REVIEW OF IMPACT OF STREET CLEANING ON PM10 AND PM2.5 CONCENTRATIONS IN NORTHERN AND CENTRAL EUROPE
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1 INTRODUCTION

Non-exhaust emissions from road vehicles are a significant source of particulate matter (PM) in the atmosphere (Harrison et al., 2001). These emissions come from several sources including the wear of vehicle parts, such as tyres and brakes, and the road surface, and the resuspension of dust deposited on the road surface (Boulter et al., 2006). Non-exhaust PM is deposited on the road surface and can become suspended (or re-suspended) in the air through the action of vehicle tyres, vehicle induced turbulence and wind blow. This road dust contributes towards the exceedence of the EU air quality limit values for PM$_{10}$ recorded in over 20 European countries, particularly the 24-hour mean limit value. The European Environment Agency (2015) has estimated that up to 30% of the EU urban population lived in areas where the limit value was exceeded in 2011-2013. This mandatory limit value was originally intended to be achieved across the EU by 2005. In addition up to 93% are exposed to PM$_{10}$ concentrations above the more stringent WHO guideline value.

As exhaust emissions decline as a result of increasingly stringent limits, the relative importance of non-exhaust emissions will grow. It has been estimated that by 2020 about 90% of road traffic emissions will be from non-exhaust sources (Rexeis and Hausberger, 2009).

Northern and central European countries where studded tyres and abrasives for traction control are used during freezing weather have high non-exhaust emissions, particularly in the spring (e.g. Kupiainen & Pirjola, 2011). Test track measurements have showed that the use of studded tyres results in higher PM emissions than studless tyres especially at speeds greater than 50 km h$^{-1}$. However, when traction sanding is used the type of tyre becomes unimportant due to the suspension of traction sand dust from the road surface (Kupiainen & Pirjola, 2011). It has also been found that road salt adds to the ambient PM$_{10}$ concentrations.

Large quantities of coarse particles are emitted due to enhanced road surface abrasion and mechanical fragmentation of the traction sand grains (Kupiainen et al., 2003, 2005). Measurement of road dust emissions after road sanding on dry roads indicated a 75% increase in PM$_{10}$ emissions after 2.5 hours, but the effect was short-lived (Kuhns et al., 2003). Zhu et al. (2009) found that road dust emissions increased by a factor of 10 when traction control material was applied to the roads after snow events.

Even in the absence of road sanding and studded tyres, non-exhaust particles are typically larger than exhaust particles. The latter are thought to be largely in the submicrometre fraction (Harrison et al., 2011), while the size of non-exhaust particles have often been assumed to be in the PM$_{2.5-10}$ fraction. Much less is known of the size distribution of non-exhaust emissions, with relatively few reported studies. However, there is some evidence that these particles can make a significant contribution to PM$_{2.5}$ concentrations. Brake and tyre wear appear to contribute to both coarse and fine PM (Pant and Harrison, 2013), but less is known of the size of particles emitted from road wear.
Dust builds up on paved road surfaces from a wide range of sources including track-out from unpaved areas such as construction and industrial sites and parking lots, spills from lorries, and transport of dirt collected on vehicle undercarriages and atmospheric deposition.

Material deposited on the road surface is resuspended due to wind blow, the turbulence caused by the movement of vehicles and the force of rolling tyres. This material may be mainly crustal material in the coarse size fraction, but will also include particles from the wear of brakes, tyres and the road surface. At a roadside monitoring station in central London it was estimated that the main source of non-exhaust emissions was brake dust followed by the resuspension of road dust. It was not possible to estimate the road wear contribution due to the lack of a suitable chemical tracer (Harrison et al. 2012).

There are a number of factors that are likely to affect non-exhaust emissions. These include driving behaviour, that is driving speed and the frequency and severity of braking, traffic volume and composition, type of brake liner, road surface materials, as well as meteorological factors such as temperature, humidity, rainfall and wind conditions.

In recent years there have been a number of trials to determine the most effective means of controlling these non-exhaust emissions. This report focuses on the potential role to reduce ambient PM$_{10}$ concentrations by street cleaning, i.e. the sweeping and washing of street surfaces. Flushing is the term often used to describe the spraying of high pressure water onto a road surface to wash dust into the drains. It can include washing pedestrian pavements as well as the highway itself. In the US flushing has led to concerns regarding the transport of contaminated dust into the water system.

Alternative control measures include the use of different road surfaces (e.g. open porous asphalt), minimising the use of studded tyres to reduce abrasion and resuspension and use of chemical de-icers prior to a snow event to minimize ice formation and reduce the need for abrasives (Amato et al. 2010). However these measures may not be suitable for southern European cities.

A separate report$^1$ addresses the efficacy of the use of dust suppressants, such as calcium magnesium acetate (CMA), which have been trialled in several European cites.

2 FACTORS AFFECTING THE EFFICACY OF ROAD CLEANING

The primary aim of road sweeping is to improve the aesthetic appearance of the urban environment by removing street debris, litter and dirt. The frequency of sweeping varies significantly, with major roads and motorways being rarely swept.

$^1$ http://airuse.eu/outreach-dissemination/reports/
Historically, neither road sweepers nor their operational procedures were designed to reduce ambient PM$_{10}$ concentrations. There is evidence that the use of some road sweepers has increased local PM$_{10}$ concentrations.

Factors that are likely to affect the efficacy of road sweeping in reducing PM$_{10}$ concentrations include the following:

1. The road dust loading;
2. Sweeper efficiency of removing PM$_{10}$ from the road surface;
3. The ability of the machine to retain the particles;
4. Road surface;
5. The portion of the road that is swept;
6. The frequency of sweeping; and
7. The length of road swept.

The sweeper exhaust emissions are unlikely to be significant in the context of the 24-hour mean PM$_{10}$ limit value.

A number of studies have investigated the road dust loading of various sizes, and the efficacy of road sweepers to remove it. However a number of other factors influence the ambient PM$_{10}$ concentrations particularly including the weather and the presence of other sources. Therefore, reducing the dust emission from a road surface may not necessarily result in an observable reduction in ambient concentrations. The focus of the AIRUSE programme is on mitigation measures that will result in the achievement of the ambient air quality limit values for PM$_{10}$ in the Mediterranean region. The focus of this report is on the evidence of street cleaning and washing reducing ambient concentrations. However a few studies measuring PM$_{10}$ emissions from a road surface (i.e. the concentrations just above the road surface) have been included because they provide additional information that is not available from the studies of the impact of street cleaning on ambient PM$_{10}$ concentrations.

3 TYPES OF ROAD SWEEPERS

There are three general types of road sweepers in use in Europe. The technology has changed relatively little over the past few decades with the exception of the use of bag filters to control fugitive PM$_{10}$ emissions from the dust collected, and diesel particulate filers to control exhaust emissions, which have recently been introduced to the market (Wiemann, 2013; Chow et al., 1990):

- **Mechanical sweepers** are the traditional type of road sweepers, but today the only European manufacturer producing these sweepers is the Swedish company (Brood). Mechanical sweepers can be used on a trailer. These sweepers lift the material from the road onto a conveyer belt, and then discharge the material into a collection hopper. Circular gutter brooms direct the material into the path of the rotating broom. In
In general, these sweepers are considered to be effective at removing large debris such as branches, leaves, litter, and large quantities of dirt, but can ‘blow’ more PM into the air than vacuum sweepers.

- **Vacuum sweepers** typically use a gutter broom to loosen dirt and debris from the road and direct it to a vacuum nozzle which sucks it into a hopper. The hopper usually consists of a chamber into which the material is collected by gravitational settling. The air passing through this chamber can be emitted directly into the atmosphere, through a bag-filter or precipitator, or to the collection nozzle for recirculation. Pure vacuum sweepers create a strong vacuum within the pickup head which draws air from outside the head, through a duct, and into the hopper. The air movement across the road surface removes particles from the pavement and entrains them in the air flow. The vacuumed air is exhausted to the outside environment after a brief time in the hopper. However, the residence time can be insufficient to allow gravitational settling of PM\textsubscript{10}. Figure 1 illustrates a state of the art vacuum sweeper fitted with a filter in the roof and shows the air flow (VDI, 2014).

![Figure 1: Example of a vacuum sweeper (VDI, 2014)](image)

- **Regenerative-air vacuum sweepers** direct the all or some of the exhaust air back to one end of the pickup head at high speed or to a nozzle located immediately behind the pickup head. The blast of exhaust air is directed at an angle to the pavement to dislodge dirt. The blast air and the entrained material move across the pickup head to a suction nozzle which transports the debris to the collection hopper. The non-recirculated portion of the exhaust air is vented into a separate settling chamber before it escapes to ambient air. This type of road sweepers is not common in Europe and only MFH currently produce models using this method.

Water sprays can be used with vacuum sweepers to reduce the resuspension of dust. Figure 2 illustrates a wet and dry vacuum sweeper.
A comparison of the efficacy of several different road sweepers, undertaken using a test procedure developed by DMT on behalf of the German Federal Environment Agency, suggests that different road sweepers may have three orders of magnitude different impact on PM$_{10}$ concentrations. The Dulevo 5000 with its patented GORE filtration system was the best performer, estimated to emit less than 0.34 kg PM$_{10}$ over 2000 hours of operation (Geddes, 2011).

The Swedish DISAB Group produces the DISA-CLEAN 130. It claims that this sweeper is “achieving measurable results for local authorities... trying to combat exposure ... PM$_{10}$”. After testing the DISA-CLEAN 130 around the City of Uppsala in Sweden, the Head of Street and Traffic for the city, Åke Westli, said: “Every time the DISA-CLEAN unit has been used to clean our streets, our measuring points show us that the problems with the unhealthy environmental particles i.e. PM$_{10}$ have been reduced considerably. The difference is amazing. We should get two of these units working continuously around our streets.” The DISA-CLEAN 130 uses a Roots vacuum pump, specially developed nozzles for road surfaces and a unique filter technology. Dust free performance is achieved due to its brushes being under vacuum throughout the whole sweeping and cleaning operation (DISAB Group, 2013).

British firm Johnston Sweepers also claim to have developed a unique system which creates a cyclone effect within the hopper, for the most efficient filtering via mesh screens, of dust and debris particles prior to discharge to the atmosphere. This design is a standard feature of all Johnston V Range sweepers. This range was the first European-manufactured sweeper to achieve full PM$_{10}$ test compliance under the Californian regulations (see next section).

**Figure 2**: Example of a wet and dry sweeper (VDI, 2014)
4 PM$_{10}$ CERTIFICATION OF ROAD SWEEPERS

4.1 California
In 1997 the South Coast Air Quality Management District in California (2015) was the first government body to introduce a certification procedure for testing the efficacy of road sweepers in removing PM$_{10}$. Rule 1186 required testing of road sweepers’ ability to remove more than 80% of the typical urban street dust loadings and limits the amount of PM$_{10}$ entrained during the sweeping process to less than 200 mg m$^{-1}$ (South Coast Air Quality Management District, 2013). This rule has been modified several times since, for example, requiring municipal road sweepers to be powered by alternative fuels since 2002. It is understood that all road sweeper sold in the US and Europe can achieve this standard, although sometimes as an optional extra.

4.2 Canada
The City of Toronto, working with the City of Hamilton, the Environmental Technology Verification Canada (EVT) and the Prairie Agricultural Machinery Institute (PAMI) developed two new test protocols: ‘The PM$_{10}$ and PM$_{2.5}$ Street Sweeper Efficiency Test Protocol’ and ‘The Operational On-street Test Protocol’. The aim was to provide independent, quantitative and comparable information on the performance of road sweepers for prospective purchasers to enable them to choose high performing road sweepers where PM pollution is an issue (City of Toronto, 2013).

4.3 EUraille
From 2004 the purchasers of new sweepers started to request information on the PM emissions and some European organisations started to develop test procedures to measure the PM concentration around a working road sweeper. The manufacturers were requested to run many different PM tests with their products. In 2007 the Brussels based organisation EUraille Municipal Equipment, which represents the main European manufacturers of mobile municipal equipment including road sweepers, launched its PM$_{10}$ certification scheme. The test was carried out using the same mix of materials as the Californian 1186 Rule test. It was undertaken outdoors with PM$_{10}$ measurements undertaken behind the sweepers. There was poor repeatability of the test results, yet most road sweeper models were certified. Some customers criticised the test and in 2012 a new test was developed in association with PAMI, the Canadian organisation involved in the development of the Toronto/Hamilton test procedure. This new European test came into effect from the beginning of 2013 and includes PM$_{2.5}$.

The test takes place in a controlled environment to exclude weather effects. Sweepers run on a defined test track four times under ‘realistic’ working conditions. The airborne concentrations during the sweeping of a defined test material and the removal efficiency are measured. The test allows the use of water to suppress dust.

To obtain at least one star a sweeper has to exceed a minimum dust collection efficiency and reduction in PM$_{10}$ concentration in the air. For two stars the concentration in the air after the test must be, at a given dust collection efficiency, at least one third below the defined maximum concentration, and for three stars at least two thirds below the defined maximum concentration.
A list of more than 60 sweepers from 24 manufacturers tested by the end of April 2013 showed that virtually all of them achieved three stars (EUnited, 2013). It represented approximately 30% of the EU market (Diedrich, 2013). In March 2015 this test procedure was adopted as an European standard (British Standards Institution, 2015).

However, it has been suggested by some manufacturers that the test procedure is not effective at distinguishing between the PM\textsubscript{10} efficiency of different machines. For example, there is no relationship between the measured PM\textsubscript{10} concentrations and the amount of water used by the sweepers during the test (Veddes, 2011).

4.4 German Test Procedure

The German Federal Environment Agency (Umweltbundesamt – UBA) commissioned DMT to develop a reliable method for the determination of particulate emissions from road sweepers under standardised conditions. This has been published as German technical guidance by VDI (2014). This document applies to dry, wet and combined wet and dry vacuum assisted sweepers produced specifically for municipal purposes. It describes the state of art sweepers with low-emission characteristics, but which are also effective at collecting dirt and litter.

Major differences between the EUnited and the draft VDI test procedures are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1: EUnited and Draft VDI Test Procedures (Geddes, 2011)</th>
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<tr>
<td><strong>EUndited</strong></td>
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<td>Test runs</td>
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<td>Metric measured</td>
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<td>Measurement</td>
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<tr>
<td>Machine equipment</td>
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<td>Test material</td>
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<tr>
<td>Test track surface</td>
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<tr>
<td>Reference machine</td>
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<td>Sweeper speed</td>
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<td>Reporting unit</td>
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Table 2 shows the percentage reduction in emissions of PM$_1$, PM$_{2.5}$ and PM$_{10}$ from the road surface measured using the VDI test (VDI, 2014) compared to reference machines.

**Table 2: Results of the VDI Test (VDI, 2014)**

<table>
<thead>
<tr>
<th>Sweeper manufacturer</th>
<th>% Reduction in emissions from test road surface compared to the reference machines operated in dry mode</th>
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<tbody>
<tr>
<td></td>
<td>PM$_1$</td>
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<tr>
<td></td>
<td>Kerb (60 cm)</td>
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<tr>
<td>Faun*</td>
<td>96</td>
</tr>
<tr>
<td>Kroll *</td>
<td>98</td>
</tr>
<tr>
<td>Bekker</td>
<td>88</td>
</tr>
<tr>
<td>Dulevo*</td>
<td>101</td>
</tr>
<tr>
<td>Brock (wet)</td>
<td>60</td>
</tr>
<tr>
<td>Brock EP**</td>
<td>67</td>
</tr>
<tr>
<td>Bucher (wet)</td>
<td>53</td>
</tr>
<tr>
<td>Bucher (dry)</td>
<td>0</td>
</tr>
</tbody>
</table>

* Fitted with a bag filter; **EP = electrostatic precipitator.

All tests were dry unless stated otherwise.

At the kerb the reference machine was a Bucher Schörling AG sweeper, operated dry.

For the road away from the kerb the reference machine was a Brock sweeper with an electrostatic precipitator.

The best sweeper of those tested on the VDI procedure was the Dulevo sweeper (Dulevo 5000 Evolution). This sweeper is not a conventional vacuum sweeper and is described as a mechanical suction machine. It uses a patented 24 m$^2$ moisture resistant Gore-Tex fabric filter to remove particulate matter from the air stream exiting the dust/dirt container. The filter includes a driver operated shaking device to release the particles trapped into the waste container, prolonging its use but avoiding the buildup of excessive pressure.

The road dust/dirt is picked up using side brushes which convey the debris towards the centre of the machine, where a central cylindrical brush throws it at high speed onto a vertical conveyor system. This loads the waste container from above. The dust raised by the central
cylindrical brush is sucked into the waste container by the vacuum created by two fans. Water can be sprinkled on the side brushes to control dust. The sweeper has a unique four wheel steering system that makes it a very mobile.

Figure 3 is an illustration of this machine from the VDI standard (VDI, 2014).

![Figure 3: Schematic Illustration of the Dulevo 5000 Evolution Road Sweeper (VDI, 2014)](image)

It should be noted that real-world operating can be very different from the test conditions and therefore there is a need for more systematic in-service testing to be undertaken with a range of different sweepers.

To control the emission of PM$_{10}$ from the air outlet of road sweepers a number of techniques have been employed including cyclones, bag filters and electrostatic precipitators. Table 2 shows that the state-of-the-art sweepers are typically equipped with a bag filter. However, these occupy a significant amount of space on the vehicle, resulting in the vehicles getting bigger and more expensive.

Tests have been undertaken in a street (Viikintie) in Helsinki to measure the PM$_{10}$ concentrations in the outlet air of the Dulevo 5000. The first measurements were conducted in August 2008 when street surfaces were relatively clean. Sand was then spread on one section of the road. Emissions during the sweeping of the road were tested using a standard bag filter and an advanced Gore-Tex filter. The particle concentrations with the Gore-Tex bag filter were approximately half those measured from the standard filtering system. A second set of measurements of the PM$_{10}$ in the air outlet of the Dulevo sweeper was conducted in early April 2009. The aim was to repeat the 2008 measurements during the spring when there are much higher dust loads. The PM$_{10}$ concentrations in the outlet air with a standard filter were on average sevenfold higher than the concentration in 2008, whereas the concentration in the outlet air from the Gore-Tex bag filter was similar to that measured in 2008. The authors concluded that the advanced Gore-Tex bag filter achieves significant reductions in the outlet air PM$_{10}$ concentrations and thus can help mitigate the negative impact on air quality of cleaning activities. However, these results apply only to the Dulevo equipment and further measurements are required to understand the outlet air concentrations of other equipment (Kupiainen et al. 2011).
5 IMPACT ON AMBIENT PM\textsubscript{10} CONCENTRATIONS

Investigating the impact of sweeping on ambient air quality is not simple because PM concentrations are dependent on a large number of variables, and small differences due to road sweeping are not easily identified, particularly if using fixed monitoring sites. In addition, evaluation of their efficacy is complicated by the use of different types of road sweeper with different PM\textsubscript{10} collection efficiencies and operating methods. Most studies investigating the impact of road sweeping have been short term and it may be that the cleaning of roads over a long period has a different impact. Finally most studies have been over a small geographical area, typically, limited to a few 100 m.

Amato et al. (2010) has reviewed the effectiveness of road sweeping and washing, as well as the application of dust suppressants. The paper notes that there is a general dearth of information available, as municipalities rarely provide details of their PM mitigation strategies on the internet. The conclusions of Amato et al. (2010), on the ability of street sweeping and washing to remove dust from the road surface and their impact on ambient PM concentrations are briefly summarised below.

5.1 Review by Amato et al. (2010)

Many of the studies on sediment removal were for larger particles than PM\textsubscript{10}, but these studies are potentially important as the traffic can generate respirable particles from larger particles. In general, mechanical sweepers appear to be better at picking up large particles (greater than 100 -125 µm) while regenerative-air sweepers are better for finer particles (<100 µm). Sediment removal efficiency increases with particle size for all sweeper types. The vacuum sweepers had a mean removal efficiency for total sediments of 41% while mechanical and regenerative-air sweepers were 54-57% efficient. The authors recommended that where there are high sediment loads it may be best to clean the streets first with a mechanical sweeper to remove the large particles followed by a regenerative-air sweeper to remove the finer particles. As 90% of the sediments are within 2 m of the kerb it was also recommended that street cleaning should focus on the extreme lanes of the roadway, except where there is snow. This is presumably because anti-skidding abrasives are applied on all lanes during freezing weather conditions. In addition, municipal cleaning schedules need to be flexible and take account of local conditions, including the weather, season and construction works. They also need to time the cleaning to take account of street parking.

Amato et al. (2010) recommended that municipalities should:

1. Evaluate the magnitude of the problem for a single street;
2. Select the critical streets with respect to dust load;
3. Evaluate the dust accumulation rate (i.e. how quickly the steady state between deposition and emission is reached);
4. Determine the most effective cleaning procedures (e.g. frequency, timing).

With regard to the impact of street sweeping on ambient PM concentrations Amato et al. (2010) reviewed 15 studies and concluded that it was ineffective in the short term. Some sweepers
produce a visible dust cloud from the brooms or the air discharged from the collection hopper, and in some studies PM$_{10}$ concentrations increased. However the authors of the studies reviewed did not discount a positive effect in the long term given that street sweeping has to reduce fugitive dust emissions given the sediment removal efficiency.

When sweeping is combined with water flushing there were more encouraging results. The authors reviewed six studies and a reduction in ambient PM concentrations was always observed. This could be due to wetting the road surface and not from actually cleaning the road. In two studies the improvement was definitely attributed to the sweeping/washing operations which yielded efficiencies of up to 30% and 24% respectively. However these showed that the benefits were short lived lasting no more than 3 to 4 hours for total suspended particulate (TSP) and 2 to 3 hours for PM$_{10}$. In two other tests it was difficult to definitely quantify the impact due to changing meteorological conditions. The final two studies found that the PM$_{10}$ reductions were too small when compared to the measurement uncertainty. The authors noted that the impact of sweeping/washing roads is likely to be small as road dust is only one source of PM in an urban area, and the atmosphere is continually mixed.

Water flushing alone without sweeping has been almost exclusively studied on unpaved roads. Research on the effectiveness of only washing in Germany and Sweden indicated a limited or no effect on PM$_{10}$ levels.

5.2 Other studies of the effect of street cleaning on ambient PM$_{10}$ concentrations

For this report a search of the literature from 2010 to 2015 was undertaken using the University of Birmingham library search facility, i.e. research published since the review of Amato et al. (2010).

The Netherlands

Keuken et al. (2010) tested the impact of road sweeping and washing in a street canyon (width 20 m and height on both sides 15 m) in Amsterdam, with 18,000 vehicles per 24 h and 5% heavy duty vehicles. The road pavement was SMA11 (stone mastic asphalt). From July to November 2008 every other week on Tuesday the road was brushed (two stainless steel brushes with each a diameter of 85 cm at a speed of 80 revolutions per minute) and vacuum cleaned at a driving speed of 5 km h$^{-1}$, followed on Wednesday by high pressure washing (using equipment supplied by Schuitemaker Ltd, Rijssen, the Netherlands). The road was swept and washed more than 200 m in both directions from the monitoring stations located at the kerb side and housing façade. Both driving lanes were treated resulting in 2000 m$^2$ road surface treated. This regime was performed nine times with the exception of one Wednesday when heavy rainfall washed the road surface. In the study ten weeks with sweeping/washing were compared with eleven weeks without sweeping/washing.

From these data, the average (and standard deviation) of the increments (i.e. the difference in concentration at the street locations and the urban background) were determined for the ten weeks with sweeping/washing and eleven weeks without sweeping/washing. The atmospheric dilution was similar during weeks with and without treatment. It was concluded that road sweeping/washing as performed in Amsterdam does not significantly reduce PM$_{10}$ concentrations in a street-canyon.
Spain

Karanasiou et al. (2011) investigated the effect of street washing on PM$_{10}$ concentrations in the urban area of Madrid. During the one-month campaign the road surface in the area was washed daily for one week while the next week the road was left untreated. This was then repeated. Ambient concentrations were measured at three sites, two in a street canyon and one at a non-canyon site dominated by traffic emissions. Daily PM$_{10}$ concentrations were 2-15% higher during unwashed conditions than those during the day after nightly street washing. However, the standard deviation was higher than the observed reduction. The diurnal variation in PM$_{10}$ concentrations showed that the reduction was short-lived (during the morning hours). It should be noted that the urban background PM$_{10}$ concentrations were also marginally reduced during the morning hours.

Karanasiou et al. 2012 investigated the effect of street sweeping/washing in a busy street canyon in Madrid during the period 17 June to 20$^{th}$ July 2009 on PM$_{2.5}$ concentrations. For one week the road surface was washed daily with high pressure water system (4 l m$^{-2}$) and the next week the road was untreated. This was then repeated for the following two weeks. Prior to washing a mechanical sweeper was used to remove the coarser particles. The study did not detect any influence of the street washing on PM$_{2.5}$ concentrations. However, the authors concluded that it cannot be ruled out that street washing influences the PM$_{2.5}$ concentrations, but that the signal is difficult to detect where there are more dominant sources.

Sweden

The Swedish National Road and Transport Research Institute (VTI) (Gustafsson et al., 2011) have undertaken a number of studies investigating the impact of measures to reduce PM$_{10}$ concentrations, particularly the number of days when PM$_{10}$ concentrations exceeded 50 µg m$^{-3}$. They note that many manufacturers of road sweepers are working to improve existing or develop new technologies to remove fine dust from road surfaces to minimise PM$_{10}$ emissions. The effects of three road sweepers were tested. Machine A was a suction machine without a water spray or a high efficiency exhaust filter, machine B was a powerful vacuum sweeper with or without a side brush and machine C was a pressure washer and vacuum sweeper. Machines A and B are commercially available, whereas machine C was a prototype.

The tests undertaken in a street environment at Sveavägen in central Stockholm showed that the sweepers’ effect on total PM$_{10}$ concentrations was generally small, but under certain meteorological conditions the local PM$_{10}$ concentrations could be reduced by up to 20%. Sweeper A contributed more often to elevated PM$_{10}$ concentrations during drive-by than sweeper B, while sweeper B more frequently contributed to elevated NO$_x$ levels, but these emissions had little impact on daily PM$_{10}$ concentrations.

Controlled sweeper tests were undertaken at the former Barkarby Airport north of Stockholm by applying a defined quantity of stone filler with a known size distribution to the surface. The efficiency of its removal was measured using the VTI Wet Dust Sampler. For operational reasons Sweeper B was only tested under dry conditions and Sweepers A and C only under wet conditions.

Under dry conditions sweeper B removed 85 to 95% of the applied material but slightly less of the fine dust (less than 10 µm). In moist conditions Sweeper A removed about 40% of the
material, but only 5% of the fine dust was removed after two successive sweepings. Sweeper C removed approximately 99% of the applied material and the same amount of fine dust.

Measurements undertaken using a Lighthouse Handheld 3016 IAQ instrument in the sweeper exhaust (not the engine exhaust) and the engine air intake suggest that the sweepers did not contribute to ambient PM$_{10}$ concentrations, although further work is required to confirm this.

The authors concluded that the use of road sweepers can contribute to reducing concentrations of PM$_{10}$ in environments where suspension of road dust is an important source but that sweeping technologies and techniques need to be further developed to improve effectiveness during different meteorological conditions and to improve access to road dust, for example when there are parked cars on the road. New sweeping techniques show good potential to remove dust less than 10 µm from the street in controlled tests, but efficiency needs to be improved during wet conditions. In addition to PM$_{10}$ collection efficiency, noise, exhaust emissions, flexibility, speed and energy consumption also need to be taken into account when choosing a sweeper.

VTI undertook further studies during the winter 2011-2012 to assess the effectiveness of a package of measures, consisting of dust suppressant, cleaning with a powerful road sweeper machine and flushing of streets, to reduce PM$_{10}$ concentrations at Hornsgatan and Sveavägen in Stockholm (Gustafsson et al. 2013). During the period from October 2011 to May 2012 a dust suppressant (CMA) was used 31 times and the roads swept 25 times and flushed 42 times. The results showed that the number of exceedences of PM$_{10}$ on both streets were fewer than the reference streets during the treatment period. However, the only action that had a significant effect was the application of the dust suppressant, while neither cleaning nor flushing caused a direct reduction in PM$_{10}$ levels. The authors concluded that it is possible that the effects of cleaning and flushing are more long term.

**Canada**

In an industrial area of Hamilton, Canada, ambient PM concentrations have been reduced by introducing a comprehensive package of measures including road sweeping/washing. Individual control programmes for companies were developed to reduce track-out onto the public highway. Again this study is not from Europe but has been included because it is a good example of the application of a package of measures which have been shown to be effective at reducing PM$_{10}$ concentrations, albeit only over a short time period. The City also replaced its road sweepers with Tynco DST-6 regenerative air sweepers. This was chosen because of its ability to control and remove of PM$_{10}$ and PM$_{2.5}$ by 90%. Street sweeping occurred at night, two or three times a week. In addition, in response to poor air quality, the roads were swept and there was increased frequency of street flushing. Other measures implemented included tree planting and replacing gravel medians with hard surfaces (concrete and asphalt). Overall the dust management plan resulted in significant reductions in PM$_{10}$ concentrations. The average short term PM$_{10}$ concentrations was 114 µg m$^{-3}$ prior to the measures being implemented, which dropped to 73 µg m$^{-3}$ afterwards (DeLuca et al., 2012).
5.3 PM\textsubscript{10} emissions from road surfaces

Two studies in which PM\textsubscript{10} emissions from roads were measured have been included in this section of the report, one from Finland and the other from the United States. This is because they provide additional information on the effect of street cleaning. However, they do not provide direct evidence of the impact of street cleaning on ambient PM\textsubscript{10} concentrations or the exceedence of the EU daily PM\textsubscript{10} limit values.

Finland

In Finland there have been two major EU LIFE projects studying the efficacy of street cleaning. The KAPU project took place over the period 2006 to 2010 to study the impacts of winter maintenance and spring street cleaning activities on the amount and composition of road dust in Finnish cities. The aim was to identify measures that reduce the high spring PM\textsubscript{10} concentrations in the ambient air of Finnish cities (Kupiainen et al. 2011). The REDUST project took place from 2010-2014 (REDUST, 2014).

The KAPU study used SNIFFER, a vehicle based monitoring system (Pirjola et al., 2009) which collects dust samples behind the left rear tyre, approximately 5 cm from the tyre, which essentially determines the PM\textsubscript{10} emission from the road. The effects of street cleaning (and the application of dust suppressants) was measured in the following Finnish towns and cities: Espoo (2008 and 2009), Vantaa (2008, 2009, 2010), Helsinki (2006, 2007, 2008, 2009 and 2010), Porvoo (2010), Tampere (2008 ad 2009) and Kerava (2008 and 2009). It is the most extensive study undertaken in Europe. The street cleaning departments used different combinations of brushing, vacuum sweeping and pressure washing, and different frequency of treatment making analysis of the data difficult.

The first phase of the KAPU project found that the efficacy of cleaning is not only dependent on the efficiency of the cleaning equipment but also on the frequency of cleaning and the amount of road dust. In early spring there is a significant amount of road dust due to the use of studded tyres and the application of traction sand in winter. At this time of the year, following cleaning, PM\textsubscript{10} emissions often return to the pre-cleaning level or even above after one or two days. Later in spring, when road dust loads are lower, the effect of cleaning lasted longer. The “summertime clean” road surface could not be achieved with one single cleaning in early spring.

The effect of using pressurised washing on PM\textsubscript{10} emissions from the street surface was tested. Emission levels were found to be 15–60\% lower after washing than before. The effect was found to be highest immediately after treatment, and to be dependent on the water pressure and volume of water used, and the orientation of the nozzles in the pressure washer.

The study also assessed the efficacy of using PIMU, which is described as a scrubber with captive hydrology, that latter being a British technology developed in the 2000s to clean airport runways. In this system high pressure washing removes dust and debris from the street surface, which together with the water forms a liquid sludge, which is removed from the surface into the machine by a strong vacuum. This equipment is used in the towns of Vantaa and Lakaisutekniikka. In early spring 2008 and 2009 street surface emission measurements were conducted with the SNIFFER vehicle during spring cleaning in Tikkurila area of Vantaa. Measurements were conducted between late March and early April. In the spring 2008 street
PM$_{10}$ emissions were measured on four days before cleaning and the following three days. After cleaning the emissions dropped on most cleaned streets, while emissions on some uncleaned streets remained at similar levels or increased. On average the PM$_{10}$ emission level was halved and remained approximately constant for several days after cleaning. However, the emission levels did not drop down to the summertime level. In spring 2009 further measurements were conducted, but over a slightly longer period, and after the initial cleaning of the streets using mechanical broom sweepers and vacuum sweepers at the beginning of March. The study found that PM$_{10}$ emissions had decreased at all the cleaned streets except one, however the reductions were less than in 2008 and did not last as long. The authors suggested that the difference was due to the lower street emissions of PM$_{10}$ in 2009. They concluded that PIMU can reduce street PM$_{10}$ emissions but its efficiency reduces when the road is cleaner. This work was continued in the REDUST Project. Results from measurements taken between 2008 and 2012 show the street dust level determines the efficiency of cleaning with the PIMU and the duration of the effect. Tests were also undertaken with a vacuum sweeper. The results are shown in SNIFFER measurements in Riihimäki (a town north of Helsinki) showed the impact of a large construction site and wide unpaved areas on PM$_{10}$ emissions during the summer. In the northern part of the measurement route in Riihimäki, there are unpaved streets crossing the route. It was observed that some dust spreads onto the route from these unpaved streets. The PM$_{10}$ emissions from different lanes and driving directions were compared, and it was concluded that dust was transported from the streets adjacent to a major construction site by construction and other traffic. When the construction works had finished, the emission levels were no longer elevated on the adjacent streets. The effect of this construction site was especially significant as it occurred in the summer when the spring street dust levels had declined. The authors concluded that the dust emissions from construction sites depend on the type of construction, how much dust is spread around by construction traffic, and the type of cleaning undertaken on the construction site (Kupiainen et al. 2011).

**Table 3.** This suggests that street cleaning will only be effective where there are high street dust levels, and street dust is a dominant source of PM$_{10}$.

SNIFFER measurements in Riihimäki (a town north of Helsinki) showed the impact of a large construction site and wide unpaved areas on PM$_{10}$ emissions during the summer. In the northern part of the measurement route in Riihimäki, there are unpaved streets crossing the route. It was observed that some dust spreads onto the route from these unpaved streets. The PM$_{10}$ emissions from different lanes and driving directions were compared, and it was concluded that dust was transported from the streets adjacent to a major construction site by construction and other traffic. When the construction works had finished, the emission levels were no longer elevated on the adjacent streets. The effect of this construction site was especially significant as it occurred in the summer when the spring street dust levels had declined. The authors concluded that the dust emissions from construction sites depend on the type of construction, how much dust is spread around by construction traffic, and the type of cleaning undertaken on the construction site (Kupiainen et al. 2011).
Table 3: Efficiency of Street Cleaning to Reduce PM$_{10}$ Emissions Measured Using SNIFFER (REDUST, 2014)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Street dust before treatment (µg m$^{-3}$)</th>
<th>Treatment day/1 day after</th>
<th>2 days after</th>
<th>3 days after</th>
<th>4 days after</th>
<th>5 days after</th>
<th>6 days after</th>
<th>7 days after</th>
<th>8 days after</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIMU</td>
<td>Over 6500</td>
<td>-40%</td>
<td>-30%</td>
<td>-20%</td>
<td>16%</td>
<td>-12%</td>
<td>-8%</td>
<td>-4%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>5500-6500</td>
<td>-35%</td>
<td>-26%</td>
<td>-18%</td>
<td>-14%</td>
<td>-11%</td>
<td>-7%</td>
<td>-4%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>4500-5500</td>
<td>-30%</td>
<td>-23%</td>
<td>-15%</td>
<td>-12%</td>
<td>-9%</td>
<td>-6%</td>
<td>-3%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>3500-4500</td>
<td>-25%</td>
<td>-19%</td>
<td>-13%</td>
<td>-10%</td>
<td>-8%</td>
<td>-5%</td>
<td>-3%</td>
<td>-0%</td>
</tr>
<tr>
<td></td>
<td>2500-3500</td>
<td>-20%</td>
<td>-15%</td>
<td>-10%</td>
<td>-8%</td>
<td>-6%</td>
<td>-4%</td>
<td>-2%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>1500-2500</td>
<td>-15%</td>
<td>-11%</td>
<td>-8%</td>
<td>-6%</td>
<td>-5%</td>
<td>-3%</td>
<td>-2%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>1000-1500</td>
<td>-8%</td>
<td>-5%</td>
<td>-5%</td>
<td>-4%</td>
<td>-5%</td>
<td>-2%</td>
<td>-1%</td>
<td>0%</td>
</tr>
<tr>
<td>&lt;1000</td>
<td>No effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum sweeper</td>
<td>&gt;1000</td>
<td>-10%</td>
<td>-8%</td>
<td>-5%</td>
<td>-4%</td>
<td>-3%</td>
<td>-2%</td>
<td>-1%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>&lt; 1000</td>
<td>No effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Measured using SNIFFER, a vehicle mounted monitoring system, with the air inlet 7cm from the road surface (Pirjola et al. 2009).

Lake Tahoe Basin

Virtually all studies of the effectiveness of street cleaning on PM$_{10}$ emissions from street surfaces have been undertaken over relatively short periods and over a limited geographical area. This study has been included in this report, despite being from outside Europe, because it is the only long term study that the authors are aware of. Zhu et al. (2012) studied the effectiveness of control measures, including street sweeping, to reduce road dust emissions using data collected over one year using a mobile sampling platform known as TRAKER and a survey of road maintenance practices in the Lake Tahoe Basin of Nevada and California. This study found that street sweeping is effective at controlling dust emissions from roads, but that secondary and tertiary roads are a continuous source of material for adjacent high-speed roads in the winter time. The authors concluded that controlling emissions requires all roads be swept after snow storms to recover the applied abrasive material.
6 MUNICIPALITIES EXPERIENCE

Less well documented and difficult to identify is the experience of local authorities in northern and central Europe in adopting street cleaning and washing to reduce ambient PM\textsubscript{10}/PM\textsubscript{2.5} concentrations.

6.1 North Rhine Westphalia, Germany

The Environment Agency of North Rhine Westphalia was one of the first European organisations to sponsor a study of the effectiveness of street cleaning to reduce PM\textsubscript{10} emissions (John et al., 2006). The study, in Corneliusstraße, Düsseldorf, was undertaken in 2004-5 and concluded that flushing the road with a pressure jet once a week could reduce daily mean PM\textsubscript{10} concentrations by 1.5 - 2 µg m\textsuperscript{-3}. From June 2005 twice weekly washing took place. This work concluded that on days with cleaning, undertaken in the early hours of the day, the reduction was in the range 0.6 to 5.8 µg m\textsuperscript{3}, with an average reduction of 1.8 µg m\textsuperscript{3}, equivalent to reducing the annual mean by 0.3 µg m\textsuperscript{3} with weekly flushing, and about 0.5 µg m\textsuperscript{3} with twice weekly flushing. On dry days the average effect of the street cleaning was 2.9 µg m\textsuperscript{3}. After 24 hours about one third of the initial concentration was reached. Since the limit value exceedences occur generally on a weekday and not on weekends, it was concluded that street cleaning should take place on 2 or 3 weekdays. It was noted that during episodes of high PM\textsubscript{10} pollution the contribution of secondary particles increases, and that rainfall was more effective than street washing at reducing ambient PM\textsubscript{10} concentrations. Also the authors note that the small improvements are within the measurement uncertainty.

The City of Dusseldorf takes account of the role of undeveloped/unpaved land in contributing to road dust in its street sweeping levies. Sweeping takes place once or twice a week, depending on the road. Owners and/or occupiers of undeveloped land adjacent to the road are required to contribute to the cost according to the following fee schedule set out by the City. The city contributes about 25 percent of the cost of street cleaning from the general budget, the rest is paid for by these levies. The rates per metre for weekly cleaning in 2015 (AWISTA, 2015) are as shown in Table 4.

**Table 4: Street Cleaning Charges for Undeveloped Land**

<table>
<thead>
<tr>
<th>Type of cleaning</th>
<th>Fee ( €/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only road cleaning</td>
<td>3.64</td>
</tr>
<tr>
<td>Roadway and sidewalk cleaning</td>
<td>7.92</td>
</tr>
<tr>
<td>Harsh cleaning</td>
<td>12.91</td>
</tr>
<tr>
<td>Self-cleaning sidewalks</td>
<td>3.41</td>
</tr>
</tbody>
</table>

The City of Dusseldorf/AWISTA do not wash the streets to control PM\textsubscript{10}. The only communities in North-Rhine Westphalia that use street washing are in Wartein and Elsdorf/Niederzier where road washing occurs close to a stone quarry and an open cast coal mine respectively (Brandt, 2013).
6.2 Other German cities

The German Federal Highway Research Institute has compiled a database of emission control methods adopted in towns and cities across the country. Over 50 cities include some form of street cleaning in this database, although details are sparse.

6.3 Bootle, Merseyside, UK

Sefton Council in Merseyside have declared an air quality management area (AQMA) due to high concentrations of PM$_{10}$ in Millers Bridge, Bootle. It is adjacent to a number of sites that generate PM from industrial processes as well as goods vehicles. This can be deposited on the road and pavement surfaces in these areas and re-suspended. The Council received funding from the UK government to investigate the impact of street washing on PM$_{10}$ concentrations from April to December 2010 and 2011.

A programme of manual ‘digging out’ and washing of pavements and more intensive sweeping of the roads was developed. Manual washing of the pedestrian pavement and highway surface at the Millers Bridge AQMA was conducted by the Council’s Operational Service department. To take account of the variation in concentrations due to meteorological conditions the ratios of daily mean PM$_{10}$ concentrations measured in the AQMA (Millers Bridge monitoring station) to an urban background site (the former St Joan of Arc School), both in Bootle, were compared for the same period prior to and during the cleaning periods. This trial has indicated reduced PM$_{10}$ levels during both the 2010 and 2011 spring/summer months.

Figure 4 shows the ratio of the daily mean concentrations measured at the Millers Bridge roadside and former Joan of Arc School (background) monitoring stations.

Although the difference has not been quantified it can be seen from the figure that the control (blue line) is generally higher than the red line when the street cleaning took place (Mahoney, 2013).

Figure 4: Millers Bridge PM$_{10}$ Daily Mean Ratio 2009 vs 2010 and 2011

6.4 Nijmegen, Netherlands

Measurements performed in 2006 in the Dutch city of Nijmegen showed that the coarser fraction contributes most to ambient PM$_{10}$ concentrations, and is also subject to greater local variation. It was found that PM$_{10}$ levels decrease by as much as 4-5 μg/m$^3$ during rainfall.
The effectiveness of wetting and cleaning of porous asphalt concrete (PAC) and dense asphalt concrete (DAC) was examined. Owing to local sources of particulate matter within the vicinity of the trials, some of the results were difficult to explain.

The following preliminary conclusions were drawn:

- The PM$_{10}$ concentrations alongside a section of a road with a new PAC surface were lower (by 8 μg m$^{-3}$ at 10 m from the road) than alongside the section with an old DAC surface.

- Cleaning the PAC had a positive impact on PM emissions.

- Spraying water on the DAC surface had a beneficial impact on particulate emissions. It was estimated that treating the entire road would result in an estimated reduction in PM$_{10}$ of 4 μg m$^{-3}$ immediately after spraying.

The weather during the trials was dry and hot, and was not representative of an entire year. Given the limited nature of this trial, no conclusions could be drawn regarding the impact on annual average concentrations. However, the results were evidence that the use of PAC surfaces and road-cleaning both have a positive effect (McCrae, 2009).
7 CONCLUSIONS

There remain a relatively small number of studies of the impact of street sweeping and washing on ambient PM$_{10}$ concentrations in Europe. Most studies have been limited spatially and temporally. The road sweeping studies have generally shown no effect when the uncertainties of the measurements are taken into account. The one widespread and long term (one year) study, undertaken in the United States, showed benefit of road sweeping in reducing road PM$_{10}$ emissions but it required all roads to be swept after the application of abrasives following snow storms.

The evidence on the effect of road washing, either alone or in combination with sweeping, is more positive with most studies showing a reduction in ambient PM$_{10}$ concentrations. This may be due to the water reducing the release of PM$_{10}$ into the air rather than removing dust from the road surface.

Most of the evidence of a benefit of street cleaning (sweeping and/or washing) comes from areas where road dust loadings are particularly high due to the use of winter tyres/tracking sanding (e.g. Finland) or near industrial sources (e.g. in Bootle, UK and Hamilton, Canada), and major construction sites (e.g. Finland).

A study of street dust loads after rainfall found that the buildup of small particles (less than 10 µm) was three times faster in Spain than in the Netherlands. The authors suggested that frequent moistening of roads might be more effective than intensive occasional cleaning to reduce dust emissions in southern Europe (Amato et al., 2012).

A preliminary trial of a prototype road sweeper suggests that new technologies are being developed that might have improved ability to remove PM$_{10}$ from road surfaces and reduce ambient concentrations. A PM$_{10}$ certification scheme for road sweepers is operated by an European trade organisation but does not appear to be able to differentiate the best sweepers from those that perform less well. This may be due to the criteria used by the scheme. A German test procedure appears to be better at differentiating between sweepers.

There is some evidence that vacuum road sweepers can increase PM$_{10}$ emissions. To overcome this some manufacturers are using filter bags to reduce the PM$_{10}$ emissions from the air outlet of the sweepers.

One road sweeper with a Patented Gore-Tex bag filter performed well in the VDI and real-world tests, suggesting that technology is available that can effectively reduce emissions. This is not a traditional vacuum sweeper, and is described by the manufacturer as a mechanical suction sweeper.

Further real world tests of a range of sweepers, as well as tests over a large area are required to increase understanding of the effects of street cleaning on PM$_{10}$ emissions, ambient concentrations and whether it can play a role in reducing exceedences of the daily PM$_{10}$ limit value.

Most to the European studies have been undertaken in Scandinavia where road dust loads are high in spring and the temperatures are moderate. In the Mediterranean countries
8 REFERENCES


Diedrich F., 2013. EUnited Municipal Equipment, personnel communication.


Wiemann J., Dulevo International Spa, personnel communication, 19th July 2013.
