in contrast to several other European cities (Van Dingenen et al., 2004). A recent review on health effects of coarse particles offers evidence of significant impacts on human health and concludes that special consideration should be given to regulate coarse particles separately from fine particles (Brunekreef and Forsberg, 2005). In order to reduce the PM10 levels during winter- and springtime in the Stockholm City area (and other Scandinavian cities) it is necessary to quantitatively assess the importance of different measures. In this study we use measurement data to evaluate the importance for PM10 levels by reducing the use of studded tyres, increased street sweeping, increased street washing and the usage of calcium magnesium acetate as road dust binding material.

2. Methods and site description

The air quality in the Stockholm area is continuously monitored by the Stockholm Environment and Health Administration. The monitoring network includes air quality measurements at three busy streets in central Stockholm and one station at roof level within the city. For PM10, automatic instruments tapered element oscillating microbalance (TEOM), Rupprecht and Pataschnik) equipped with PM10- and PM2.5-inlets are used. Two electrical ball-valves are used to automatically switch between the two inlets. NO_x is monitored with Chemiluminescence analyzers (Thermo Electron). Number of vehicles of different types and their speed is measured continuously.

Hornsgatan is oriented from east to west and the traffic intensity is about 35,500 vehicles per day during weekdays. The measurements are performed on the northern side of the street. The measuring site at Hornsgatan is described in detail by Gidhagen et al. (2004a).

Norrlandsgatan is a 15 m wide two lane one-way street surrounded by 24 m high buildings on both sides. The street is directed from north to south and the traffic intensity is about 10,000 vehicles per day during weekdays. The measurements are performed on the western side of the street 2 m above street levels.

Sveavägen is a 33 m wide four lane street surrounded by 20 m high houses on both sides. The street is directed from north to south and the traffic intensity is about 30,000 vehicles day during weekdays. The measurements are performed on the western side of the street 2 m above street levels.

Identical instruments for NO_x and PM10/PM2.5 as for the street sites are located at the urban background station Rosenlundsgatan, about 600 m SE of Hornsgatan and at 30 m height. At this site traffic emissions on nearby streets have limited influence of the concentrations and it may therefore be regarded as representative for the urban background.

Meteorological parameters including wind speed, wind direction, temperature, temperature vertical profile and relative humidity are measured at roof level in central Stockholm. The wetness of the street surface was monitored at Norrlandsgatan using a simple electrical resistance wire during January 2003 until March 2004.

Additional measurements were performed along a four lane highly trafficked highway (around 60,000 vehicles per day) between Stockholm City and Arlanda airport at Vallstanäs north of Stockholm during Feb–May 2004. The highway is directed north to south, and surrounded with open fields. The same site was used in 2003 and is described in Gidhagen et al. (2004b). Three sites along the highway were established for automatic PM10 measurements. They were placed about 1 km apart and located 2 m from the road on the eastern side. Around each station was a 1 km stretch treated in different ways. One road stretch (S) was left untreated as control, on one stretch (E) the road surface was washed with high-pressure water systems and on the third road stretch (N) the road surface was treated with calcium magnesium acetate (CMA) to prevent suspension of road-dust. Meteorological parameters such as wind speed, wind direction and temperature were monitored right next to the highway. Before any treatment was made the differences in PM10 concentrations between the three stations were less than 5% of the daily averages if only westerly winds were considered (cf. Table 3).

3. Results

3.1. Influence of studded tyres

During each spring (February–April) a significant increase in the PM10 levels have been observed for three street stations in Stockholm, as presented in Fig. 1. There are no indications of elevated NO_x levels during winter and springtime (c.f. Fig. 1) showing that the elevated PM10 levels during the same period not is caused by variations in meteorological conditions like the frequency of stable conditions. During each fall there is also an increase in the fraction of studded tyres used, while the opposite situation occurs during springtime as shown in Fig. 1. Studies in laboratories using a road simulator by Gustafsson et al. (2005) have shown that the use of studded tyres increased the PM10 emission 40–50 times in comparison to winter tyres without spikes. Similar studies by Kupiainen et al. (2005) have also shown that particle emissions increases several times with the use of studded tyres but it also further increased if traction sand were applied to the pavement. Kupiainen et al. (2003) further reported that the average fraction of the particle emissions from asphalt was around 75% compared to 25% from the sand, which is similar to results obtained in real world urban studies in the city of Hanko in Finland (Kupiainen and Tervahattu, 2004). The observed time-lag between the increase in use of studded tyres and maximum PM10 levels in Fig. 1 is explained by the fact that the emission of road dust, independent of source, mainly takes place during periods with a dry road surface (Johansson et al., 2006), which is more common during springtime. This is clearly exemplified in Fig. 2 where elevated PM10 levels only occur when the street was dry. For the same time periods

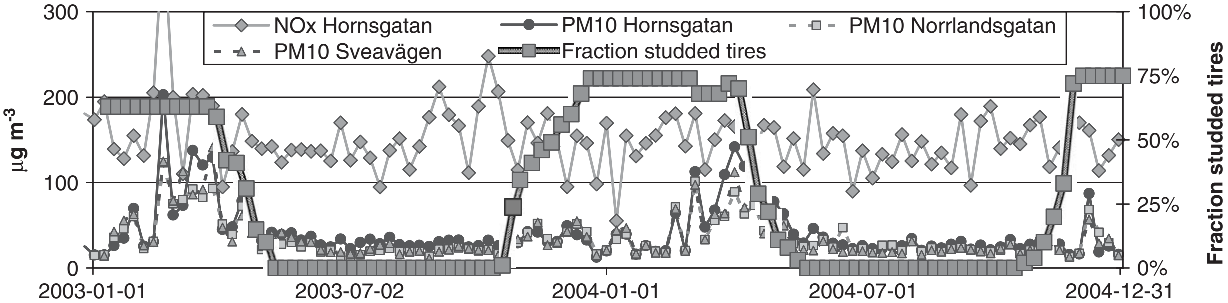

Fig. 1. Weekly average PM10 and NO_x levels together with the fraction of studded tyres on light duty vehicles in Stockholm City.

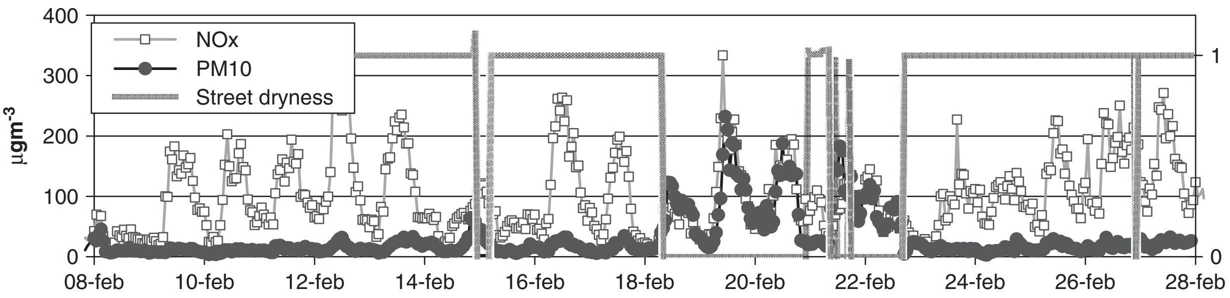

Fig. 2. Observed PM10, NO_x and street wetness at Norrlandsgatan during February 2004. The street sensor signal is one during wet street conditions and zero during dry conditions.

no difference between wet and dry conditions is observed in NO_x.

Our hypothesis is that local emissions of dust particles from the streets originate from:

(i) direct emissions during dry conditions due to abrasion of the road surface by studded tyres,
(ii) direct emissions during dry conditions due to wear (mainly by studded tyres) of traction sand or wear of accumulated dust (formed due to wear during wet periods),
(iii) vehicle induced suspension of accumulated dust or traction sand during dry conditions. Accumulation of dust on the roads occurs mainly during wet periods and can be due to (increased) wear due to studded tyres, but is also further increased if traction sand is added.

For measurements in street canyons it may be difficult to distinguish between the three different source mechanisms. In this study we have tried to minimize the influence from traction sanding and suspension, i.e. mechanism ii and iii, as well variation in the background levels in order to estimate the source strength for PM10 due to road wear from vehicles equipped with studded tyres, i.e. mechanism (i). The fraction of light duty vehicles using studded tyres is manually counted every week from October through May in central Stockholm with around 500 vehicles being counted each time. We assume the fraction to be constant during the weeks as well as homogeneously distributed within the Stockholm City area. The importance of the fraction of studded tyres on the PM10 levels was assessed by using the street station measurements. Local background levels (taken from measurements at roof level at Rosenlundsgatan) have been subtracted from all PM10 data in order to minimize the influence of other sources than the local traffic. Data during hours with wind directions (WD) that bring roof level air down to the stations have been excluded (southerly winds i.e. $135<WD<225$ for Hornsgatan and easterly winds i.e. $45<WD<135$ for Norrlandsgatan and Sveavägen) as described by Gidhagen et al. (2004a). Also only hours with dry street surface conditions during daytime (07:00–19:00) were included. Dry street surface conditions were estimated using the street surface wetness measurements at Norrlandsgatan, together with no precipitation for the three previous hours and a relative humidity $<90\%$. During October through early December 2003 the weather was unusually warm with the temperature rarely below zero (in total 5 days during October and November). Due to this no traction sand was applied on the streets until the beginning of December. In Fig. 3 we present the weekly average PM10 levels in Stockholm in relation to the fraction of studded tyres for the period without any traction sand on the streets. Note that the data in Fig. 1 correspond to all road conditions, whereas only daytime and dry condition is included in Fig. 3. The results from least squares linear regressions (shown in Fig. 3 and Table 2) shows that during autumn an increase in the fraction studded tyres with 10% causes an increase in the weekly PM10 levels of between 10 and 11 $\mu g\,m^{-3}$ during daytime with dry road conditions with $r^2 = 0.60$–0.64. Only small variation between the streets could be observed even though the amount of traffic on the streets differs. No correlation between fraction of studded tyres and NO_x levels is observed ($r^2 < 0.2$ for all streets, not shown), supporting the indication that the increase is not caused by the variation in meteorology.

The decrease in PM10 levels during the spring 2004 also showed a linear correlation with the use of

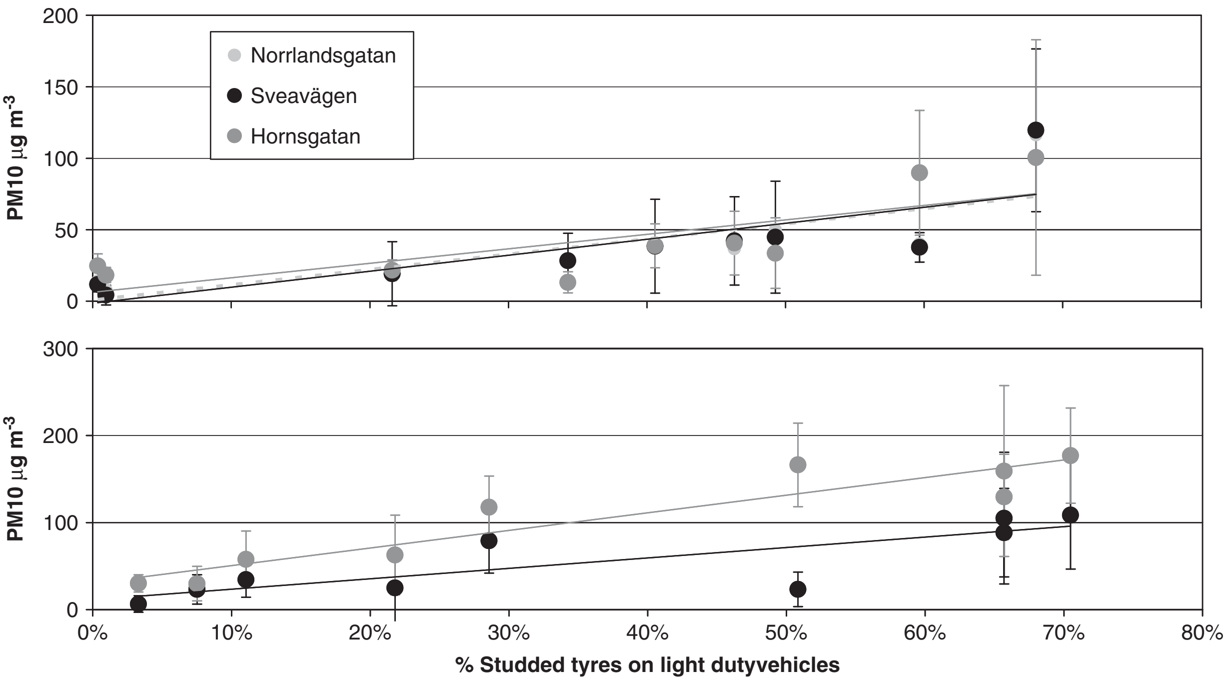

Fig. 3. Scatter plot of weekly average PM10 levels in Stockholm City against fraction of studded winter tyres on light duty vehicles. Upper panel: data from October–December 2003. Lower panel: data from February-May 2004. Only data during dry street conditions daytime has been included. The vertical bars denote the standard deviation.

Table 2
Observed relationships between weekly PM10 levels and fraction of studded tyres used shown in Fig. 3

	October–December 2003			March–May 2004		
	Relation	r^2	N	Relation	r^2	N
Hornsgatan	$PM10 = 101.3*a_{st} + 6.2$	0.60	207	$PM10 = 202.3*a_{st} + 30.3$	0.87	312
Sveavägen	$PM10 = 111.7*a_{st} - 1.5$	0.64	275	$PM10 = 119.8*a_{st} + 11.6$	0.67	216
Norrlandsgatan	$PM10 = 106.8*a_{st} + 0.8$	0.64	275			

a_{st} denotes the fraction of light duty vehicles using studded tyres. N is number of data points included.

studded tyres (Fig. 3 lower panel). During winter and spring traction sand was applied on the street pavement with in general the same frequency at all studied streets. Later in spring also cleaning of the streets took place but the decrease was observed well before the first cleaning (data points above 40% studded tyres were before any street cleaning). The PM10 levels at Sveavägen decreased with almost the same linear relationships during springtime as the increase in autumn. On Hornsgatan however, a 20 $\mu g\,m^{-3}$ decrease for a 10% decrease in the fraction of studded tyres was observed which was about double as during autumn. The result from this study clearly shows that there is a strong relationship between the use of studded tyres and the PM10 levels in Stockholm. The exact quantity of the relationship is difficult to estimate due to other influencing factors. For example although no traction sanding was applied for the autumn the particles emitted from the abrasion by the studded tyres might to some part accumulate on the streets and later cause increased emissions due to the so called sandpaper effect. Another important factor is the length and duration of the dry surface period used for the study. In the study by Omstedt et al. (2005) they found that the emission of particles increases if the wet period before the dry period was longer since the abrasion continuously occurs, but that the actual emission into the air only occurs when the surface later gets dry.

Studies in Oslo by Bartonova et al. (2002) also showed a linear relationship between the use of studded tyres and the observed PM10 concentrations. The average wintertime PM10 concentration decreased with 1 $\mu g\,m^{-3}$ for a decrease of 10% in the use of studded tyres and up to 2 $\mu g\,m^{-3}$ if only days with low wind speed and no precipitation was considered. Even though, the different way of analysing the data between this study and the one by Bartonova et al., is not directly comparable, the finding of a linear relationship between PM10 concentration and the use of studded tyres supports the findings in this study.

3.2. Intense sweeping of the streets

The use of street sweeping has been proposed to be a way to reduce the emission of particulate matter from pave roads (Chow et al., 1990). In Stockholm tests with intense sweeping of the road surface have been performed in order to evaluate the possible reduction of the PM10 levels. During 10–18 March and 10–22 April 2003, the street at Norrlandsgatan was cleaned every night by mechanical street sweepers (Scania, Broddway). The PM10 levels were compared with Sveavägen that has the same orientation and similar impact from meteorological factors, like wind direction, wind speed and road surface dryness. Fig. 4 shows the daily ratio of the PM10 levels at Norrlandsgatan and Sveavägen. The results show that no statistically significant reduction could be observed at Norrlandsgatan during the periods with intense sweeping. Instead in most cases the results shows an increase in the PM10 at Norrlandsgatan during days with sweeping. A comparison between the spring 2003 and 2002 shows that the average PM10 levels as well as the number of days with PM10 levels exceeding 50 $\mu g\,m^{-3}$ was even higher during the spring 2003 compared to 2002, when the street was swept at normal frequency (two times each spring). Our results are in agreement with several other studies. For example a recent study for winter condition in Nevada by Gertler et al. (2006) found a significant increase in the PM10 emissions after sweeping of the roads. Both Kuhns et al. (2003) and Etyemezian et al. (2003) compared the PM10 emissions from paved roads that had been swept or vacuum cleaned with roads with no treatment in Idaho, USA. Nor the sweeping or the vacuum cleaning had any significant effects of the emitted PM10 levels. Fitz (1998) also concluded that street sweeping had no significant effect on the PM10 levels in California. A study in Taiwan by Chang et al. (2005) showed that intense sweeping together with high pressure water washing caused no reduction in the PM10 levels. In the study by Kantamaneni et al. (1996) they only observed a significant decrease in PM10 emission by sweeping if the relative humidity was lower than 30%.

However, although the sweeping did not cause any significant decrease in the PM10 levels for the following days, it might still on the long term have an effect. The removal of large gravels might prevent some of the formation of smaller PM10 particles later due to a reduction of the sandpaper effect. There exist also several more efficient machines and techniques for street sweeping and further studies are needed to see how they might affect the PM10 levels under different conditions like in this study but according to our knowledge no study has shown a significant decrease in PM10 due to street sweeping.

3.3. Washing with high pressure water systems

Test of the effects from washing with high-pressure water system was performed on the highway at Vallstanäs during Feb 20th until May 10th

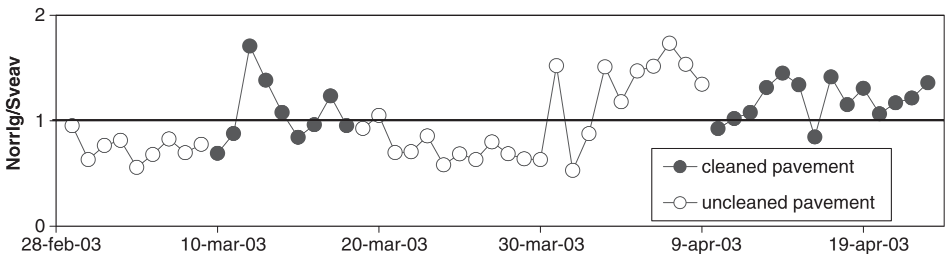

Fig. 4. Daily average PM10 ratios between Norrlandsgatan and Sveavägen during March and April 2003.

2004. The verge next to the carriageway was washed during night time when the weather forecast predicted westerly winds and dry road conditions for the forthcoming day. Both the northbound and southbound lanes were washed. Visual observations in the early morning clearly showed that the verge was wet and there was also a clear reduction in visible dust and debris. Only periods with westerly winds (190–350 WD) together with dry road conditions were included in the analysis of the effects on PM10. An additional criteria was that only days with more than 5 h of westerly winds have been used to calculate the daily averages. In total 21 days fulfilled these criteria. Fig. 5 shows the ratio between the daily averages PM10 levels of the washed stretch (E) compared to the untreated stretch (S). During a majority of the days slightly lower concentrations were observed due to the washing. The reduction was more than 10% during 8 days but there were also two days with more than 10% higher PM10 levels at the washed stretch. During most days the observed effect was larger during the morning compared to the afternoon (not shown). The average reduction for the 21 days was 6% (statistical significant at 95% confidence interval), as shown in Table 3. For 10 out of the 21 days exceeded the daily average PM10 levels 50 $\mu g\,m^{-3}$ compared with 12 days for the untreated stretch. The reduced PM10 levels on the washed stretch could however, have been due to wetting of the road surface, which reduce suspension of dust, rather than actually removing PM10 particles. This could also explain the larger reduction during the morning hours. It is unlikely that PM10 from the untreated stretch would affect the PM10 measurements along the treated stretch since periods with only westerly winds are studied. Studies next to a highway by Kalthoff et al. (2005) showed that the traffic induced turbulence causes a significant transport perpendicular of the road and not only parallel.

The study in Taiwan by Chang et al. (2005) observed up to 34% reduction of TSP-concentrations by using both street sweeping and high pressure washing, but no reduction in PM10 was observed. Studies in Paris reported by Bris et al. (1999) found that the water jet cleaning procedure removal efficiency was around 25% for the total street deposit. They further conclude that the removal and collection efficiency for particles smaller than 50 μm probably was small.

3.4. Use of CMA

CMA (CMA, ICEAWAY, CMA 25) has been used as anti-freezing agent on roads in for example USA and Denmark. In our study CMA was applied to the streets as liquid solution (40 $g\,m^{-2}$, 25% water solution) along a highway at Vallstanäs on

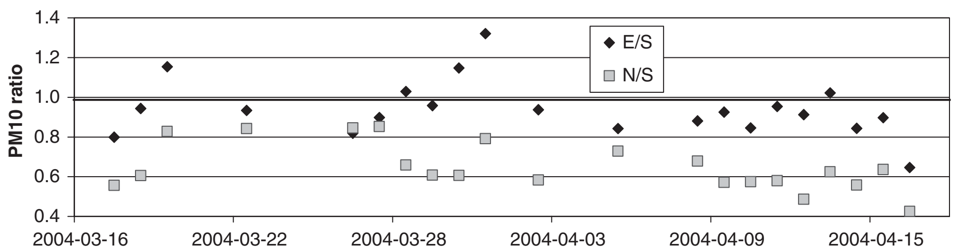

Fig. 5. Ratio of the daily average PM10 levels at the washed stretch (E) and the CMA treated stretch (N) compared to the untreated stretch (S) in spring 2004 at Vallstanäs.

Table 3
Average PM10 levels based on daily averages at Vallstanäs 2004

	No. days	Average daily averages			Average of daily ratios		Daily averages above 50 $\mu g\,m^{-3}$		
		S ($\mu g\,m^{-3}$)	*E* ($\mu g\,m^{-3}$)	*N* ($\mu g\,m^{-3}$)	*E*/*S*	*N*/*S*	*S*	*E*	*N*
Untreated period	26	42.0	43.4	42.6	1.05	1.03	7	7	7
Treated period	21	64.4	60.4	42.3	0.94	0.65	12	10	3

"*S*" is untreated, "*E*" washed and "*N*" CMA treated road stretch.

the northern road stretch (N) and on both the northbound and southbound lanes. Around 80% of the area of the carriageway was covered with CMA. The solution was applied during the same nights as the high pressure washing and the same criterion for selecting data was used as described above. The daily averages of the 21 days are compared with the untreated and the washed stretches in Fig. 5. The daily average PM10 concentration along the CMA treated stretch showed a reduction of between 15% and 60% compared to the untreated stretch. During the treated days the observed effect was lower in the afternoon, probably caused by removal of the CMA solution as it sticks to the tyres on passing vehicles and is being transported away from the studied stretch, but also due to evaporation. The average reduction in the daily average PM10 concentration was 35% (statistical significant at 95% confidence interval, Table 3). The reduction in the PM10 levels slightly increased if CMA was applied several days in a row. The daily average PM10 concentration exceeded 50 $\mu g\,m^{-3}$ during 3 of the 21 days for the CMA treated stretch compared to 12 days for the untreated stretch and 10 for the washed stretch, showing that CMA might be useful if the EU-limits are to be reached. The observed effect from the CMA application is also probably slightly underestimated compared to if the entire road would be treated, because of the removal on the tyres along the highway. The hygroscopic properties of the CMA solution might change with the relative humidity in the air, which in turn might influence the potential reduction in the PM10 levels. However, no consistent relation between the RH and the reduction in PM10 levels could be deduced from the observed data.

Only a few test of dust binding material on paved roads could be found in available literature. In Trondheim (Norway) Berthelsen (2003) report that by applying a 15% solution of $MgCl_2$ on a highway an average reduction in the PM10 levels of 17% was observed during dry days. The effect was increased if the application was repeated several days in a row.

3.5. Suspension of road dust due to vehicle induced turbulence

Visually the carriageway on the highway was clean, indicating that dust and debris is not accumulated on a dry carriageway due to the turbulence caused by the passing vehicles. Experiments by Nicholson et al. (1989) and Nicholson and Branson (1990) have shown that up to 40% of the particulate material on a paved road could be removed by a single vehicle passage, but also that the removal is increased with driving speed. However, a substantial amount of dust and debris is accumulated on the verge or beside the highway. During a major field campaign along a German highway Kalthoff et al. (2005) found that traffic induced turbulence extended as far at 50 m away from the highway which may cause a significant suspension of the deposited dust on the verge, which causes elevated particulate levels next to the road. So far no studies have been made in Scandinavia to determine the impact on the observed PM10 levels of continuous emission of particles from road wear due to the studded tyres or from suspension (either from wind or from traffic) of previously deposited road dust under real road conditions.

At Vallstanäs (explorative) measurements were undertaken to evaluate the effect of dust suspension using a DustTrak™ (TSI model 8250) with PM10 inlet. The experiment took place on the 29th of March 2003, which was a dry and sunny day during the period with high use of studded tyres (Fig. 1) and a significant dust layer was present on the verge, although no traction sanding takes place along the Swedish highways. The DustTrak was placed in a passenger car with the inlet tubing out of the window on the right hand side. A second car was driven about 20 m ahead of the measuring car and both were driving about two meters into the verge. Behind the first car a dust cloud was produced from suspension of the deposited dust in the verge and the measuring car was driving inside this dust cloud. All three measuring sites were passed northbound as well as southbound with the driving speed of 70 $km\,h^{-1}$ and repeated with 90 $km\,h^{-1}$. The PM10 concentration was monitored at 1 Hz. The average concentration from the DustTrak together with a comparison to the TEOM stations is shown in Fig. 6. An absolute comparison of the PM10 levels between the TEOM and the DustTrak is probably not that accurate due to the different measuring techniques (up to a factor of two difference with direct comparison), but a relative comparison between the three different stretches should reflect the impact on PM10 levels. In general the highest concentrations were recorded along the untreated stretch (S) and the lowest along the washed stretch (E) consistent with the visual observation of available dust on the verge. As also clearly seen in

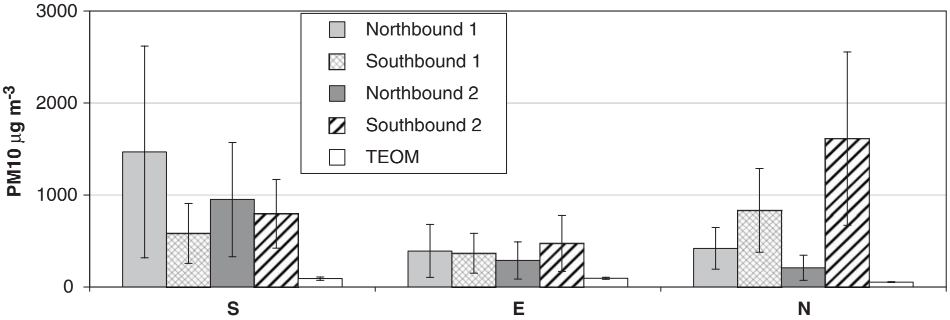

Fig. 6. The average PM10 concentrations along the highway 20 m behind a car that is driving in the verge of the highway. The driving speed for northbound 1 and 2 were 70 and 90 km h^{-1}, respectively, and the same for southbound 1 and 2. The vertical bars represent the standard deviation. "S" denotes the untreated stretch, "E" the washed stretch and "N" the CMA treated stretch.

Fig. 6 were the concentrations measured with the DustTrak much higher than the concentration at the fixed stations (using TEOM) at the same time. Thus, in contrast to what was observed based on the stationary PM10 measurements (small difference between the washed verge and the untreated verge, as shown above), the mobile data show significant difference between "potential" suspension of PM10 from the verge depending on the amount of dust present. Based on this comparison we conclude that suspension of accumulated road dust on the verge has only marginal influence on the PM10 levels observed next to the highway during normal driving conditions (not in the verge). This study was performed during a dry period with a substantial dust layers on the verge and we hence conclude that the PM10 levels next to the highway mostly are caused by continuous road wear in the carriageway from studded tyres and not due to susupension of road dust from the verge.

4. Conclusions

In this study we present results from assessments of different measures in the Stockholm region in order to reduce the PM10 levels that are due to emissions of road dust. The weekly average PM10 levels were highly correlated with the fraction of studded tyres on light duty vehicles. The exact quantitative effect of reducing the share of studded tyres in the traffic in Stockholm depends on the meteorological conditions such as frequency of wet and dry periods and wind speeds. An estimate based on our regression analysis considering only dry periods during day time indicated 10 $\mu g\, m^{-3}$ lower levels along the streets (street canyons) in Stockholm for each 10 percent reduction of studded tire use for weekly averages. A 50% reduction of the vehicles using studded tyres during winter would according to our measurement reduce the weekly daytime PM10 levels during dry conditions with around 30–40 $\mu g\, m^{-3}$ during period with highest fraction of studded tyres. Such reduction would be of large importance if the EU-limit value for PM10 shall be achieved within Stockholm.

Application of CMA-solution to minimize suspension of PM10 from the road surface of a highway reduced the daily PM10 levels with on average 35%. The use of CMA can therefore be an effective measure to reduce peaks of the PM10 levels during dry road conditions.

Intense washing of the verge of the highway with high-pressure water systems resulted only in a marginal reduction of the PM10 levels (~6%). Intense sweeping of roads in the city centre was also found to have none or marginal effect on the PM10 concentrations.

Along a highway the influence from suspension of deposited dust from the verge was found to be of marginal importance. Instead particles from road wear of the carriageway due to the use of studded tyres are concluded to be the most important mechanism for the high PM10 levels observed along the highway.

Acknowledgements

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