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# THE EFFICACY OF DUST SUPPRESSANTS TO CONTROL ROAD DUST RE-SUSPENSION IN NORTHERN AND CENTRAL EUROPE

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INDEX

# 1 INTRODUCTION

In Northern and Central Europe many cities have exceeded the EU daily limit value for $PM_{10.}$ In colder regions with significant snowfall, studded tyres are frequently used together with traction control and de-icing materials. Studded tyres have been shown to increase road wear (Amato et al., 2010). These sources all add to the road dust, which accumulates in the winter months when the road surface is generally wet. In the spring, as the road surface dries, the dust is released into the atmosphere, giving rise to significant increases in $PM_{10}$ concentrations (e.g. Kupiainen et al., 2010, Gustafsson et al., 2009).

Work undertaken in Sweden suggests that road abrasion due to the use of studded tyres is the most important source of the high $PM_{10}$ concentrations measured in spring. $PM_{10}$ emissions resulting from the use of studded tyres are an order of magnitude higher than from the use of non-studded winter tyres. In addition to higher rates of road wear, winter tyres also potentially generate greater re-suspension. The use of grit/sand to prevent road freezing is also likely to contribute to re-suspension of particulate matter (Gustafsson et al., 2009).

The contribution of non-exhaust emissions to ambient $PM_{10}$ concentrations varies significantly depending on a range of factors including the meteorological conditions and the amount of road dust accumulated. Vehicle exhaust emissions only marginally contribute to $PM_{10}$ concentrations in Stockholm (Omstedt et al., 2005); with non-exhaust emissions contributing up to 70% of kerbside annual mean $PM_{10}$ concentrations in Swedish cities. This can be compared to less than 50% in the UK and central European cities. In Spain the contribution from exhaust and non-exhaust sources appear to be similar (Querol et al., 2004). In southern European cities the resuspension of road dust is more important than in central Europe because of lower rainfall and higher temperatures which can quickly dry road surfaces.

The proportion of the $PM_{10}$ derived from road dust, and hence available for mitigation using dust suppressants varies between locations and countries. In colder climates the use of studded tyres results in a high surface dust loading due to the abrasion of road surfaces, whilst in warmer countries the low precipitation rates will also lead to high dust loading. In the UK dust loadings are likely to be lower than these in both colder and warmer climates as studded tyres are not used but there are high precipitation rates. Various estimates suggest that road dust can contribute a similar amount as direct exhaust emissions to traffic related emissions of particulate matter, but in some northern European countries where studded tyres are used it can be much higher (Thorpe and Harrison, 2007).

A range of studies have also identified paved road surfaces around industrial and construction sites as locations with higher than normal dust loadings. These routes have higher potential for $PM_{10}$ re-suspension and hence emissions from these roads may be effectively reduced by dust suppressant applications.

Amato et al. (2011) compared the strength of the road dust (less than 10 µm) loadings in Barcelona, Girona and Zürich. Loadings of road dust in Zürich ranged from 0.2 to 1.3; Girona 1.3 to 7.1; and Barcelona 3.7 to 23.1 mg $m^{-2}$ in the city centres. Four main sources were identified: mineral (road wear and urban dust generated mainly by construction activities), vehicle exhaust, brake wear, and tyre wear. Mineral is the dominate source in the Spanish cities (60 %), but represents only 30 % of road dust loadings in Zürich where contributions are more equally distributed among the four main sources.

Omstedt et al. (2005) have suggested that road surface moisture is one of the most important parameters that controls the re-suspension. They suggest that during wet conditions a road dust layer builds up. This dust is removed during dry road conditions and by wash-off due to precipitation. Amato et al. (2012) found that the loading of particles less than 10 µm are generally constant day-to-day, except during and in the hours after rain events when the mobility of particles drops dramatically to close to zero. After the rain event the mobile dust load increases exponentially to return to the maximum value. This is thought to be the result of the equilibrium between the build-up of dust, the moistening of the dust layer and resuspension processes. Following rainfall the mobilisation of particles smaller than 10 mm was found to be three times faster in Barcelona than in Utrecht due to the greater sunshine and independent of the amount of precipitation. The authors suggest that for reducing road dust emissions light but frequent moistening of roads might be more effective than intensive occasional cleanings (Amato et al. 2012).

Other factors though to affect the re-suspension of road dust include the intensity and speed of local traffic (Gehrig et al., 2010; Gustafsson et al., 2008; Amato et al., 2013), vehicle composition with heavy duty vehicles being responsible for much of the traffic induced turbulence (Boulter et al., 2006; Düring et al., 2002). Gehrig et al. (2010) report that particle emissions due to abrasion from pavements in good condition are low, but considerable abrasion emissions can occur from damaged pavements. Porous pavements seem to retain deposited dust better than dense pavements (e.g. asphalt concrete), thus leading to lower emissions due to resuspension. Amato et al. (2013) showed that there is a negative power relationship between the mean size of pavement aggregates and road dust loadings. This is thought to result from the higher wear rate of finer aggregates, probably due to the higher surface available for friction with tyres or to the softer minerals used.

Mediterranean countries are more often exposed to African dust events than central or northern Europe. Escudero et al. (2007), for example, showed that more than 70 % of the days when $PM_{10}$ concentrations were greater than 50 µg $m^{-3}$ at regional background sites in Spain were due to African dust. Rodriguez et al. (2001) identified up to 23 African dust events per year in rural southern Spain that resulted in the daily mean concentrations exceeding 50 µg $m^{-3}$, while Ryall et al. (2002) predicted the occurrence of just one or two episodes per year with $PM_{10}$ concentrations exceeding 50 µg $m^{-3}$ in the British Isles.

Chemical dust suppressants have been used on unpaved roads and in the minerals industry to suppress dust for a long time in some countries. Since the 1990s they have also been used on paved roads in Norway, both in tunnels and on open roads. It has only been more recently that their effectiveness at reducing road dust emissions has been more widely investigated in a number of European cities, generally as part of a package of measures to meet the European daily $PM_{10}$ limit value of 50 µg $m^{-3}$ not to be exceeded more than 35 times in a calendar year (Directive 2008/50/EC). There is very little published peer reviewed literature on the effect on $PM_{10}$ concentrations of applying dust suppressants to paved roads in urban environments, although a number of studies have been undertaken, particularly in Sweden, Finland, Italy, Austria and Spain.

The emission of road dust requires energy to overcome the gravitational and cohesive forces that bind dust particles to the surface. In general this comes from the wind or turbulence generated by moving vehicles. The factors that affect emissions include surface friction, gravity, and cohesion of particles into agglomerations of larger particles. Emissions can be reduced by increasing the strength of these parameters, for example by use of water, binding agents, or substances that maintain moisture content.

# 2 EFFECTS OF DUST SUPPRESSANTS

## 2.1 Introduction

Moisture causes dust particles to agglomerate into larger entities and to adhere to the surface. Dust can be suppressed using water but it lasts only until the water evaporates from the surface. Evaporation can be slowed down by adding dust suppressants to the water.

Many different types of dust suppressants have been tested around the world (e.g. Gillies et al., 1999), but in Europe the focus has been on two types to control $PM_{10}$ concentrations:

- Surfactants which reduce surface tension making the available moisture more effectively wet the particles and aggregates in the surface layer.
- Salts which absorb water when relative humidity exceeds 50 % (i.e. hydroscopic compounds).

The main dust suppressants that have been tested on paved roads in Europe to reduce $PM_{10}$ concentrations are:

- magnesium chloride ($MgCl_2$);
- calcium chloride ($CaCl_2$);
- calcium magnesium acetate (CMA); and
- potassium formate (referred to as KF in some publications).

Both CMA and potassium formate have been used for de-icing at airports because sodium chloride (NaCl) can corrode metal aircraft parts. Sugar has also been trialled as a dust suppressant in Scandinavia.

Consideration needs to be given to the potential environmental effects of the dust suppressants themselves as well as their benefits in reducing ambient $PM_{10}$ concentrations. These include damage to vegetation and human health, and contamination of soil and ground water. Other potential effects include reducing road friction and corrosion to highway infrastructure such as bridges and the road surface.

CMA is commercially available and is marketed under the name 'ICE & DUST AWAY'. It consists of a 25 % by weight aqueous solution of CMA. It contains no additives. A mixture of CMA and potassium formate is also commercially available as 'ICE & DUST AWAY PLUS 50'. This contains 50 % CMA and 50 % potassium formate, and has a lower freezing point than ICE & DUST AWAY. Potassium formate solution is available as KemDust.

Dust suppressants are sprayed onto the road surface, which binds the particles that come into contact with it and prevents them from becoming airborne when agitated by the wind, tyre action or vehicle turbulence. It has proved most effective when sprayed onto Nordic and Alpine unpaved roads where resuspension rates are relatively high.

Dust suppressants also lower the freezing point of precipitation. In studies performed in the Nordic countries, it has been noted that efficient dust suppression requires repeated application and treatment over large areas. In general, tests of their efficacy have been undertaken on relatively short stretches of road.

As the majority of resuspended particles are larger than 2.5 µm in diameter (Karanasiou et al., 2012) the application of CMA is not expected to have any significant impact on $PM_{2.5}$ concentrations.

Robustly quantifying the effectiveness of mitigation measures to reduce $PM_{10}$ derived from road dust is difficult as a range of factors influence the results including the meteorological conditions, the surface moisture content, the volume, speed and type of traffic using the road, the roughness and condition of the road surface and dust suppressant concentration, application rate and road coverage.

### 2.2 Amato et al. (2010) Review

Amato et al. (2010) reviewed seven published studies of the efficacy of dust suppressants to reduce $PM_{10}$ emissions from paved roads. Three of these were undertaken in tunnels, three at motorway locations and one in an urban environment. The tunnel measurements showed a reduction in $PM_{10}$ concentrations of approximately 50 %. For example, the impact on $PM_{10}$ concentrations of the application of $MgCl_2$ solution, using a dosage between 20 and 40 g $m^{-2}$ on a road in a Norwegian tunnel resulted in a 56 % reduction in $PM_{10}$ concentrations and 70 % in $PM_{2.5–10}$ concentrations up to 10 days after the application, but with a large uncertainty (Aldrin et al., 2008). The results of tunnel experiments are unlikely to be directly relevant to the reduction of ambient $PM_{10}$ concentrations in urban environments because of the greater potential to accumulate road dust in tunnels due to the lack of wind and precipitation.

Measurements taken close to streets generally show a smaller benefit of the application of dust suppressants on ambient $PM_{10}$ concentrations. Approximately 25 % reduction in $PM_{10}$ concentration was measured in Trondheim (Berthelsen, 2003). However Aldrin and Steinbakk (2003) did not find any significant effect close to motorways in Oslo with a speed limit of 80 km $h^{-1}$. Norman and Johansson (2006) tested a 25 % CMA aqueous solution, applied at a rate of 40 g $m^{-2}$, on a motorway with a daily vehicle flow of approximately 60,000 and a speed limit of 90 km $h^{-1}$ in Stockholm. Approximately 80 % of the surface area was covered. The daily average $PM_{10}$ concentration along the CMA treated stretch showed a reduction of between 15 % and 60 % compared to the untreated stretch. The average reduction in the daily average $PM_{10}$ concentration was 35 % (statistically significant at the 95 % confidence interval). The authors concluded that the use of CMA can therefore be an effective measure to reduce $PM_{10}$ levels during dry road conditions.

Hafner, 2007 showed that the application of CMA solution in an urban environment resulted in a 29 to 43 % reduction in $PM_{10}$ concentrations in Klagenfurt, Austria.

The above studies were undertaken using different suppressants, rates of application and/or application methods etc. and therefore direct comparisons are difficult. For example, some studies recorded sweeping and/or jet washing as well as the application of dust suppressants, while others did not mention whether the test streets where cleaned before or during the period of suppressant application.

The majority of these studies have shown that the application of suppressants can reduce daily $PM_{10}$ concentrations, with the greatest improvements shown in the tunnel studies (approximately 50 % reductions), followed by the urban study (approximately 29 to 43 % reductions) and the motorway studies (approximately 20 %, although one of the motorway studies provided similar results to the urban study). The one study which did not identify significant effects was also a motorway study. All the studies were undertaken in locations where studded tyres are used in winter and as such the high percentage of reductions in $PM_{10}$ concentrations are unlikely to be observed where the road dust loading is much lower.

Three of the studies included information concerning the longevity of dust suppressant effects. Norman & Johansson (2006) noted that on the treated days the observed effect was lower in the afternoon, probably caused by the removal of the CMA solution as it sticks to the tyres on passing vehicles and is transported away from the treated stretch, and also due to evaporation.

Aldrin et al. (2008) noted that dust suppressant effects are most pronounced immediately after application, with effects steadily diminishing with time, but estimated the duration of the effect to be 10 days, but with a large uncertainty. Two studies suggest that treating on consecutive days result in increased effects. Berthelsen (2003) noted that effects are increased if treatment occurs over consecutive days and Norman and Johansson (2006) suggest that the reduction in the $PM_{10}$ levels slightly increases when CMA was applied several days in a row. Norman and Johansson (2006) also suggested that the hygroscopic properties of CMA solutions, and hence the effectiveness of the solution to reduce $PM_{10}$ concentrations, may change with relative humidity. However, the authors found no consistent relationship between the relative humidity and the reduction in $PM_{10}$ levels. Another suggestion by Aldrin et al. (2008) is that magnesium chloride may be a dust source in itself when used at a high concentration.

## 2.3 Finland - KAPU and REDUST projects

Two major studies of the efficacy of street sweeping, cleaning and the application of dust suppressants have been undertaken in Finland. The KAPU project (Kupiainen et al., 2011) took place over the period 2006 to 2010 to study the impacts of winter maintenance and springtime street cleaning on the amount and composition of road dust in Finnish cities. The aim was to identify measures including the use of dust suppressants to reduce the high springtime $PM_{10}$ concentrations in the ambient air of Finnish cities.

The current project is the LIFE+ funded REDUST project which will be undertaken from 2010 to 2014 (REDUST, 2013).

KAPU

In the KAPU project (Kupiainen et al., 2011) the efficacy of a $CaCl_2$ solution as a dust suppressant was studied. This suppressant is routinely used as a part of the winter maintenance practices in some Finnish cities.

The study used a vehicle based monitoring system known as SNIFFER (Pirjola et al., 2009). The SNIFFER vehicle (VW LT 35) collects dust samples behind the left rear tyre, approximately 5 cm from the tyre. The lower edge of the inlet is 7 cm above the street surface, and the upper edge is as high as the geometry of the wheel arch allows. The width of the inlet is approximately 2 cm less than the tyre. Particle mass was measured using a TEOM (Tapered Element Oscillating Microbalance; series 1400A, Rupprecht & Patashnick) and ELPI (Electrical Low-pressure Impactor; Dekati Ltd.). At the front of the van another ELPI measured the background concentrations.

Since measurements are taken very close to the source, the sample has no time to dilute, and therefore, the authors refer to the measured $PM_{10}$ mass concentration as the 'emission' or 'SNIFFER emission'. The concentrations reported are one or two orders of magnitude higher than the ambient concentrations measured at roadside monitoring stations.

The efficacy of $CaCl_2$ as a dust suppressant was studied in Helsinki in March 2006. A 69 % reduction in average emissions was detected immediately after the application of the dust suppressant, whereas emissions in the streets with no treatment showed no systematic decrease. In Espoo in early April 2009 emissions decreased on average by 35 % on the treated streets, whereas no clear trend was detected on the untreated streets. A second measurement was taken 5 to 8 days after the $CaCl_2$ treatment. It was concluded that after 5 days the dust suppression efficacy had decreased and the treatments should be repeated to guarantee sufficient emission reduction (Kupiainen et al., 2011).

In another test in the centre of Helsinki in April 2010 the $PM_{10}$ emissions were reduced by 23 to 45 % with an average reduction of 35 % (Kupiainen et al., 2011).

During the final phase of the KAPU project an index was developed to provide guidance on when action is needed to reduce $PM_{10}$ concentrations. A SNIFFER emission of 1,500–2,000 $\mu g\ m^{-3}$ (measured with a friction tyre, dry street surface conditions) was identified as a threshold below which adverse air quality would not occur in normal weather conditions.

REDUST

The aim of the REDUST project (REDUST 2014) is to demonstrate the $PM_{10}$ reduction potential of dust suppressants. Finnish cities generally use calcium chloride ($CaCl_2$) applied as a 10 % (by mass) solution.

In 2012 two different concentrations of CaCl2 solution were tested (17%- and 8.5%- mass concentration). Both solutions were spread only to the kerbs. • In 2014 dust binding was performed side by side (on adjacent sections) with street cleaning in order to compare the reduction potential of these two methods with similar initial street dust levels. The tests were carried out twice, on two different street dust levels. The application method in the first test was targeted to the kerbs, and in the second test the dust binding solution was spread to the whole lane.

In 2011 the project demonstrated the effect of applying it to the whole street surface and just to the kerbside and between the lanes, which are expected to be the areas of highest dust load and potentially highest source of $PM_{10}$. In 2012 the efficacy of two different concentrations (17 % and 85 %) of $CaCl_2$ solution applied at 28 g $m^{-2}$ was tested. In 2013 trails were also undertaken using a potassium formate solution. The use of the latter is considered preferable in areas where ground water is a source of drinking water. In 2014 the efficiency of dust binding and street cleaning were compared. The tests were carried out twice, on two different street dust levels. The application method in the first test was targeted to the kerbs, and in the second test the dust binding solution was spread to the whole lane.

The measurement campaigns used both the SNIFFER vehicle (as in the KAPU project) and an Opel Vector gasoline car fitted with TRAKER (Testing Re-entrained Aerosol Kinetic Emissions from Streets), developed in the USA (Etyemetzian et al., 2003). In TRAKER the dust is sampled isokinetically through a nozzle into a horizontal pipe which runs below the body of the car. The nozzle is 5 cm from the tyre and 21 cm from the road surface. The Vectra was equipped with two $PM_{10}$ DustTrak (TSI, model 8530) monitors. In addition ambient $PM_{10}$ and $PM_{2.5}$ concentrations were measured at Suurmetsäntie in Helsinki using Osiris monitors at 6 sites (in pairs on the opposite sides of the three test road sections). The instruments were 3 m from the kerb and the air was sampled at a height of 4 m. The SNIFFER van was equipped with instruments to measure concentrations of CO, $NO_x$ and $CO_2$ above the windshield or the front bumper. Number concentration and size distribution of particles in the size range of 7 nm to 10 µm were measured by two ELPIs with 1 s time resolution. One ELPI measured street dust particles behind the left rear tyre, and the other the background particles in front of the van. $PM_{2.5}$ mass concentration was calculated from the ELPI measurements. $PM_{10}$ was monitored behind the tyre by TEOM. $PM_{10}$ was also monitored by two DustTrak instruments.

The spreading system used in Helsinki was attached to the front of the truck (the tank for the suppressant solution is in the back) and has two high pressure nozzles that can be adjusted to spread the $CaCl_2$ either to the sides of the vehicle or to the whole road. The cities of Espoo and Vantaa use a different system with the spreading system at the back of the vehicle but using the same method.

Approximately 10 % $CaCl_2$ solution was used with typically 8 $m^3$ stored on the truck. The driver can adjust both the flow rate and pressure, depending on how dusty the road is. Approximately 20-30 g $m^{-2}$ was applied where there is no visible dust layer but up to 100 g $m^{-2}$ where there was a clearly visible dust layer.

The study found that dispersing the dust suppressant across the whole of the road surface was more effective at reducing $PM_{10}$ emissions than dispersing it only near the kerbside and between the lanes. The effect also lasted longer, however, the suppressant reduced the road surface friction, increasing the risk of accidents. In these tests both systems used a solution with the same $CaCl_2$ concentration, whereas the system that disperses the suppressant to the kerbside and between the lanes could, in theory, use a more concentrated solution.

The system that dispersed the dust suppressant to the whole of the street surface showed the following $PM_{10}$ emission reduction potential:

- On the day of treatment: 90 % or more reduction
- 1 day after the treatment: 60 % reduction
- 2 days after the treatment: 30 % reduction
- 3 days after the treatment: no effect

The system that dispersed the suppressant to the kerbside and between the lanes showed following reduction potential:

- On the day of treatment: 40 %
- 1 day after the treatment: 20 %
- 2 days after the treatment: no effect

The 2012 tests were started after a dry day when there was a forecast of dry weather. The spring 2012 was generally rainy which resulted in the tests being undertaken later than in 2011, from 8 to 10 May 2012, 5 to 6 days after the cleaning test. However, during May agricultural activities adjacent to the test street might have interfered with the measurements.

Two different concentrations of $CaCl_2$ solution were tested (17 % and 8.5 % by mass). Both solutions were spread only near the kerbsides at a rate of 28 g $m^{-2}$ as the street surface looked relatively clean. The tests demonstrated that both solutions can potentially reduce street $PM_{10}$ emissions. However, the results indicate that application of dust suppressants does not result in significant reductions in emissions where there are low dust levels.

In 2013 $CaCl_2$ and potassium formate (manufactured by Kemira under the trade name KemDust) were tested on both Suurmetsäntie (Helsinki) and Vanha Porvoontie (Vantaa). Potassium formate is more expensive than $CaCl_2$, which is one of the reasons why it is not more commonly used on roads. However, it is not harmful for vegetation and can potentially be used in sensitive areas, such as where ground water supplies drinking water. It is fully biodegradable and very hygroscopic. Both dust suppressants were applied as 10 % (by mass) solutions, and spread to the kerbsides and in between the lanes.

In both locations melting waters interfered with the measurements, particularly at Vanha Porvoontie. Therefore the results from this location were discounted. Also, although the amount of solution applied was supposed to the same, the spray ended up being considerably wider for $CaCl_2$. Therefore the effectiveness of the two dust suppressants cannot be fully compared. These problems illustrate the difficulties of assessing the real-world effectiveness of applying dust suppressants. However, it was concluded that the reduction potential of potassium formate was similar to $CaCl_2$. The reductions measured at 2pm on the day of treatment were:

- $CaCl_2$ (whole road) – 90 % reduction
- Potassium formate (kerbside only) – 40 % reduction

It was found that weather conditions affected the emission reductions and duration of the effect. The dust binding effect diminished after 2–3 days when there was no reapplication. $CaCl_2$ may remain active for longer periods, when conditions such as air humidity and temperature are favorable. Because humidy fluctuates during the day, the timing of the pplicaiton of the suppressant affects its efficiency. Applicaition during the night or very early in the morning is msot effective.

### 2.4 Sweden

Several Swedish cities have problems with complying with the EU daily $PM_{10}$ limit value. In Stockholm it is exceeded practically every year. A range of measures have been tested, including the application of dust suppressants, but no single measure appears to be sufficient on its own.

Gustafsson et al. (2010) compared the efficacy of using CMA (25 % solution), $CaCl_2$ (10 % solution), $MgCl_2$ (25 % solution) and sugar (25 % solution) as dust suppressants. Ambient measurements by the road all showed 30 to 40 % reductions in $PM_{10}$ concentrations immediately after spreading. After that concentrations started rising slowly and were back to the level before the treatment in 4 or 5 days. There were no differences between the efficacies or duration of different solutions. They concluded that the dust binding ability of a solution depends on its concentration: stronger solutions have a longer duration, but is more expensive and might increase the slipperiness of the surface. Also that dust suppressants cannot solve the street dust problem as it does not remove the dust from the street, and there is a risk that the dust will be resuspended back into the ambient air.

During the winter 2011–2012, the city of Stockholm tested a combination of measures, including using CMA as a dust suppressant, powerful street sweeping and street flushing with water. During the season, 31 applications of CMA, 25 road sweepings and 42 road flushes, were conducted. The CMA was applied as a 25 % (by mass) solution at a rate of 10 g $m^{-2}$. The results showed that the number of days $PM_{10}$ concentrations exceeded 50 µg $m^{-3}$ on the two test streets was considerably fewer than on the reference streets. The only measure having a significant effect was the use of CMA. Sweeping and flushing did not reduce $PM_{10}$ concentrations. An obvious relationship between road surface texture and road dust deposit could be identified (Gustafsson et al., 2013).

It was estimated that the two streets tested with CMA, Sveavägen and Hornsgatan, had 6 days less with $PM_{10}$ concentrations over 50 µg $m^{-3}$ compared to when CMA is not used. This calculation did not take into account that CMA also has an effect on the days after application, and there may be a cumulative effect over several days. The reduction of the number of days with the daily average concentration above 50 µg $m^{-3}$ is thus likely to be larger than the 6 days calculated (Gustafsson et al., 2013).

### 2.5 Norway

In Norway the effect of $MgCl_2$ on $PM_{10}$ concentrations in a road tunnel has been studied (Aldrin et al., 2008). During the winter 2004/2005, the road inside the tunnel of Strømsås was salted 43 times with a 20 % (by mass) $MgCl_2$ solution, 27 times at a rate of 20 g $m^{-2}$ and 16 at 40 g $m^{-2}$. In addition, the road was swept 11 times and washed twice. Simultaneously, the hourly concentrations of $PM_{10}$ and $PM_{2.5}$ were measured. The study revealed no clear effect from sweeping and washing, however, the impact of the dust suppressants was significant. The largest effect occurred immediately after applying the dust suppressant, and diminished steadily afterwards. The duration of the effect was estimated to be 10 days, but with a rather large uncertainty (95 % confidence intervals between 3 and 16 days). A 70 % reduction in the concentration of coarse particles $PM_{10-2.5}$ and 56 % in the concentration of $PM_{10}$ were estimated. The estimated effect on $PM_{2.5}$ was 17 % but barely significant.

In Oslo to reduce ambient $PM_{10}$ concentrations sweeping is undertaken when possible, and dust suppressants are used when necessary. $MgCl_2$ as a 15 % (by mass) solution is applied before the morning rush hour at a rate of 10 to15 g $m^{-2}$ using traditional salting equipment. The air quality forecast is used to determine when dust suppressants are required, and it is typically applied every second day. There have been no exceedences of the daily $PM_{10}$ limit value since 2007 when the application of $MgCl_2$ started (Kristoffersen, 2012).

### 2.6 Austria / Italy – KAPA and CMA+

Three EU co-financed projects have been undertaken in Klagenfurt to reduce $PM_{10}$ concentrations: KAPA GS (2004-7), SPA (2006-9), and CMA+ (2009-2012) (Hafner, 2013). The first and third projects included trials of dust suppressants.

The KAPA GS project studied measures to reduce $PM_{10}$ concentrations in Austria and South Tyrol (Klagenfurt, Graz and Bolzano), which included testing the effectiveness of using CMA as a dust suppressant as part of the winter maintenance of roads. In Klagenfurt CMA was applied during the winter months of 2005 to 2007, initially on a major road (Aufwirbelungsanteil) and later in the centre of the city. It was found that kerbside $PM_{10}$ concentrations could be reduced by (Hafner, 2012):

- 30 % daily mean
- 20 % monthly mean
- 10 % annual mean

The regular use of CMA in the year 2006/2007 was estimated to reduce the annual mean concentration by between 0.5 and 1 µg $m^{-3}$ (winter months: 1 to 2 µg $m^{-3}$) near major roads and by ca. 3 µg $m^{-3}$ near major road junctions. It was also estimated that using CMA could reduce the number of days when the $PM_{10}$ concentration exceeds 50 µg $m^{-3}$ by 14 days from 80 days per year.

The EU LIFE+ project CMA+ tested the efficacy of the application of CMA in two Austrian cities, Klagenfurt and Lienz, and the Italian city of Bruneck (Bachler and Sturm, 2012). CMA was applied to:

- paved roads during the winter period;
- paved streets, squares and pedestrian zones as a de-icing agent; and
- unpaved roads and construction sites for dust control

In the winter 2011-12 CMA was applied to 164 km in Klagenfurt and Lienz, and 12 km in Bruneck. Table 1 shows the emission reductions measured.

**Table 1**: Emission Reductions measured in CMA+ Project (Bachler and Sturm, 2012)

| City | Street | Traffic $PM_{10}$ emission reduction (%) | Non-exhaust emission reduction (%) | $PM_{10}$ reduction potential on days of CMA application (µg $m^{-3}$) |
|---|---|---|---|---|
| Klagenfurt | Völkermarkter Straße | 8 | 12 | 3 |
| | Rudolfsbahngürtel | 11 | 11 | 3 |
| Lienz | Amlacherkreuzung | 11 | 19 | 4 |
| Bruneck | Dante Straße | 8 | 15 | 1 |

In 2012 the number of days when the $PM_{10}$ concentration exceeded 50 µg $m^{-3}$ fell below 35 days in Klagenfurt for the first time, while in Lienz it fell from 63 days in 2006 to 10 days in 2011. In Bruneck the $PM_{10}$ concentrations never exceeded the limit of 35 days greater than 50 µg $m^{-3}$.

The study concluded that CMA can reduce $PM_{10}$ emissions from paved streets by 10 to 20 % (of the non-exhaust share of PM). This translates to a 1 to 4 µg $m^{-3}$ reduction in daily $PM_{10}$ concentrations on the day of CMA application.

A cost-benefit analysis was undertaken that shows that applying CMA on the main roads in Klagenfurt would lead to savings in the health sector greater than the cost of CMA application.

## 2.7 Germany

A trial of the use of CMA in Halle, Germany (State Agency for Environmental Protection of Saxony-Anhalt, 2009) found that its use on Merseburger Straße, a road where the $PM_{10}$ limit was being exceeded, could reduce the daily $PM_{10}$ concentrations.

Measurements were taken at a fixed monitoring station adjacent to where the CMA was applied, and a mobile monitoring station on the same road with similar traffic flow at approximately 1.1 km distance. One of the difficulties of the study was that the mobile monitoring station generally measured higher $PM_{10}$ concentrations than the fixed one. Also during most of the trial period $PM_{10}$ concentrations were low. The study concluded that the use of CMA resulted in an average reduction in daily concentrations of 0.7 µg $m^{-3}$.

Tests were also undertaken on the effect of applying CMA to the city's tram tracks on the tram stopping distance. It was found that at both 30 km $h^{-1}$ and 50 km $h^{-1}$ braking distances increased.

### 2.8 The Netherlands

Wet or dry cleaning of the surface of high speed roads is a greater practical challenge than its application on local roads. In the Netherlands a competition was organised in which companies were invited to develop innovative methods of cleaning motorway surfaces. Various ideas were submitted. Field trials were undertaken of the application of $CaCl_2$ as a dust suppressant, as well as two dry vacuum methods (Hooghwerff and van Beers, 2006). A new on-road measurement method was also developed in collaboration with Delft Technological University. This method made it possible to measure the resuspended particulate matter after the passage of each individual vehicle.

The effects of the application $CaCl_2$ on $PM_{10}$ concentrations were investigated on the A73 motorway near Maastricht between December 2008 and March 2009, and in Rotterdam in the autumn of 2009. The preliminary conclusion from the experiments on the A73 was that the application of $CaCl_2$ led to a reduction in $PM_{10}$ concentration of around 12 % (McCrae, 2009).

### 2.9 UK Studies

Transport for London has trialled the application of CMA in nine locations. Phase 1 was undertaken between 9th December 2010 and 27th May 2011, and encompassed two road corridors in $PM_{10}$ priority hotspots (URS, 2011). Phase 2 included a larger number of road corridors where there was evidence of high $PM_{10}$ concentrations and public exposure, and four industrial sites, as well as a more robust analysis of the data. It was undertaken between September 2011 and April 2012, although some limited application was continuing at the time of the data analysis. In both phases a 25 % solution (by mass) of CMA was used, typically applied at a rate of 10 g $m^{-2}$ (Barrett et al., 2012).

The findings suggest that dust suppressants can reduce local $PM_{10}$ concentrations in specific locations where there is a high proportion of local resuspended $PM_{10}$. In these locations application is likely to have a significant impact on local $PM_{10}$ concentrations. Examples include roads around waste transfer sites, construction and demolition sites; and major road works were there is significant dust generating activity.

CMA was sprayed onto the roads surrounding the industrial sites, using the same vehicles as along the road corridors, and manually from backpack sprayers within the yard by the site operators. Some of the highest $PM_{10}$ concentrations in London have been measured adjacent to these industrial sites.

The 'local PM component' was calculated to remove the influence of regional and transboundary pollution sources. Four techniques were used – NOx tracer analysis, meteorological normalisation, diurnal characterisation and chemical mass closure. Several independent methods were used to provide more robust conclusions.

A summary of the results on $PM_{10}$ concentrations of Phase 2 is shown in Table 2. $PM_{2.5}$ measurements were also evaluated, but no CMA effect was identified.

Of the road corridor sites where CMA application was trialled the strongest evidence of a positive effect was found at the A3211 Upper Thames Street site which is located under a bridge. This effect was only seen at application rates greater than 10 g $m^{-2}$, i.e. when there were two or three applications per day. It was estimated that had CMA been applied along Upper Thames Street at high intensity every day during 2011, the number of exceedences recorded may have decreased from 53 to 30 days. It should be stressed that this potential change is only applicable to the unusual location of the site. The result is not applicable to the whole of the A3211

The monitoring was not optimal for assessing the impact of CMA at Victoria Embankment, Tower Hill in Phase 1, and at Upper Thames Street in Phase 2. At the A2 Blackheath site there was evidence that the results were influenced by a local construction site. Also only one lane was treated.

The authors considered it unlikely that CMA application prevented any exceedences of the daily EU limit value for $PM_{10}$ at A501 Marylebone Road, A2 New Cross and A12 Blackwall. It was also considered unlikely that continued application of CMA along these corridors would result in the prevention any future exceedences. At New Cross a lack of clear effect reflects the small proportion of $PM_{10}$ recorded at the site that is likely to be related to resuspension and therefore available to be removed by CMA.

Close to three of the four industrial sites there were beneficial impacts of CMA application on the adjacent roads and/or on the process yard. At the fourth, Mercury Way, no robust analysis was possible due to limited measurements and CMA applications.

The most robust findings were at Horn Lane. A clear drop in local $PM_{10}$ concentrations occurred in the hour following on-site CMA application of between 31 % and 59 % relative to the control. A smaller decrease was associated with the on-road applications. Analysis at Manor Road was restricted due to a lack of pre-trial period, but a similar decrease in local $PM_{10}$ (41 %) was associated with on-site CMA application. The complexity the industrial area surrounding the Neasden Lane study site made robust analysis difficult, but some limited benefit of CMA application was identified.

**Table 2**: Summary of Results from Phase 2 of the London CMA Trials (Barrett et al., 2012)

| Site name | Site description | Results | $PM_{10}$ 'residual' * |
|---|---|---|---|
| Neasden Lane, Brent | Large mixed industrial site | Limited analysis possible due to small number of application days and mixed on-site applications. Tentative 22 % reduction in local $PM_{10}$ compared to non CMA days following on-site application. | 13 µg $m^{-3}$ |
| Horn Lane, Acton | Medium industrial site | On-road application: 18 % reduction in local $PM_{10}$ compared to non CMA days. On-site application: 36 % reduction in local $PM_{10}$ compared to non CMA days. | 8 µg $m^{-3}$ |

| Site name | Site description | Results | $PM_{10}$ 'residual' * |
|---|---|---|---|
| Manor Road, Erith | Medium industrial site | On-site application: mean 41 % reduction in local $PM_{10}$ compared to non CMA days. On-road application: analysis not possible. | 8 µg $m^{-3}$ |
| A2 Blackheath | Road corridor impacted by emissions from construction site opposite. | 44 % reduction in local $PM_{10}$ compared to pre-trial period, equating to a decrease in annual mean of c. 12 %. No effect compared to non CMA days. | 6 µg $m^{-3}$ |
| A3211 Upper Thames Street | Congested road corridor beneath a wide bridge. | Daily CMA application >10 g $m^{-2}$ only: 38 % reduction in local $PM_{10}$ compared to non CMA days, equating to a decrease in annual mean of c. 16 %. No effect at 10 g $m^2$ application rate. | n.a.** |
| Mercury Way, Lewisham | Small industrial site. | No robust results due to limited monitoring and few on-site application days. | n.a.** |
| A501 Marylebone Road | Heavily trafficked road corridor in a street canyon. | The analyses could not identify any significant effect. | 1 µg $m^{-3}$ |
| A2 New Cross | Single lane road corridor. | The analyses could not identify any significant effect. | -1 µg $m^{-3}$ |
| A12 Blackwall | Heavily trafficked road corridor in an open location, partial application. | The analyses could not identify any significant effect. | -1 µg $m^{-3}$ |

Notes

*The residual is calculated from the deviation from the linear relationship between the annual mean $PM_{10}$ and annual mean $NO_x$ relationship for the monitoring stations in the London Air Quality Network. This indicates the 'expected' concentration of $PM_{10}$ relative to the concentration of $NO_x$, principally related to vehicle emissions

** $NO_x$ was not monitored at these sites, so a residual calculation was not possible.

It was concluded that CMA could have a role in reducing ambient $PM_{10}$ concentrations in London where levels of resuspended $PM_{10}$ are unusually high. It is likely to be most beneficial when it is applied frequently and across a wide area.

The Greater London Authority has also investigated the effect of using CMA at two construction sites. However it has been observed as part of this trial that CMA reacts with bentonite, a substance used during piling. This may inhibit its use as a dust suppressant at construction sites. Insufficient records on the application of CMA were available to allow meaningful analysis (The Great London Authority, 2013).

### 2.10 CMA+ LIFE Project Recommendations

The CMA+ project produced a manual (CMA+, 2013) which provides guidance on the use CMA to suppress the suspension of road dust to reduce $PM_{10}$ emissions. CMA is also used as a more environmentally-friendly replacement for NaCl as a de-icing agent. For de-icing higher applications rates (approximately an order of magnitude higher) are required which can reduce the surface friction and increase the risk of skidding.

The recommendations below relate only to its use as a dust suppressant:

<u>Application of CMA during Winter to Roads</u>

1. The application of CMA may turn roads into wet surfaces when one would normally expect dry roads. Road sections with reduced skid resistance or showing major wear or track grooves should not be treated. It is therefore recommended to perform grip tests on the roads which are intended for treatment
2. Prior to starting the CMA application, with sufficiently long notice, the road sections or areas should be properly signposted and the community informed through publicity campaigns.
3. The application is weather-dependent and should be done only under the following conditions: dry weather; air humidity below 80 %; no precipitation forecast; rising trend of PM pollution; and limit values (>50 $\mu g\ m^{-3}$) have already been exceeded or are expected to be exceeded.
4. The decision to apply CMA should be taken by a team of experts (air quality, meteorology, winter maintenance) on a daily basis. A daily updated planning and forecasting tool should be used as the basis for decision-making by the winter maintenance staff.
5. The dose for a single treatment should no higher than 10 $g\ m^{-2}$ for traffic safety reasons.
6. Intersections, pedestrian crossings, bends, roundabouts and bridges as well as road sections with reduced skid resistance must be excluded from treatment.
7. Road should be treated according to the following schedule:
    - More than 15,000 vehicles per lane per day - twice a day;
    - More than 7,500 vehicles per lane per day - once a day;
    - Less than 5000 vehicles per lane per day) - every other day;
    - Less than 2,500 vehicles per lane per day - every third day; and
    - Less than 1000 vehicles per lane per day – no treatment.
8. If possible, the liquid dust suppressant should be applied before the onset of the morning rush hour (not later than 7.00 a.m.).

9. The determination of the residual CMA on the road is recommended to optimise the application intervals.
10. If the outside temperature is below -10°C, there should be no treatment because of the danger of ice formation.
11. As soon as the weather conditions permit, the road sections should be cleaned and washed as often as possible (using a sweeper with low PM emissions and suitable for operation up to -5°C, and a high-pressure washing vehicle)
12. To make the optimal use of CMA the application may be done alternatively, once across the entire road width and once only across the wheel track.
13. Detailed records should be kept of the quantity of CMA applied. After each spreading journey the average application rate should be calculated and compared to the target application rate.
14. The road maintenance staff and, in particular, the operators of the sweepers should be trained, and information shared with other winter service authorities.
15. Laboratory tests have shown that a 50:50 mixture of CMA and potassium formate solution is more efficient as a dust suppressant, and lasts longer compared to using a CMA solution. However further field tests are needed.
16. According to the CMA+ project results, if applied consistently, the kerbside fine dust reduction potential is up to 30 % relative to the daily average and 10 % relative to the annual average.

CMA Application on Unpaved Roads and at Construction Sites

1. Unpaved roads should be treated with a dose of 100 to 200 g $m^{-2}$.
2. In principle, CMA can be applied onto gravel roads in open land or in gravel pits with the same equipment as used for winter maintenance of roads or with a conventional spray lance and a water barrel.
3. The frequency of application depends on weather conditions, surface characteristics and traffic volume.
4. According to the results in Austria, the effect may last for several weeks until dust becomes visible.
5. The ground to be treated should be wet before application to improve wetting of the soil by the CMA droplets. Wetting of the ground may either occur naturally (morning dew, rain) or mechanically (spraying with water).
6. A slight smell of vinegar may be perceived close to the area of application, which is not harmful to the environment.
7. CMA can be applied at construction sites. However, dirt may be carried from unpaved areas to paved public road by vehicle tyres due to the strong dust-binding effect. Construction sites where the use of CMA is intended should therefore be equipped with a wheel-washing facility.
8. Centimetre thick dry dust layers prevent the surface from being wetted due to the high surface tension of water. This effect is particularly obvious on hot mid-summer days.
9. When there are strong winds, the drifting of dry dust from large unpaved opencast mining areas (opencast extraction of mineral resources, gravel pits) cannot be prevented using CMA.

# 3 CONCLUSIONS

A number of North and Central European cities have tested the effectiveness of applying dust suppressants to road surfaces to reduce ambient $PM_{10}$ concentrations. It is noteworthy that all studies were conducted in regions with relatively wet climates (Sweden, Norway, Finland, Netherlands, UK, Germany, Austria and North Italy). Before March 2014, no studies were available for the Mediterranean region.

In North and Central Europe, where there were high dust loads, the application of dust suppressants has been shown to be effective at reducing the daily average $PM_{10}$ concentrations and the number of days when it exceeds 50 µg $m^{-3}$, and in these locations may have a role to play in achieving the EU limit value (which allows 35 days above 50 µg $m^{-3}$per year).

Based on the literature review it can be concluded that, in Northern and Central Europe, dust suppressants are effective only where the road dust load is high and the road dust contributes a significant proportion of the daily average $PM_{10}$ concentrations, such as in the countries where the use of studded types and de-icing agents give rise to high $PM_{10}$ concentrations when the snow melts in the spring. The use of dust suppressants on unpaved roads is more effective than on paved roads in terms of the $PM_{10}$ emission reduction potential. For the best results dust suppressant application needs to be applied over a wide area. Application of dust suppressants at a rate of 10 g $m^{-2}$ generally appears to be effective on Nordic and Central European paved roads; for unpaved roads, and industrial and construction sites a higher application rate is needed (100-200 g $m^{-2}$). The effects of dust suppressants seem to last for several days after application, but are dependent on the traffic flows, weather conditions and road surface characteristics.

There is conflicting evidence as to whether a mixture of CMA with potassium formate is more effective than the use of CMA on its own. CMA and potassium formate are considered preferable to the use of chlorides ($CaCl_2$ and $MaCl_2$) because they are less corrosive to metals and more biodegradable in ground water, which is important where it is the source of drinking water. However, they are more expensive. In general, the use of $MgCl_2$, $CaCl_2$, CMA and potassium formate appears to be equally effective in Nordic and Central Europe.

It should be noted that AIRUSE has undertaken the only study to investigate the effectiveness of dust suppressants on PM concentrations in the Mediterranean region (Amato et al., 2014). It showed no statistically significant reductions in $PM_{10}$ and $PM_{2.5-10}$ concentrations. This is thought to be due to the high solar radiation drying the road surface rapidly and thus reducing the efficiency of the suppressant.

# 4 REFERENCES

Aldrin M., and Steinbakk G.H., 2003. Effect of salting to reduced particular matter. An analysis of data from the winters 2001/2002 and 2002/2003 (in Norwegian). Technical Report SAMBA/19/2003, Norwegian Computing Centre, Oslo, Norway. Quoted in Amato et al., 2010.

Aldrin M., Haffa I.H., Rosland P., 2008. The effect of salting with magnesium chloride on the concentration of particulate matter in a road tunnel. Atmospheric Environment 42, 1762–1776.

Amato F, A. Karanasiou, P. Cordoba, A. Alastuey, T. Moreno, F. Lucarelli, S. Nava, G. Calzolai, and X. Querol, 2014. Effects of road dust suppressants on PM levels in a Mediterranean urban area. Environmental Science and Technology. 48, 8069-8077.

Amato F., Querol X., Johansson C., Nagl C., Alastuey A., 2010. A review on the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods. Science of the Total Environment 408, 3070–3084.

Amato F., Pandolfi M., Moreno T., Furger M., Pey J., Alastuey A., Bukowiecki N., Prevot A.S.H., Baltensperger U., Querol X., 2011. Sources and variability of inhalable road dust particles in three European cities. Atmospheric Environment 45, 6777-6787.

Amato F., Pandolfi M., Alastuey, A, Lozeno J., Contreras Gonzalez J., Querol X., 2013. Impact of traffic intensity and pavement aggregate size on road dust particles loading. Atmospheric Environment 77, 711-717.

Bachler G. and Sturm P., 2012. Results of Air Quality Measurement Campaigns in the Partner Cities Klagenfurt, Lienz and Bruneck within EU-LIFE Project CMA+. Fine Dust Congress 2012 Klagenfurt, 20th to 21st June 2012, http://feinstaubfrei.at/images/Referenten/BACHLER.pdf, accessed 24th September 2013.

Barrett B., Carslaw D., Fuller G., Green D., Tremper A., 2012. Evaluation of the impact of dust suppressant application on ambient $PM_{10}$ concentrations in London. Prepared for Transport for London under contract to URS Infrastructure & Environment Ltd., Kings College London.

Boulter J., Wayman M., McCrae, I., Harrison, R.M., 2006. A review of abatement measures for non-exhaust particulate matter from road vehicles, TRL.

Berthelsen, B,O., 2003. The use of magnesium chloride as dust reducer at E6 through Trondheim (in Norwegian). Report No. TM2003/2, Trondheim Municipality, Environment Division, Trondheim, Norway, ISBN:82-7727-087-9. Quoted in Amato et al., 2010.

CMA+, 2012. Instruction manual 1.1 for the reduction of fine-dust (PM) pollution through the application of a liquid “fine-dust glue” (calcium-magnesium-acetate), http://www.life-cma.at/english/downloads/MONITOR_Bedienungshandbuch1.1_A4_eng_121003l.pdf accessed 23rd August 2012.

Düring I., Jacob J., Lohmeyer A., Lutz M., Reichenbacher W., 2002. Estimation of the "non-exhaust pipe" $PM_{10}$ emissions of streets for practical traffic air pollution modelling. In: 11th Internationa. Symposium on Transport and Air Pollution, Graz University of Technology, Institute for Internal Combustion Engines and Thermodynamics, vol. 1, pp. 309 - 316.

Escudero M., Querol X., Avila A., Cuevas E., 2007. Origin of the exceedances of the European daily PM limit value in regional background areas of Spain. Atmospheric Environment 41, 730–74.

Etyemezian V., Kuhns H., Gillies J., Green M., Pitchford M., Watson J., 2003. Vehicle-based street dust emission measurement: I - methods and calibration. Atmospheric Environment 37, 4559- 4571.

Gehrig R., Zeyer K., Bukowiecki N., Lienemann P., Poulikakos L.D., Furger M., Buchmann B., 2010. Mobile load simulators - A tool to distinguish between the emissions due to abrasion and resuspension of $PM_{10}$ from road surfaces. Atmospheric Environment 44, 4937-4943.

Gillies J. A., Watson J.G., Rogers C.F., DuBois D., Chow J.C., Langston R., and Sweet J. J., 1999. Air and Waste Management Association 49, 3-16.

Greater London Authority, 2013, Clean Air Fund – End of Programme Report Final, January 2013.

Gustafsson M., Blomqvist G., Johansson C., Norman M., 2013. Operational measures against $PM_{10}$ pollution on Hornsgatan and Sveavägen in Stockholm – evaluation of winter season 2011–2012. VTI report 767, Linköping, Sweden.

Gustafsson, M., Blomqvist G., Gudmundsson A., Dahl A., Jonsson P., Swietlicki E., Johansson C., Norman M., Westerlund K-G., 2009. Factors influencing $PM_{10}$ emissions from road pavement wear. Atmospheric Environment 43, 4699–4702.

Gustafsson M., Blomqvist G., Jonsson P., Ferm M., 2010. Effects of dust binding of paved roads, VTI Rapport 666. VTI, Linköping, Sweden.

Johansson C., Norman M., Westerlund K-G., 2005. Försök med dammbindning längs E4-Vallstanäs och i Norrmalm i Stockholms innerstad. SLB 10:2005, SLB analys, Stockholm.

Karanasiou A., Moreno T., Amato F., Tobías A., Boldo E., Linares C., Lumbreras J., Borge R., Alastuey A., Querol X., 2012. Variation of $PM_{2.5}$ concentrations in relation to street washing activities. Atmospheric Environment 54, 465-469.

Hafner W., 2007, SPAS Project Manager, Department of Environmental Protection, City of Klagenfurt. Quoted in Amato et al., 2010.

Hafner W., 2013. http://www.life-spas.at/deutsch/includes/22_hafner_cma_091002.pdf, accessed 26th September 2013.

Hooghwerff J., van Beers P., 2006. Road-bound Dust: High-efficiency PAC dust Cleaner: Phase A (in Dutch). Report number DWW-2006-082. Heijmans Infrastuctuur and M+ P – raadgevende Ingenieurs. IPL Report.

KAPA,2013.http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=2708 assessed 24th September 2013.

Karanasiou A., Moreno T., Amato F., Tobías A., Boldo E., Linares C., Lumbreras J., Borge R., Alastuey A., Querol X., 2012. Variation of $PM_{2.5}$ concentrations in relation to street washing activities. Atmospheric Environment 54, 465-469.

Kristoffersen T., 2012. Winter Maintenance Reducing Street Dust in Olso. Best practices to reduce respirable street dust. REDUST Seminar, October 31st, 2012, http://www.redust.fi/tiedostot/kvseminaari2012/Kristoffersen.pdf accessed 24th September 2013.

Kupiainen K., Pirjola L., Ritola R., Väkevä O., Viinanen J., Stojiljkovic A., Malinen A., 2011. Street dust emissions in Finnish cities – summary of results 2006–2010. City of Helsinki, Environment Centre, Publication 5/2011, Helsinki.

Norman M., Johansson C., 2006. Studies of some measures to reduce road dust emissions from paved roads in Scandinavia, Atmospheric Environment, 40, 6154–64.

McCrea I., 2009, Scientific Board Review, International review of the Air Quality Innovation Programme (IPL), Report number IPL-8, Rijkswaterstaat Dienst Verkeer en Scheepvaart, Delft.

http://www.rijkswaterstaat.nl/images/Eindrapport%20Scientific%20Board_tcm174-282754.pdf

Omstedt G., Johansson C., Bringfelt B., 2005. A model for vehicle induced non-tailpipe emissions of particles along Swedish roads. Atmospheric Environment 39, 6088–97.

Öttl D., Hafner W., 2006. Summary Report on the use of CMA in winter service in Klagenfurt. 29.06.2006, Institute for Internal Combustion Engines and THD, Graz University of Technology in cooperation the City of Klagenfurt.

Pirjola L., Kupiainen K.J., Perhoniemi P., Tervahattu H.,Vesala H., 2009. Non-exhaust emission measurement system of the mobile laboratory SNIFFER. Atmospheric Environment 43, 4703-4713.

REDUST, 2014. Deliverable product of the REDUST LIFE09 ENV/FI/000579 Actions 1 and 2 Demonstration test final report, Main results and conclusions 15-08-2014. http://www.redust.fi/en/results/. Accessed 27 November 2015.

Rodriguez S., Querol X., Alastuey A., Kallos G., Kakaliagou O., 2001. Saharan dust contributions to PM10 and TSP levels in Southern and Eastern Spain, Atmospheric Environment, 35, 2433-2447.

Ryall D.B, Derwent R.G., Manning A.J., Redington A.L., Corden J., Millington W., Simmonds P.G., O'Doherty S., Carslaw N., Fuller G.W., 2002. The origin of high particle concentrations over the United Kingdom, March 2000. Atmospheric Environment 36, 1363-1378.

Saxony-Anhalt Pollution Control and Environment Department, City of Halle (Saale), 2009, Trail of the use of calcium magnesium acetate for the reduction of particulate matter in Halle (Saale) (in German)

http://www.mu.sachsen-anhalt.de/lau/luesa/Berichte/Sonderberichte/CMA_Bericht_final.pdf accessed 26th September 2013.

Tønnesen, D., 2006. Dust measurement in Festningstunnelen (in Norwegian). Technical Report, Note 104020. Norwegian Institute for Air Research, Kjeller, Norway. Quoted in Amato et al, 2010.

Thorpe A. and Harrison R.M., 2008. Sources and properties of non-exhaust particulate matter from road traffic: a review. Science of the Total Environment, 400, 270-282.

Værnes E., 2003. Measurements of particular matter in the Hell Tunnel late autumn 2002 (in Norwegian). Technical Report, Project No. 223181, Sintef, Trondheim, Norway. Quoted in Amato et al, 2010.

URS, 2011. Targeted application of calcium magnesium acetate (CMA) pilot study monitoring report. Report for Transport for London, August 2011, http://www.tfl.gov.uk/assets/downloads/corporate/dust-suppressant-results.pdf. Accessed 26th September 2013.