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The scientific basis of street cleaning activities as road dust mitigation measure

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INDEX

1. INTRODUCTION

Road dust emissions increase considerably PM concentrations in urban air, causing exceedances of the air quality standards for PM10 (2008/50/EC), and related health effects also due to the high content of heavy metals and carbonaceous compounds.

This review is the result of the compilation of the available scientific documents reporting results on the effectiveness of road sweeping and washing activities in reducing PM emissions due to road dust resuspension. This document is aimed to gather all available and relevant information (often not in English), and divulgate them among relevant stakeholders. The present report is updated to October 2013.

1.1. Road dust contributions on PM levels

With respect to the impact on air quality an important geographical variability has been observed.

In Scandinavian countries, a high road dust contribution in PM10 is recorded as a consequence of road sanding, salting and the use of studded tires in winter months (Norman and Johansson, 2006; Tervahattu et al., 2006; Areskoug et al., 2004). Such emissions generate very large quantities of coarse particles by enhanced pavement abrasion and mechanical fragmentation of traction sand grains (Kupiainen et al., 2005 and 2003). Measurement of road dust emission potentials after road sanding on dry roads indicated a 75% increase in PM10 emissions after 2.5 h. This effect was short lived and emission potentials returned to their pre-sanding levels within 8 h of the sand application (Kuhns et al., 2003). Hussein et al. (2008) stated that as compared to friction tires, studded tires may increase the road dust resuspension by a factor of 2.0-6.4. Kantamaneni et al., (1996) found that the addition of traction material increased road dust emission factor from 1.04 to 1.45 g veh^{-1} km^{-1}. Moreover, when roads were sanded, the correlation found between emission factors and relative humidity, was not observed. Concerning road dust contributions Swietlicki et al, 1996 estimated that road dust source was explaining 32 and 54% of the variance of PM10 and PM coarse levels in the city of Lund (Sweden) during spring. In Copenhagen Wahlin et al. (2006) estimated by means of COPREM receptor modelling, that road dust resuspension accounted for 8 $\mu g\ m^{-3}$ of the kerbside PM10 mass, while motor exhausts reached 6 $\mu g\ m^{-3}$. Such difference was even greater for particles in the coarse size fraction. In a number of studies from Scandinavia, vehicle exhaust emissions have been found to contribute only around 10% to traffic related PM10 emissions, with much of the remainder accountable for by resuspension (Forsberg et al., 2005; Omstedt et al., 2005).

In dry climates such as South European countries, the low and infrequent precipitations hamper the wash-out or the moistening of road surface, favouring road dust resuspension. Moreover additional inputs of dust come from the urban soil resuspension due to the little vegetal covering and from sporadic intensive deposition of Saharan dust outbreaks or construction/demolition activities.

The experimental evidence is given by the higher suspended PM10 mineral matter at the urban areas of Southern Europe as compared to Central Europe (Amato et al., 2010a, Putaud et al., 2010 and 2004; Perez et al., 2008; Rodriguez et al., 2007; Ariola et al., 2006; Marelli et al., 2006; Querol et al., 2004b, 2001 and 1998). In a comparative study between European sites, Querol et al. (2004b), highlighted that in Central Europe, the mineral contribution increases from 3-5 µg m^{-3} from urban background sites to 4-7 µg m^{-3} at kerbside sites. In Spain the increase found induced by traffic resuspension was much higher: from 10 to 16 µg m^{-3}. In Sweden the mineral aerosol accounts for 7–9 µg m^{-3} in urban background but increases dramatically to 17–36 µg m^{-3} at the traffic sites, as a result of the sanding and salting of roads during the winter and spring period and the use of studded tires. Consequently, the local road dust emissions account for up to 9–24 µg m^{-3} in Sweden, 6 µg m^{-3} in Spain and for 1–5 µg m^{-3} for the rest of countries studied: England, Switzerland, UK, Germany and Austria. These differences in levels of crustal components may be attributed largely to the higher dust accumulation and resuspension effect during dry conditions in the southern EU countries, whereas higher rainfall in the central European countries may help to clean the road dust from streets or to maintain surface wet.

The application of receptor models permitted to better quantifying the contribution of road dust emissions. At the urban background of Barcelona Amato et al., 2009a applied a constrained positive Matrix Factorization (PMF) (by means of the ME-2 program) revealing that road dust emissions were responsible in average of 16% of PM10 concentrations. An interesting outcome of this study was that the contribution did not change over the five years of study, contrarily to industrial emissions for example (Amato et al., 2009a). The same ME-2 approach was followed by the US EPA that implemented it in EPA PMF v5.0 (of soon release). In Madrid (Spain) similar contributions from vehicular exhaust and road dust emissions (31% and 29% respectively) to kerbside daily PM10 measurements were estimated by PMF (Karanasiou et al., 2011) over one-month measurements. In Greece, Karanasiou et al., (2009) resolved road dust, motor exhaust and a soil factors by coupling PMF2 and PMF3 models on multiple size in Athens, estimating the road dust contribution between 12 and 34% of PM10. Manoli et al., (2002) applied in Thessaloniki (Greece) multiple regression on absolute principal component scores estimating that road dust was responsible of 28% and 57% of PM10 and coarse PM respectively.

Central Europe experiences the lowest road dust contributions due to the wet climate and the absence of studded tires. This low “signal” hampers the task of quantifying road dust contribution. In Germany, Beuck et al., (2011) estimated the contribution to PM10 from road dust in 2.4 ug/m3 (8%) and 0.3 (2%) at the urban and regional background sites respectively. In Stuttgart non-exhaust emissions from road traffic are estimated to be about twice as high as exhaust emissions (Ingenieurburo Lohmeyer 2004). Bukowiecki et al. (2010) have analysed the traffic related emissions (through trace elements, BC and nitrogen oxides) at a heavily congested street canyon in Zürich and assigned 21% of the traffic related PM10 emissions to brake wear, 38% to road dust and 41% to exhaust emissions. Astel (2010) could distinguish road dust contributions from those of soil and vehicular exhaust in Cracow and Vienna by combining several models (CMB, PCA-APCS, PMF and UNMIX).

Thorpe et al., (2007) proposed the roadside incremental concentration of coarse particles above the urban background as a first estimate of the sum of source strength road dust resuspension and the coarse fraction of wear emissions. Other studies succeeded in separating different traffic emissions by means of multivariate receptor models applied to PM size distribution data (Harrison et al., 2011; Gu et al., 2011). Harrison et al. (2012), estimated in London a road dust contribution of 38% to the $PM_{1\text{-}10}$ roadside increment, by combining metals size distribution and tracer concentrations in emission profiles.

1.2. Impact of road dust emissions on health

Brunekreef and Forsberg (2005) concluded in a review of a number of epidemiological studies that 'there is some evidence for effects of coarse PM on mortality, mostly in arid regions'. Transition metals embedded in road dust, such as Cu. Fe, Mn, Ni and Ti contribute to the oxidative capacity of PM (Prahalad et al., 1999; Clarke et al., 2000). Valavanidis et al. (2005) demonstrated that redox-active transition metals act synergistically with redox cycling quinines and PAHs to produce reactive oxygen species, and that particularly ferrous ions in PM play an important role in the generation of hydroxyl radicals. Schlesinger et al. (2006) indicated that transition metals such as Cu, Zn, Fe, Ni, Cr and Mn, which may act as redox compounds, are likely related to PM toxicity.

Moreover coarse particles can elicit inflammatory effects (Schins et al., 2004; Schwarze et al., 2007). Association between high levels of coarse man-made particles and daily mortality in Barcelona (Spain) has been shown by L. Perez et al. (2008) who also found a worsening during outbreaks of Saharan dust. In a more recent work L. Perez et al. (2009) found that cardiovascular and cerebrovascular mortality were associated with increased levels of both PM_1 and $PM_{2.5–10}$. De Kok et al. (2006) found a positive correlation between the cytotoxicity of TSP and the sum of transition metal concentrations. A recent study in Sweden, found that PM_{10} generated by erosion of road pavement by studded tires provoked an inflammatory responses in cells as potent as the response caused by diesel particles (Gustafsson et al., 2008). Comparisons of six European cities (Jalava et al., 2007, 2008; Happo et al., 2007) evaluated the cytotoxic and inflammatory activities of atmospheric PM in contrasting air pollution scenarios. Coarse particles showed higher inflammatory effect than the other PM size fractions, especially in Southern Europe. This high activity for these samples was attributed to the lack of rain, which may account for the poor washout of road dust and the consequent accumulation of coarse PM (with high levels of brake pads metals) on the road pavement.

2. ROAD CLEANING ACTIVITIES

In order to reduce road dust emissions either preventive or mitigating strategies can be adopted. Preventive strategies aim to avoid dust deposition in the first place, such as paving the access to unpaved lots, covering truck loads, or road traffic restrictions. Mitigating measures attempt instead to remove or bind those particles already deposited. This document provides a comprehensive review of studies analysing the effect of road sweeping and washing (separately or combined) on reducing emissions and PM concentrations in ambient air. However, there is a general dearth of information on the effectiveness of road cleaning activities in reducing road dust emissions and on air quality improvement.

A few municipalities, before establishing street cleaning as PM abatement method, ordered apposite evaluation studies (Regierungspräsidium Stuttgart, 2005; Düring et al., 2004, 2005, 2007; John et al., 2006, Baumbach et al. 2007), but in the majority of cases such information is provided only to the municipality, in the native language and is rarely available on internet. Aware that some possible extra information (from industry for instance) available is not covered by this review, the general objective of this document is reviewing the current state of the art on the effect of street cleaning in the abatement of PM emissions, identifying the best available techniques and practices. Moreover, it is necessary to stimulate and intensify mutual exchange of experiences between European cities on investigations on sources of PM_{10} pollution, as well as on development of effective control strategies (Lenschow et al., 2001).

Street sweeping, either manual or mechanical, has been a normal operation for most municipalities for hundreds of years with aesthetics and sanitation purposes. Therefore investigation on street sweepers efficiency have been focused on the minimization of transport of pollutants (PAH, metals) to receiving waters. Currently, street sweeper types fall into three main categories: mechanical broom, vacuum-assisted broom and regenerative-air units. Schilling (2005) provides a list of sweeper manufacturers for US, available models and common specifications for such equipment. Vacuum-assisted and regenerative air sweepers are generally better than mechanical sweepers at removing finer sediments, while mechanical sweepers are better at removing larger debris (FHWA 2007).

Street washing has been considered by several studies as a method able to reduce the mobility of dust load deposited on street surfaces and therefore being a potential effective measure for abating dust resuspension (Amato et al., 2009b; Chang et al., 2005; Bris et al., 1999; Gromaire et al., 2005; Dobroff, 1999). Street washing normally uses pressurized (non-drinking) water. Water flushing can be integrated in a street sweeper or manually applied by means of hoses. Water flushing can be expected to reduce particle resuspension by transport particles into the curb or by simply increasing their aggregation while the road surface is still wet. When water adheres to deposited particles, it increases their mass and surface tension forces, decreasing the likelihood of suspension and transport, especially as cohesion of wetted particles often persists after the water has evaporated due to the formation of aggregates (Watson et al., 2000). Gromaire et al., (2000) found that the for solid sediments and soluble organic matter removed on a daily basis from street surfaces by street cleaning waters was similar to that removed during one rainfall event. However, this effect was five times lower for heavy metals. In any case, the proportion of removed dust load vs the starting one was very low.

3. METHODOLOGICAL APPROACH FOR REVIEW

In Science Direct, Scopus and Google Academic, we searched for publications on street cleaning and dust suppressant studies in combinations with the search terms: effectiveness, sweeping, washing, road dust, air quality, fugitive emissions, mitigating, and benefits. As we aimed to review the effectiveness both on ambient PM samples and on road dust load, results from studies evaluating efficiency of street sweepers and water flushing effect were also included. However, the main contribution to this review came from the personal awareness of authors about any kind of related reports, often not in English, ordered by local authorities and aimed to the municipalities. Studies evaluating efficiency of street sweepers in removing trash, litter and debris, which are clearly perceived and easily removed, were excluded. However, basing on this methodology some relevant information might be still missing (reports not available, experts not in the list of authors).

4. EFFICIENCY OF CLEANING ACTIVITIES

An important distinction must be made between efficiency in reducing emissions (either by binding or removing particles from road) and reducing ambient air PM concentrations in the vicinity of the road. It is noteworthy that observing a reduction in emission (dust loading, mobility of dust, emission factor, potential or strength) does not imply that a reduction in ambient PM levels is also observed. Meteorology and other sources contribute largely to the PM concentrations and their variability measured at the receptor. Therefore it is important to remark that, observing no reduction in PM levels does not mean that emissions have not been reduced, mostly if the share of abated emissions is little compared to total emission impacting the receptor. Several methodologies can be applied to favour the “detection” of PM abatement such as:

- Concurrent PM measurements at control sites;
- Studying only the local contribution to PM10;
- Conducting tests in environments where resuspension is an important source;
- Normalizing PM concentrations by NOx, Black Carbon or other tracers of motor exhaust emissions;
- Chemical characterization of PM samples;
- High time resolved measurements.

However, most studies focused only on one type of effectiveness, either on the emission rate or on the ambient air PM concentrations.

4.1. Efficiency in emission reduction

Efficiency in emission reduction can be expressed as the fraction, with respect to the pre-cleaning conditions, of:

- Dust load mass (total or micrometric fraction)
- Dust load mobility (total or micrometric fraction)
- Emission factor
- Emission potential (or strength)

Analysing the effect on total sediments (rather than on the fraction <10µm) could apparently go beyond the interest of air quality, given that the total mass is dominated by coarse non-resuspendable particles. However, the fact that finest (micrometric) particles originate also from the cracking of coarser particles, may imply also air quality benefits.

4.1.1. Sweeping

Currently the most common types of sweeping vehicles are the following:

Mechanical broom sweepers remove debris by sweeping material with gutter brooms rearward into the path of a pick-up broom. The pick-up broom sweeps the material moving it upward with a conveyor system into a hopper. These are generally used for gross pollutant pick-up, not chemicals (soluble) adsorbed onto sands and silt particles (mean aerodynamic diameter <75µm).

Vacuum sweepers were developed in the last two decades in an attempt to remove the large and small materials within typical pavement structure. These units will have gutter brooms and strong vacuum head(s) for picking-up both large and small materials. While some models use water as a dust suppressor, others can operate in a dry mode.

Regenerative-air sweepers attempt to increase the removal of both large (not resuspendable) and small (resuspendable) materials on typical pavement with cracks or uneven sections where sediment would become lodged. To capture sediments, these sweepers are equipped with gutter brooms and a pick-up head. The gutter brooms direct materials towards the pick-up head. The regenerative-air process blows air into one end of the horizontal pick-up head and onto the pavement dislodging materials entrained within cracks and uneven pavement. The other end of the pick-up head has a suction hose that immediately vacuums out the materials within the pick-up head into a hopper.

The University of California was pioneer in evaluating the PM_{10}-efficency of different street sweepers and several further tests were conducted as part of the NURP directed by the EPA. Pitt (1979) considered different street textures and conditions, multiple passes, vacuum-assisted, and two types of mechanical street cleaners, a wide range of cleaning frequencies and effects of parking densities and parking controls. Pitt and Shawley (1982) considered street slopes, mechanical and regenerative-air street cleaners, and several cleaning frequencies. From both studies, very few differences resulted in performance between regenerative-air and standard mechanical street cleaners. In Washington, NURP tests (Pitt, 1985) considered mechanical, regenerative-air, and modified regenerative-air street cleaners, different cleaning frequencies, street textures in a humid and clean area (much lower dust loads). The improved performance was much greater for finer particle sizes, where the mechanical street cleaner did not remove any significant quantities of material. The larger particles were removed with about the same effectiveness for both street cleaner types. Several tests in Nevada (Pitt and Sutherland, 1982), Illinois (Terstriep et al. 1982) and Wisconsin (Bannerman et al. 1983) considered different land-uses, street textures, equipment speeds, multiple passes, full-width cleaning, vacuum and mechanical street cleaners in an arid and dusty area and also spring clean-up in snowy areas.

Basing on the NURP findings, a testing protocol to certify sweepers for PM_{10} emissions was developed and local governments were required to replace existing sweepers with PM_{10} efficient models (Public rule 1186, SCAQMD, 1999). The protocol purpose was to assure that PM_{10} efficiency included both the sweeper's ability to remove typical urban street loadings and limit the amount of PM_{10} entrained during the sweeping process (SCAQMD, 1999). Achieving the entrained PM_{10} materials requirement is provided by the filtering mechanism on-board each sweeper. Thus having PM_{10} certification means a sweeper has achieved the 80% pick-up efficiency on the test track and entrained PM_{10} particles are filtered adequately to not exceed the 200 mg/m requirement based upon the ambient particulate air monitors. Generally all brands of street sweepers in use today in US and Europe have achieved PM_{10} certification (Schilling et al., 2005), even if some models do not include it in the start price and to some authors the certification method is questionable (van Breugel et al., 2005). Some PM_{10} efficient models include also a dust controller spreading pressurized water from the head of the brooms in order to create a moistening cloud in the vicinities (15 cm height) of the swept area.

Fitz and Bumiller (2000) investigated the PM_{10} emission factors of several vacuum sweepers and one mechanical broom sweeper in a tunnel study. When estimating the PM_{10} emission factors, Fitz and Bumiller (2000), compared with the background emission consisting almost exclusively in the diesel exhaust emissions. They found that emission during operations where nearly the double than exhaust emissions, and that gasoline exhaust emissions were below detection limit.

Out of about 30 articles we found regarding efficiency in emission reduction, only a third did actually estimate quantitatively the efficiency for total or size-fractionated sediments. Table 1 resumes our current knowledge of sweeping vehicle efficiencies for different particles size bins. Generally, although sweepers effectively pick up visible material from the road surface, some studies have shown that both mechanical and vacuum sweepers are not very effective at collecting small particles. (Clark and Cobbins, 1963; Sartor and Boyd, 1972). Alter (1995) and Sutherland and Jelen (1996) pointed at the sweeper technology used as the cause of such unsuccessful results. Sutherland and Jelen (1997) employed the Simplified Particle Transport Model (SIMPTM) to predict the average annual expected reduction in total suspended solids (TSS) at two sites in Portland, Oregon. Sweepers used in their simulations included the NURP era broom sweeper, a mechanical broom sweeper, a tandem operation involving a mechanical broom followed by a vacuum sweeper and a newer technology, the small-micron sweeper. The predicted reductions in TSS showed that all of the newer street sweeping technologies were significantly more effective than the NURP era broom sweeper.

Claytor, (1999) explored the effectiveness of traditional mechanical sweepers, vacuum-assisted sweepers, and regenerative-air sweepers. Using the SIMPTM computer model, results showed the latest street sweeper technology picks up more street dirt and finer-grained particles than NURP-era sweepers. The vacuum-assisted dry and regenerative-air sweepers appeared to have the best performance.

Pitt and Bissonnette (1984) found that street sweeping equipment was unable to remove particles from the street surface unless the loadings were greater than a certain threshold amount. Such threshold has been documented also by other authors (Walker and Wong, 1999; Pitt et al., 2004). This value was found to be three times higher for a mechanical broom cleaner, most referred to in the NURP studies, compared to the regenerative air street sweeper trialled for a comparison in a study by Pitt and Bissonnette (1984). This threshold load was found to vary by particle size range.

Table 1. Summary of quantitative efficiency estimates (%) for total size-fractionated sediments. Size bins are in ranges given some differences between different studies. Efficiencies ≥50% is grey shaded.

	Mechanical broom	Vacuum assisted	Regenerative air			Mechanical and vacuum	High frecuency broom
sizes (µm)							
0 – 10	55 ↔	>90 ⌂					
0 – 40/63	15 • 57 ↔	10 ‡	-50 ‡	10-98 ▫	32 ⁻	16 †	-25 ‡
40/63 – 100/125	20 •	18 ‡	-8 ‡		94 ⁻	24 †	-15 ‡
100/125 – 250	50 •	28 ‡	10 ‡			29 †	-5 ‡
250 – 500/600	60 •	30 ‡	20 ‡			32 †	5 ‡
500/600 – 850/1,000		38 ‡	34 ‡			34 †	10 ‡
850/1,000 – 2,000	65 •	40 ‡	38 ‡			34 †	15 ‡
>2,000	80 •	50 ‡	35 ‡			43 †	18 ‡
Total sediments	19-37 †*	14-47 †*	25 ‡	52-100 ▫		31 †	
	13-53 †*	45-60 †*	50-75 ↨				
	54 ₣	30 ‡					
	5-45 ↨	31-48 ₣					
	60 ↔						

† Pitt, (1979)
‡ Selbig and Bannerman (2007) (values are extracted from a graph)
• Sartor and Boyd (1972) (efficiencies grew with the number of passes)
⁻ Minton et al.,(1998)
₣ Clark and Cobbins (1963)
Sartor et al. (1972)
Pitt and Amy (1976)
↨ Duncan et al.,(1985) (values depends from initial loads)
↔ Ang et al.,(2008) (mechanical sweeper with water wash and fine dust filter in the hopper)
⌂ Amato et al.,(2009) (tandem with water flushing; sampling performed the morning after)
▫ Chang et al.,(2005) (in tandem with washer)
*depending on road surface type

Sutherland and Jelen (1996) and Sutherland et al., (1998) suggested that improved efficiencies of newer street sweeping technologies (i.e. small-micron surface cleaners or tandem sweeping) employed in some American States could significantly reduce road dust load. This is a built-in tandem machine, incorporating rotating sweeper brooms within a powerful vacuum head. This machine was capable of much improved removal of finer particles from the streets compared to any other street cleaner tested, even in the presence of heavy loadings of large particles (Sutherland and Jelen, 1996). Waschbusch (2003) tested this machine at a highway test site in Milwaukee (WI) removing about half of the street dirt when the loading was about 140 kg/curb-km, and reduced to about zero near 30 kg/curb-km. The small-micron surface cleaning technology has been shown by Sutherland and Jelen (1997) to have total removal efficiencies ranging from 70% for particles <63 µm up to 96% for particles >63-70 µm, without any initial dust threshold.

Other new technologies have resulted in a significant increase of efficiency for the lowest particles size range as compared with regenerative air sweepers: High efficiency sweeper (Minton et al., 1998), street scrubbers/cleaners (Duncan et al., 1985) and Captive Hydrology technique invented in UK.

Minton et al., (1998) tested a high efficiency sweeper equipped with a strong vacuum coupled with mechanical main and gutter brooms using a dry system combined with an air filtration system (down to 2.9 µm). The pickup performance for < 63 µm range was higher (70%) than regenerative air sweeper (32%). For the > 63-70 µm particle size range instead very similar.

Duncan et al., (1985) tested the performance of an improved vacuum sweeper (ISS) for finer particles by adding partial hoods to the gutter brooms, and venting air stream through a spray venturi scrubber. The new vehicle clearly eliminated the dust plume during the sweep and increased the sediments pick-up efficiency to 80%. As compared with the regenerative air sweeper, the advantages offered by the ISS were only concerning particles smaller than 500 µm, since for larger particles the efficiency were similar. Moreover the residual sediments left by the ISS were constant, independently from the initial load. With respect to the initial PM10 load, the emission, at the head of the venturi scrubber was within 2-40%, with an average of 10%. No evaluations were made on air quality.

Captive Hydrology technique was developed to clean airport pavement surfaces (http://buyersguide.dsvr.co.uk/profiles/a/associated_asphalt/ or http://www.veegservice.nl/). The pick-up heads may include a high-pressure washer system followed by intensive vacuum pressure. Relatively small amounts of water are entrained leaving a nearly dry pavement surface. Water is recycled within the machine. Mobility is a big advantage, as cleaning can be done where and when needed. A captive hydrology machine is currently being used as the pollutant control device for the controversial Cross Israel Highway. The initial application of this technology was for airport runway resurfacing (rubber and paint removal) to increase skid resistance and industrial applications where very clean surfaces are required. The City of Olympia (Washington) has included it in its 2005 budget (Olympia, City of., 2005). However the Captive Hydrology technique has yet to be reported extensively for routine worn surfaces with cracks and uneven sections. The units have a high capital cost.

In Nevada local protocols establish to remove residual abrasive within four days following the drying out of the road surface; during one of these intervals Gertler et al., (2006) could compare emission potential before and after broom sweeping event. They found a slight increase of PM_{10} emissions after the road sweeping. For $PM_{2.5}$, there was a more dramatic increase after sweeping (from 133 to 211 mg/km). These results are consistent with the study conducted in Idaho by Kuhns et al. (2003), where the authors found by means of TRAKER (testing re-entrained aerosol kinetic emission from road) an unexpected mean increase of 16% of emission potential after a road sweeping and vacuuming (Table 2), even if authors indicated a possible displacement of dust, from the curb to the active lane, induced by the sweeper. They outlined the importance of considering, beside a negative effect on the short term, a long term effect of sweeping. Indeed although the sweepers are ineffective for reducing PM10 road dust emissions in the short term, it may be premature to conclude that street sweeping has no effect on the urban scale PM10 emission inventory. If street sweeping can remove large particles, that may evolve into PM10, then sweeping may have a beneficial effect on air quality over the long term. This mechanism, not examined by the studies reviewed, should be studied since it may have important implications for the effectiveness of street sweeping programs in PM10 emission reduction.

More recently VTI (2012) tested three different cleaning vehicles at two locations in Sweden: central Stockholm and Barkarby airport. The three vehicles were:

- Sweeper A, which could be used with or without water and used water in the city trials.
- Sweeper B did not use water, but only high pressure vacuuming assisted with a curb brush.
- Sweeper C (only used at the airstrip experiment) uses high pressure water cleaning combined with vacuuming.

Concerning the removal efficiency of dust load, tests at Barkarby showed that sweeper B, under dry conditions (sweeper A was deleted) managed to clean up an applied material to about 85–95% (slightly lower for material <10µm). In moist conditions (sweeper B was deleted) the efficiency of sweeper A was slightly over 40% for the entire material, while significantly lower (approx. 5%) for material <10µm. Sweeper C, which only took part in the moist test, cleaned approximately 99% of the applied material and the efficiency for material <10µm was the same.

4.1.2. Street washing and rain

On paved roads the sediment removal efficiency of the water jet cleaning alone was investigated only in Paris (Bris et al., 1995; Gromaire et al., 2005). Bris et al., (1999) investigated the effect of street washing on heavy metal and aromatic hydrocarbon load. Both dry and wet vacuum sampling procedures have been applied being the wet one coupled with injection of water and the hand-brushing of the surface. Although solids cleaning efficiency was highly variable 20-65%. and somewhat higher for particles larger than 100 µm, particulate metal cleaning efficiency is even more variable 0-75%; and particulate PAHs appear not to be significantly removed. Again in Paris, Gromaire et al., (2000) analysed the suspended solid and heavy metal load both in street runoff and street washing waters before and after rain and street cleaning events. The samples were not street dust, but the residual street waters. They found only a limited effect of street cleaning on abating runoff pollutants. Even if this effect was similar to a rainfall event, the picked-up load of suspended particles and organic matter was nevertheless far less to the total mass of pollutants stored on the street surface.

More information can be found in studies evaluating the impact of *rain events* on road dust loading, assuming that road washing has an effect similar to precipitation, as found by Gromaire et al., (2000). Amato et al, (2012 and 2013) investigated the recovery rates of road dust particles (fraction <10µm) and components after rain events in Spain and the Netherlands. They found that, regardless of rain amount, the average recovery of road dust particles reach 99% within 24 hours in Spain and 72 hours in the Netherlands. Authors concluded the moistening effect of rain being more important than actual particle removal and that water evaporation was the main process controlling the recovery of road dust mobility. Concerning road dust components, they identified distinct recovery rates for different sources of road dust (tire wear, brake wear, mineral, motor exhaust, Amato et al, 2012 and 2013). Based on these results it can be concluded that road washing activities should be performed in the first morning hours (5-6 am), in order to abate maximally the morning peak of emissions (7-9 am).

Vaze and Chiew (2002) analysed coarse (>20 microns) road dust load after rain events in Australia concluding that build-up over the dry days occurs relatively quickly after a rain event, but slows down after several days as redistribution occurs. The surface pollutant also becomes finer over the dry days as it is disintegrated. The wash off of surface pollutant is dependent on the rainfall and runoff characteristics, but typical storms only remove a small proportion of the total surface pollutant load.

Egodawatta et al., (2007) found that the common storm (>20 mm h^{-1}) events are not capable of removing all of the build-up (total) particles. They showed that the fraction of washed-out (total) road sediments was low (10-20%) and constant for different storm intensities but of the same duration. Moreover, Herngren (2005) observed that there is no significant wash-out of pollutants beyond a threshold value of rainfall duration. Furumai et al., (2002) showed a coarser size distribution of suspended solids in run-off water than in road dust sediments.

4.1.3. Combination sweeping-washing

Some research studies have tested street cleaning protocols combining sweeping and water flushing. Ang et al., (2005) applied in Stuttgart a modified mechanical broom and water wash street sweeper equipped with fine dust filter in its hopper along the six lanes paved roadway. Efficiency in reducing the dust loads varied between 60 and 80 % depending on the particle size, lasting over one rush hour. Efficiencies were respectively 60%, 57% and 55% for total dust, PM75and PM_{10} efficiency was approximately 55%, but no details were given about the efficiency calculations.

Chang et al., (2005) experimented in Taiwan a modified regenerative-air vacuum sweeper followed by a washer. This process was effective at removing the sources of road dust particles. Two kinds of efficiency (η) were calculated: for deposited dust (η_d: 52-100%) and for deposited silt (η_s: 10-98%). Moreover they found a correlation between silt load and η_s. On the contrary traffic intensity and wind speed did not show correlation with any kind of η.

In Barcelona (Spain), Amato et al, (2009b), tested several times a street cleaning process combining a vacuum-assisted sweeper followed by manual washers (flow rate 0.95 l m^{-2}). By comparing the load of the PM_{10} fraction of deposited dust in the untreated stretch, they found high decreases (efficiency >90%) at the swept stretch of the street. The street cleaning activities were performed at night, while road dust samplings in the following mornings. This could have led to an overestimation of the efficiency given the effect of the still remaining humidity of the pavement.

There is some evidence that suggest that sweeping frequency could increase the amount of sediments removed (Pitt, 1979; Marais and Armitage, 2003 and 2004; Armitage et al., 2001; Bannerman 1999). Other factors such as number of passes, road conditions, sanding/salting, car parking, presence of construction/demolition works, unpaved areas, accumulation curve and sediment size distribution have been also studied (Pitt, 1979; Grottker, 1987; Duncan et al., 1985) and found to influence significantly the sweeper efficiencies requiring therefore consideration before any thorough assessment of street sweeping efficiency for air pollution control.

Several studies also investigated the impact on PAH, metals, metalloids and organic matter loads (Bris et al., 1999; Selbig and Bannerman, 2007; Pitt, 1979; Gromaire et al., 2000; Yee, 2005; Grottker, 1987). Grottker (1987) modelled the street cleaning efficiency for heavy metals and eight size fraction bins load. All pollution parameters except particles $<25\mu m$ and between 25-80 µm were removed with nearly the same range of efficiency. He also found that the larger the particles the higher the street cleaning efficiency, the efficiency of fraction $<25\mu m$ being negative. However the cleaning methodology was not specified. Contrarily, Yee (2005) did not find significant difference in metals abundances before and after street sweeping, neither for TSS.

4.2. Efficiency on air quality

4.2.1. Sweeping

As already mentioned, the studies on the air quality benefit induced by street sweeping are very scarce. Air quality benefits should be evaluated with respect to control sites and control periods, where and when no cleaning activities are carried out. After sweeping procedures some of these studies registered an increase in PM_{10} levels (Fitz, 1998; Norman and Johansson, 2006) or modelled an increase of the mineral contributions to PM_{10} levels (Chow et al., 1990) (Table 2). Fitz (1998) evaluated the upwind-downwind PM_{10} measurements before and after sweeping and calculated emission factors from the PM_{10} concentration differences by means of dispersion modelling. The differences found between upwind and downwind measurements were near the uncertainty of the method. In Stockholm, Norman and Johansson (2006) did not register any significant reduction in PM_{10} after intense sweeping in spring. Moreover, in most of days, PM_{10} levels were higher, with respect to a reference station. Aldrin et al., (2008) after sweeping 11 times at a Norwegian tunnel did not find any beneficial effect by means a generalized additive model (GAM) and PM_{10} and $PM_{2.5}$ measurements. In the winter 2006/07 a trial with improved street sweeping was undertaken in Berlin. Thereby all lanes were swept from Monday to Thursday with a vacuum cleaning street sweeping vehicle equipped with a particle filter. No significant reduction of PM_{10} levels on dry days was observed (Düring et al., 2007). A vacuum cleaning street sweeping vehicle with motor exhaust particle filter was also used in Stuttgart (Baumbach et al. 2007). Similar to Berlin, no significant reduction of PM_{10} levels was found.

As shown in Table 2 street sweeping may have actually an adverse effect on pollutant removal, Vaze and Chiew (2002) found that, after street sweeping, particle size distribution was finer when compared with that before sweeping. By means of receptor modelling (Chow et al., 1990) found no discernable differences in airborne mineral PM_{10} concentrations measured either during or after one 10- and one 7-day long street sweeping campaigns in a Reno, Nevada neighbourhood.

In other studies a reduction of PM concentrations was observed (Hewitt, 1981; Cuscino et al., 1983; Cowherd, 1982; Fitz and Bumiller, 1996; Kantamaneni et al., 1996), but none of these studies conclusively demonstrated the effectiveness of sweeping on reducing suspended PM_{10}. For example Kantamaneni et al., (1996) could not find any correlation between emission factor and the time passed after the sweeping event. Moreover some meteorological influence was probably the cause of these limited successes (Table 2). Meteorology and other emission sources indeed add large uncertainties to the small benefits obtained in the ambient PM_{10} concentrations (Cowherd et al., 1982; Cuscino et al., 1983).

Table 2. Summary of only those studies that investigated air quality efficiency for sweeping, washing and combinations of the two. White rows refer to sediment removal efficiency in the case this was also evaluated. Grey rows refer to air quality efficiency.

Study	Type of cleaning	Location	Cleaning method	Background assessment	Effect	Detailed effects	Estimation method	Notes
Chow et al., 1990	Sweeping	Nevada, USA						
						No discernable differences in airborne geologic PM10	CMB	Receptor modelling
Kantamaneni et al., 1996	Sweeping	Spokane, Washington, USA	Regenerative air vacuum sweeper	Upwind/downwind technique				
						Only a little decrease in PM10 emission	TEOM. Low volume samplers. SF6 as tracer to track emission rates	No correlation was found between emission factor and the time passed after the sweeping event for HR>30%
Dobroff, 1999	Sweeping/washing	Hamilton, Canada	Several combinations of mechanical, vacuum sweeper and flushing	Upwind/downwind technique	☺			
						Only the combination of vacuum or mechanical sweeping could reduce road dust contribution to PM10: 2-3 µg/m3 at kerbside	High volume samplers	No impact on a wider area
ARPA, 2003 (cited by CAFÉ 2004)	Washing/sweeping	Milan, Italy	Mechanical sweeper	1 reference site				
						No discernable decrease in PM10 due to street cleaning	Report not found; methods not specified in CAFÉ, 2004	An area of 1 km2 in the city centre was cleaned in winter-time
Kuhns et al., 2003	Sweeping	Treasure Valley, Idaho, USA	Mechanical and vacuum sweepers	Upwind/downwind technique				
						No measurable reduction in PM10 emission potentials	TRAKER vehicle used for PM10 emission potentials estimate	
Düring et al., 2004	Washing	Berlin, Germany	Water flushing	NOx and meteorology monitoring				
						No significant difference was found in PM10 levels	Continuous PM10	Trial conducted for 22 weeks
Düring et al., 2005	Washing	Bremen, Germany	Water flushing	NOx and meteorology monitoring				
						No significant difference was found in PM10 levels	Continuous PM10	Water flushing applied on 45 out of 105 days during the trial
Norman and Johansson, 2005	Sweeping	Stockholm, Sweden	Mechanical sweeper	Ratio with a reference site	☺			
						No reductions in PM10 (short term)	TEOM	In most of sweeping days an increase was observed
	Washing		Water flushing	Ratio with an untreated stretch of the road				
						6% reduction in PM10	TEOM	The verge next to the carriageway was washed
Chang et al., 2005	Sweeping/washing	Taipei, Taiwan	Modified regenerative-air vacuum sweeper and a washer	Concentration upwind subtracted to the downwind ones	☺	Dust efficiency 52-100%; Silt efficiency 10-98%		Silt load efficiency is a function of silt load
						Measurable reduction in TSP emission potentials up to 30%	ß-attenuation and high volume samplers	Short-lived effect of the only sweeper; TSP efficiency is a good function of silt load efficiency

Ang et al., 2005	Sweeping/washing	Stuttgart, Germany	Mechanical broom and water wash street sweeper equipped with fine dust filter	2 reference sites and normalization with NOx concentrations	☺	High efficiencies on several size fractions		Effect over one rush hour
						Reductions in ambient PM10 concentrations	ß-attenuation, Cascade impactors, high and low volume samplers	Evaluation not quantitative due to meteorological dilution
John et al. 2006	Washing	Dusseldorf, Germany	Water flushing	NOx and meteorology monitoring	☺			
						Reduction of 2 µg/m³ of the daily PM10 mean	Continuous PM10	Water flushing applied during several weeks in variable intensity
Yu et al., 2006	Sweeping/washing	Kaohsiung, Taiwan	Not specified	Background concentrations were modelled and corrected with yearly measurements	☺			
						All models revealed decrease in the road dust contributions (TSP and PM10)	Gravimetric samplings. PCA, CMB and ISCST3 modelling	Receptor and dispersion modelling
Gertler et al., 2006	Sweeping	Lake Tahoe, Nevada, USA	Wet and dry broom sweepers	Upwind/downwind technique				
						Deicers emit less than abrasives; Sweeping increased the PM10 re-entrainment rate	TRAKER vehicle used for PM10 emission potentials estimate	
Düring et al., 2007	Sweeping	Berlin, Germany	Vacuum sweeper	NOx and meteorology monitoring				
						No significant difference was found in PM10 levels	Continuous PM10	Street sweeping applied on 87 out of 157 days during the trial
Chou et al., 2007	Sweeping/washing	Taipei, Taiwan	Modified regenerative-air vacuum sweeper and a washer	Efficiency is averaged with an untreated area	☺	Dust efficiency 52-100%; Silt efficiency 10-98%		
						Measurable reduction in PM10 emission potentials up to 24%	ß-attenuation	PM10 efficiency is a good function of silt load efficiency
Baumbach et al. 2007	Sweeping	Stuttgart, Germany	Vacuum sweeper	NOx and meteorology monitoring				
						No significant reduction of PM10 levels	Continuous PM10	Water flushing applied on 52 days
Aldrin et al., 2008	Sweeping	Drammen, Norway	Sweeper (not specified)	Tunnel study, meteo conditions were assessed				
						No reductions in PM10 nor PM2.5	TEOM, GAM model	No definitive conclusions
	Washing		Water flushing					
						No reductions in PM10 nor PM2.5	TEOM, GAM model	No definitive conclusions
Amato et al., 2009	Sweeping/washing	Barcelona, Spain	Vacuum-assisted sweeper followed by manual washers	A mean background decrease was subtracted	☺	High efficiencies on PM10 sediments		Road dust samplings on the morning after cleaning
						7-10% reduction of daily PM10 levels	Optical counters. High volume samplers	
Keuken et al., 2010	Sweeping/washing	Amsterdam, Spain	Stainless steel brushes and vacuum cleaned. High-pressure washing	A background site was used as reference				
						No clear reduction on PM coarse levels	Optical counters	
Karanasiou et al., 2011	Washing	Madrid, Spain	4 l m-2 pressured water	A background site was used as reference	☺			
						2 µg/m3 reduction of daily PM10 levels	Optical counters. High volume samplers	
Amato et al., 2010	Sweeping/washing	Barcelona, Spain	Vacuum-assisted sweeper followed by manual washers	A mean background decrease was subtracted	☺			
						4.7 µg/m3 reduction from 12:00 to 18:00 hours	1 hour elemental composition, optical counters, high volume samplers	
Karanasiou et al., 2012	Washing	Madrid, Spain	4 l m-2 pressured water	A background site was used as reference				
						No clear reduction on PM2.5 levels	Optical counters. High volume samplers	

As in previous studies, the study from VTI (2012) showed that the sweepers' effect on the total PM10 concentrations was small (not detectable). Other sources than the local resuspension contributed to the total concentration of PM10 and these were not affected by the sweepers. In order to be able to discern the sweeper effect it was thus necessary to study only the local contribution to PM10. During especially favourable meteorological conditions, significant reductions of the local PM10 contribution up to 20% could be established. This shows that the sweepers to some extent can reduce the PM10 concentrations, but the effect is difficult to discern due to influence of other sources and meteorological factors. Since earlier measurements in Stockholm (Norman and Johansson, 2006) have indicated that sweepers can cause raised levels of PM10 due to resuspension of road dust in connection to sweeping, the emissions from the tested sweepers were studied when they passed the measurement stations. The results show obviously increasing concentrations, but the effect was short -lived and the contribution to the daily mean value (which is regulated by the environmental quality standard) was marginal. Sweeper A (wet and dry vacuum sweeping) contributed more often to increased PM10 concentrations than sweeper B (high pressure dry vacuum). On the other hand, sweeper B contributed to increased NOx emissions more often.

4.2.2. Street washing (alone or in combination with sweeping)

Road washing activities are generally performed by municipalities for sanitary and esthetical purposes. However, an improved (in frequency and/or intensity) road washing protocol has been proved to have a beneficial effect on road dust emission potential and on PM10 concentrations in cities.

Water flushing has been generally applied in combination with sweeping given that the water jet alone could hardly displace dust till achieving the sewage system, unless a large water flow is used. However, as it will be shown, recent studies demonstrated that the effectiveness of road washing is more linked to the moistening effect rather to an effective removal of particles. Generally, mechanical or manual washers go after the sweeping vehicles.

Road washing alone (without sweeping) has been almost exclusively studied on unpaved roads (Watson et al., 2000). On paved roads the air quality efficiency of street washing alone was studied only in Germany and Scandinavian countries (Düring et al. 2004, 2005; John et al. 2006; Norman and Johansson, 2005; Aldrin et al., 2008). In Berlin water flushing of a main road was performed twice on two working days and once on Saturday. No significant difference was found in PM_{10} levels on dry days with and without street washing (Düring et al., 2004). The same was found for a trial in the city of Bremen (Düring et al., 2005). Contrary to these findings a reduction of about 2 µg/m³ of the PM10 daily mean was found in Düsseldorf, where water flushing was performed twice a week in a busy road (John et al. 2006).

In Stockholm, street washing was performed to the verge next to the carriageway of a highway and only in days with favourable weather conditions (Norman and Johansson, 2006). Only during 8 days (out of 21 days) PM_{10} reductions were observed. The mean decrease was 6% and limited to morning hours, suggesting that the reduction could have been to wetting of the road surface, which reduce suspension of dust, rather than actually removing particles from the road surface. Two out of twelve exceedances of 50 µg/m^3 registered at the control station were not registered in the street washing site.

In a Norwegian tunnel study, Aldrin et al., (2008) applied PM_{10}, $PM_{2.5}$ measurements and GAM modelling to evaluate the effect of water jet cleaning, but such test was performed only twice. Although any PM decrease was found, authors could not definitively state the inefficiency of such methods, given the small number of observations.

In the rest of cases, air quality efficiency was therefore evaluated for a combination of sweeping and washing. To our knowledge only eight studies are currently available (only three were published in scientific journals). Yu et al., (2006) modelled an improvement in TSP air quality levels due to street sweeping and washing in Taiwan. Factor analysis and Chemical Mass Balance permitted to identify a decrease (28% to 17% and 51% to 17%, respectively) of street dust contribution to TSP. Model simulations showed that maximum improvement in urban annual mean PM_{10} was around 2 µg/m^3 (Table 2).

Chang et al., (2005) tested also in Taiwan combination of modified regenerative-air vacuum sweeper and a washer finding that the Sweeping/washing activity was effective at mitigating TSP concentrations; however the direct impact of street cleaning on ambient PM emissions was short-lived, lasting no more than 3–4 h. They found that the efficiency for TSP (η_{TSP}) achieved values to 30%, depending on the silt load. Indeed they found a good correlation between silt load efficiency and η_{TSP}. In the same location Chou et al., (2007), investigated the performance of the same process for PM_{10} concentrations. Even if not specified, the two studies are likely to be developed at the same time since the results obtained for dust and silt load efficiency are the same. However, with respect to the ambient PM_{10} benefit, Chou et al., (2007) found a significant efficiency varying within 0-24%. However, it is unclear why authors decided calculating the efficiency by averaging the concentration delta between the swept and the unswept areas.

In the Barcelona city centre, Amato et al., (2009b) tested the effect of a cleaning procedure consisting in manual washing after a vacuum assisted broom sweeping. Such protocol was followed during eight nights within one month in spring 2008. Averaging the daily mean concentration of PM_{10} on the 24 hours following each cleaning event and on the rest of dry days, they found a mean decrease of 8.8 µg/m^3. Given the presence of some atmospheric dilution during the same days, authors discounted the 3.7-4.9 µg/m^3 decrease registered in some of the reference stations, obtaining a net kerbside decrease within 7-10%, which was likely related to street cleaning interventions.

Also in The Netherlands (Nijmegen) a beneficial effect could also serve (http://www.ipl-airquality.nl/project.php?name=nat-reinig) even if effectiveness may vary depending on local conditions such as road pavement, meteorology and solubility of particles (Keuken et al., 2010).

The effect of the combination of washing, in this case *followed by* road sweeping, on PM_{10} concentrations was also investigated in Milan by the Regional Environmental Agency for Lombardy (ARPA) in winter 2002 on an area of 1 km^2 in the city centre during ten days. The variation of PM_{10} was studied both in concentration and composition at 2 and 25 meters and compared with a reference site outside the test area. The study concluded that even when extending the washed area, no substantial reduction in PM_{10} concentrations are obtained. The 10% decrease of PM_{10} concentration from ground to 25 meters height was not attributed to the cleaning operations (ARPA, 2003).

In Madrid, Karanasiou et al., (2011) found that during a one-month campaign, the mass contribution from the road dust source was ~2 µg m^{-3} lower during the days that street washing was implemented with this corresponding to a reduction of 15% of road dust mass contribution during the days that the road surface was left untreated. After nightly street washing, the PM10 reduction was observed during the morning hours. In the same study no effect on ambient PM2.5 was found (Karanasiou et al., 2012).

Escrig et al., (2011) tested the effectiveness of street washing on road dust deposits at one ceramic industrial cluster in Castellón (Spain), finding that due to the very high deposition rate, a reduction of road dust load was hardly detected.

In 2005, the city of Hamilton (Canada) proposed to improve street cleaning operations to abate ambient air PM levels (Dobroff, 1999). A relatively frequent combination of mechanical and vacuum sweeping with water flushing resulted in air quality improvements. The decrease of the downwind PM_{10} levels in the immediate vicinity of the road was estimated in 2-3 $\mu g/m^3$, but it was not found significant in the wide areas. Moreover either vacuum or mechanical sweeping alone did not reduce road dust contribution to PM_{10}. Already in 1979 encouraging results were obtained when a 7% decrease in TSP levels was recorded during the vacuum sweeping period (mechanical sweeping alone resulted ineffective for TSP). More recently Ang et al., (2008) evaluated the efficiency of sweeping vehicles with a modified filter for fine particles in mitigating road dust emissions. After three daily wet sweepings a reduction of ambient air PM_{10} levels was observed. However, such decrease was disturbed by a meteorological dilution which did not allow quantitative conclusions.

5. CONCLUSIONS

The results gathered in this review are rather dissimilar and an additional uncertainty is given by the different methodology used for street cleaning. Most of studies reported the type/mechanism of sweepers whilst in some others information is not detailed. The information gathered is in general available, even if some reports cannot be accessed directly on internet. Taking into account that some extra information might be available, basing on the literature used, the following conclusions can be drawn.

5.1. Emission potential

The studies relating to the efficiency of sweepers in sediments removal have yielded rather variable results, given the variety of particle size fractions and some contrasting results. In general mechanical broom sweepers can easily pick larger particles (>100-125µm) while the regenerative air sweepers are recommended for finer particles (<100µm).

Independently from the sweeper technology, sediment removal seems to improve with increasing particle sizes. When averaging all sweeping vehicles, efficiency increases with particle size from 26% to 64%, achieving the 50% threshold for particles >100-125µm. For total sediments, performances are less different, probably given that efficiencies are more affected by good performances on the larger particles (more weight). Averaging all results obtained for total sediments, the vacuum-assisted sweepers offered a mean efficiency of 41%, while mechanical and regenerative air sweepers behave better (54-57%). Such values are consistent with those obtained averaging all the particle size bins.

Although the sweeping technology is developing and improving to remove finer particles for a variety of initial loads, further certification of the vehicles is needed.

A number of factors are identified as influencing the effectiveness of street sweeping for the collection of road dust sediments. These factors include environmental conditions (climate, season), type of vehicle (sweeping mechanism), particle size and loadings, sweeping frequency and timing, surface type and moisture, parked cars among others. The effect of water jet flushing alone was studied only in two cases revealing efficiencies varying from limited (similar to a rainfall event) values up to between 20-65% and somewhat higher for particles >100 µm.

5.2. Best practices for sediment removal

From the review of a number of studies found on sediment removal performances, we can conclude that, for high loadings, it may be best to use a tandem operation, where the streets are first vacuumed-swept and then washed.

In not snowy countries, the street cleaning is recommended to be performed almost exclusively on the extreme lanes of the roadway, given that some studies demonstrated that, due to the vehicle-induced turbulence, particles are transported towards the extreme lanes, and about 90% of sediments are within 2 m from the curb (Duncan et al., 1985; Grottker, 1987; Pitt, 1979). Furthermore Pitt (1979) investigated the best practices to minimize the parking interference to street cleaning activities. Sweeping timing should be also adjusted in order to minimize such interference. The cleaning program has to be flexible and drawn *ad hoc* for the specific local conditions (works, weather, season variability). Before planning street cleaning, local authorities are recommended to develop or sponsor previous investigations in order to (1) evaluate the magnitude of the problem for a single street, (2) selecting those streets more critical for the dust load situation, (3) know the accumulation rate of sediments (i.e. how rapidly the steady state between deposition and emission is reached), and (4) determine the most effective cleaning criteria (frequency, timing etc.). In this context, analysis of rainfall statistics are also important to ensure street sweeping is compatible with the frequency of rainfall events and therefore optimize the effectiveness of street sweeping for air quality improvements.

Based on this review it can be concluded that road washing activities should be performed in the first morning hours (5-6 am), in order to abate maximally the morning peak of emissions (7-9 am).

Road washing can be proposed both as a continuous activity and as a short-term measure, to be applied in periods of droughts, and during high pollution episodes.

5.3. Reduction of ambient air PM levels

From the review of a dozen of articles, street sweeping alone resulted ineffective in reducing PMx concentrations in the short term. Beside, some sweeping vehicles produce a dust cloud for the brooms or from sweeper air discharged from the unit, although some authors (Fitz and Bumiller, 2000) considered as not significant. However along-term benefit induced by street sweeping cannot be discarded. Some studies found a decrease in ambient air PM concentrations but due to the presence of some meteorological influence they could not definitively conclude a benefit from the sweeping. Only one study could find a positive effect by means the use of multivariate and dispersion modelling (Yu et al., 2006) but water flushing (of not specified amount) was also performed, even if another similar study found the opposite (Chow et al., 1990). In any case, most of authors did not discard a positive effect on the long term, given that street sweeping has to improve the fugitive dust situation given the well documented effectiveness in removing the sediment loads. Additional study is needed to determine whether long term emission reduction can be associated with street sweeping.

When water flushing was used, alone or in combination with sweeping, more encouraging results were obtained. In the fifteen studies we reviewed, an ambient air PM10 reduction was observed in most of cases (11). However, this could result simply from the wetted condition of the surface that inhibit resuspension, rather than from the actual removal of particles. Results showed that effectiveness depends very much on the local situation. PM10 reductions were observed in Spain, Germany, Sweden, Canada and Taiwan. The reduction attributable to washing activities varied within 7-30% of the daily average PM10 concentration.

Beside the uncertainty given by different equipment and environments which can led to contrasting results, it emerges that road washing is a reliable practice to mitigate PM emission from road dust resuspension. In this sense, it is important to remark that also little PM decrements can be an indication of an effective emission reduction: in urban open-air (not tunnel) trials, the total street washing benefit of road dust emissions is probably very low when compared to the total PM emissions (traffic and non-traffic sources) in the wider urban area, and given that atmosphere is continuously mixed, great PM decreases induced by street washing are likely unexpected. No definitive quantitative estimates of street washing benefit can be today done given the scarce number of studies. More investigations and experience-exchange are needed in order to increase the number of observations and account for different types of environments. There is the objective necessity that local authorities promote and carry out specifically aimed research campaigns.

6. FURTHER RESEARCH

As previously mentioned even when sweeping vehicles were generally effective in removing sediments, no satisfactory results were obtained for the ambient PM concentrations suggesting that the emission benefit obtained was too small when compared to all emission plumes reaching the receptor. Langston et al., (2008) showed that the near term effects confound the ability to generalize on emissions reductions over urban areas where the number of streets treated may be low. Therefore authors would like to encourage street cleaning investigations on wider areas (some km^2) in order to increase the absolute emission benefit. Studies are particularly interesting in relatively dry environments, where the difference between washed and unwashed conditions can produce larger and more easily identifiable benefits. Moreover this kind of research could also yield to evaluate the benefit not only at kerbside stations but also in the urban background. There is actually only one study on the effect of a wide urban area cleaned (ARPA, 2003). Such study did not produce encouraging results, but the fact that tests were performed in a very humid city such as Milan and in winter-time must be taken into account. Moreover, the fact that washing was performed before sweeping might had a negative impact on the performance of the following sweeping.

Programming this kind of campaigns is logistically difficult for research groups and the help from local authorities is fundamental. In this sense we want to encourage and promote the co-operation between researchers and air quality managers, when planning the best practices for urban street cleaning program.

An important and still open question concerns the life-time of street cleaning efficiency. Some studies suggest a life time of few hours but there is no an exhaustive assessment of the duration of such reduction. This issue can be approached in several ways:

Directly monitoring PM (or tracers);

- Modelling road dust emissions and contributions to ambient PM (or surrogates);
- Indirectly, by comparing deposition flux and emission factor per unit area;
- Monitoring time-evolution of road dust load after a cleaning event (i.e. the time necessary to reach the steady state correspond to the time-efficiency of street cleaning);

The impact of desert dust outbreaks is also a gap of knowledge. It is known that atmospheric desert dust intrusion yields to an increase deposition, therefore it is expected that also road dust emissions increase in the hours immediately after a desert dust event. Currently there are no studies able to evaluate this impact.

For future research studies we strongly recommend the use of receptor and dispersion modelling, continuous measurements of NOx, CO, black carbon and number of particle concentrations in addition to ambient PMx and road dust load measurements which could all help for minimizing any meteorological effect, which could mask the benefit produced by street cleaning maintenance. The chemical characterization of PM and the monitoring of road dust emission tracers can be of great help for detecting emission reduction, and in this sense we would like to encourage the use of those instruments which can provide high time-resolution chemical characterization.

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