Variation of $PM_{2.5}$ concentrations in relation to street washing activities

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ABSTRACT

Several studies conducted in urban areas have pointed out that road dust resuspension contributes significantly to PM concentration levels. Street washing is one of the methods proposed to reduce resuspended road dust contributions to ambient PM concentrations. As resuspended particles are mainly found in the coarse mode, published studies investigating the effects of street washing have focused on PM_{10} size fraction. As the $PM_{2.5}$ mass fraction of particles originating from mechanical abrasion processes may still be significant we conducted a study in order to evaluate the effects of street washing on the mitigation of resuspension of fine particles. The $PM_{2.5}$ mass concentration data were examined and integrated with the occurrence of street washing activities. In addition, the effect of the meteorological variability, traffic flow and street washing activities, on ambient $PM_{2.5}$ levels was evaluated by means of a multivariate regression model. The results revealed that traffic flow is the most important factor that controls $PM_{2.5}$ hourly concentrations while street washing activities did not influence fine particle mass levels.

1. Introduction

Several studies conducted in urban areas have pointed out that road dust resuspension contributes significantly to PM concentration levels (Thorpe and Harrison, 2008). Street washing is one of the methods proposed as an abatement strategy to reduce resuspended road dust contributions to ambient PM concentrations. Street washing activities might reduce the amount of dust on the road and/or reduce their ability to suspend as the increased moisture might capture the particles on the road surface (Karanasiou et al., 2011).

The majority of published studies investigating the effects of street washing have focused on PM_{10} size fraction. However, the current knowledge about the size of particles which are emitted (in addition to the exhaust) by mechanical abrasion processes from tyres, brakes, clutches and road surfaces, is still very scarce. The impact of resuspension process is yet not entirely characterised. Previous studies in the United States have indicated that the resuspension of paved road dust contributes significantly both to PM_{10} and $PM_{2.5}$ concentrations (Schauer et al., 1996; Kleeman and Cass, 1999). Kleeman and Cass (1999) found that the entrainment of road dust from paved roads accounted for 34% of PM_{10} and 22% of $PM_{2.5}$ emissions in Los Angeles. The fact that the same study showed that exhaust emissions from on-road vehicles were responsible for 5% of all PM_{10} and 16% of all $PM_{2.5}$ illustrates the potential importance of resuspension processes. Chow et al. (1994) conducted experiments using a resuspension chamber found that $PM_{2.5}$ contributes 20% to resuspended PM_{10} paved road dust. In the study of Hildemann et al. (1991) paved road dust was the second largest source of fine aerosol organic carbon particles to the urban atmosphere of Los Angeles.

Concerning the emissions from tire and break wear previous studies state that abrasion processes not only produce coarse particles but also produce particles that lie in the fine mode. According to Lough et al. (2005) brake wear products are equally distributed in the fine and coarse mode while road/tire abrasion has significant contributions mostly in the coarse particle fraction (Hussein et al., 2008). Garg et al. (2000) recorded airborne brake wear particle mass fractions of 88% and 63% for PM_{10} and $PM_{2.5}$ respectively. Iijima et al. (2007) found that 12–36% of particle mass of brake wear particles lies in the fine ($PM_{2.5}$) mode. Thorpe and Harrison (2008) calculated that PM_{10} accounts for 98% of emitted brake wear particles, whilst $PM_{2.5}$ accounts for 39%. Berdowski et al. (1997) indicated that around 70% by mass of PM_{10} tyre wear particles can be classified as $PM_{2.5}$. Gustafsson et al. (2008) generated wear particles from studded and friction tyres running on two different pavements. The size distributions of these wear particles had a considerable (~20%) $PM_{2.5}$ fraction. Similarly, in the study of Kupiainen et al. (2005) the contribution of $PM_{2.5}$ wear particles was approximately 15% in PM_{10}.

Previously, Oliveira et al. (2010) and Ilacqua et al. (2007) have found that road dust particles along with motor vehicles' emissions are the major contributors to the measured fine particle mass. Similarly, Karanasiou et al., 2009 found that road dust contribution to $PM_{2.5}$ was 18–20% while the vehicle emissions were responsible for 27–34% of $PM_{2.5}$ mass in Athens (Greece). Consequently the $PM_{2.5}$ mass fraction of particles originating from mechanical abrasion processes and resuspension may be significant (Amato et al., 2010).

The new Directive 2008/50/EC of the European Parliament requires from the Member States to reduce exposure to $PM_{2.5}$ in urban areas by an average of 20% by 2020 based on 2010 levels. Under this new Directive it would be interesting to examine the effectiveness of PM reduction methods like street washing in relation to the size of ambient particles. To the best of our knowledge no other study reports on the effect of street washing on the $PM_{2.5}$ mass concentrations.

The primary aim of this study was to evaluate the effects of street washing on the mitigation of resuspension of fine particles, $PM_{2.5}$. The $PM_{2.5}$ mass concentration data (continuous measurements) were examined and integrated with the occurrence of street washing activities. In addition, the effect of other parameters, such as the meteorological variability and traffic flow, on ambient $PM_{2.5}$ levels was also evaluated by means of a multivariate regression model.

2. Methods

2.1. Sampling

A detailed description of the sampling procedure is given in Karanasiou et al. (2011). In brief, an intensive sampling campaign was conducted during summer 2009 (17 June–20 July 2009) in central Madrid (Spain), along one extremely busy road (Velázquez Street) at Maldonado site (Fig. 1). Velázquez Street can be characterized as a street canyon since it is surrounded by six-story buildings (typical height of ~20 m). One air pollution measuring mobile units was placed at Maldonado site equipped (among other instrumentation) one light scattering particle counter (Grimm Labortechnik GmbH & Co. KG; model 1107) set to 30 min time intervals was used for the continuous monitoring of PM_{10}, $PM_{2.5}$ and PM_1 mass concentrations. Simultaneously in Maldonado site, traffic measurements and meteorological parameters (temperature, humidity, wind speed and direction inside the street canyon) were monitored continuously.

Fig. 1. Madrid urban area with the sampling site marked. The arrow indicates the direction of the traffic flow in Velazquez St. (one-way street).

During the one month campaign the followed procedure included: For one week (17–24 June 2009) the road surface was washed daily with high-pressure water systems to prevent suspension of road dust. The next week (25 June – 1 July 2009) the road was left untreated to observe any potential increase in PM ambient concentrations. The same procedure was repeated for another two weeks period, 2–20 July 2009. Street washing was carried out during the early morning hours (00:00–03:00) by the urban cleaning agency using a pressurised (minimum pressure 10 Kp cm^{-2}) groundwater volume of 4 l m^{-2} for each washing. The water supplied for urban cleaning vehicles was recycled groundwater. The washed area comprised sidewalks, active lanes and parking lanes. In addition, previously to this wash a mechanical sweeper vehicle was employed with the aim of vacuuming coarser deposited particles. The washed water was not specifically removed but moved along into the urban drainage system.

2.2. Regression analysis

The dependence of continuous measurements of $PM_{2.5}$ emission potentials on washing activities, meteorological parameters and traffic flow was examined using simple and multiple linear regression models controlling for a time trend and allowing for residual autocorrelation by using the Cochrane–Orcutt procedure (Cochrane and Orcutt, 1949). Statistical analyses were done using Stata statistical software, release 11 (StataCorp LP, College Station, TX, 2009).

3. Results and discussion

3.1. $PM_{2.5}$ continuous measurements

As the weekday-weekend variability might be higher than the effect of street washing we analyzed the $PM_{2.5}$ data excluding the weekends. The diurnal variation of $PM_{2.5}$ levels was evaluated in order to detect out any effect of street washing activities. The continuous measurements were averaged in hourly concentrations and separated into two subsets: 11 days that the road surface was washed daily (StW days) and 12 days where the street was left untreated (no StW days). No difference was observed in the average (24 h) $PM_{2.5}$ concentrations between the two subsets; both were equal to 8 μg m^{-3}. The continuous $PM_{2.5}$ data indicated a small reduction in $PM_{2.5}$ mass levels, only during the morning hours (06:00–10:00), when street washing was implemented, Fig. 2. The mass difference between the two periods during 06:00–10:00 is ~ 1 μg m^{-3} about 7% of the average $PM_{2.5}$ mass levels. However, this reduction is lower than the standard deviation of the $PM_{2.5}$ measurements. On the other hand a completely different pattern was observed for the evening hours with $PM_{2.5}$ levels being considerably higher during StW days. During the sampling campaign the air quality network of Madrid did not include any $PM_{2.5}$ monitoring station. Thus with the absence of parallel $PM_{2.5}$ measurements at a reference site (not influenced by the street washing activities) we could not conclude that this reduction in the morning hours is induced by street washing or by the background conditions. In order to examine the possible influence of background conditions, the continuous $PM_{2.5}$ data at Maldonado site were compared with the PM_{10} data (hourly TEOM measurements) obtained from the urban background station Casa de Campo belonging to the local air quality monitoring network (Fig. 3). For Casa de Campo urban background station, a different pattern was observed in the 24 h PM_{10} average concentrations, these being comparatively higher during the StW days in Velázquez street. The average 24 h PM_{10} mass concentration for StW days was 23 μg m^{-3} and for no StW days was 21 μg m^{-3}. However, the diurnal trend was similar to that observed in Maldonado site although shifted in time. During the morning hours (08:00–11:00) PM_{10} concentrations, were lower during StW days in Maldonado site. Again, during the evening the two sites Maldonado and Casa de Campo had similar trends, PM concentrations were higher during StW days. Since, Casa de Campo (reference site) is not directly influenced by nearby exhaust emissions neither by the street washing activities, the decrease during the morning hours could be explained by the prevailing atmospheric conditions such as atmospheric dilution that might was more intense during the StW days. It is certain that these phenomena have also influenced to some extent the reduction of aerosol concentrations in Maldonado site during days that street washing occurred. This implies that with the absence of $PM_{2.5}$ background concentrations, conclusions cannot be drawn about the influence of street washing activities on fine particle levels).

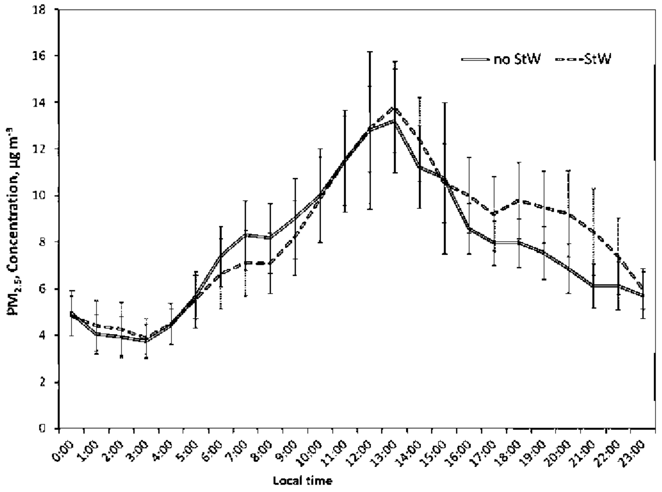

Fig. 2. Daily variability of $PM_{2.5}$ concentrations between StW days and no StW days for Maldonado sampling site (error bars represent the standard deviation of the measurements).

3.2. Multivariate regression analysis

Ordinary multiple linear regression with meteorological parameters as explaining variables in time-series analysis of PM has been previously used (Van der Wal and Janssen, 2000). In order to

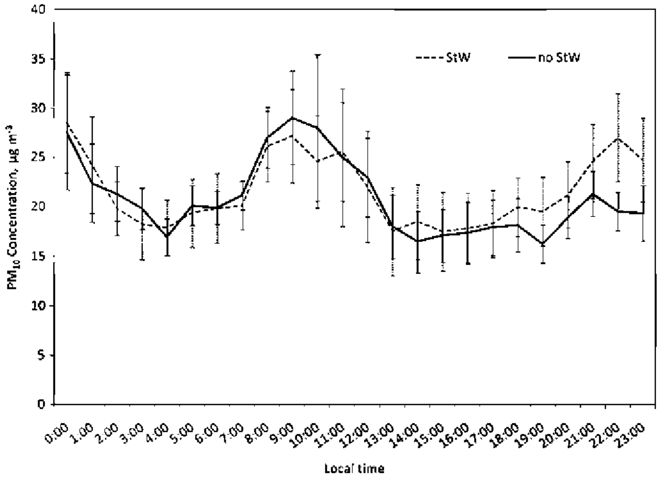

Fig. 3. Daily variability of PM_{10} concentrations between StW days and no StW days for Casa de Campo urban background site (error bars represent the standard deviation of the measurements).

Table 1
Hourly average concentrations and standard deviations (in brackets), of $PM_{2.5}$ concentrations, traffic volume ambient temperature, and relative humidity, and wind direction and velocity between StW and no StW days at Maldonado site.

Variables	StW days		no StW days	
	mean	(sd)	mean	(sd)
PM2.5 (mg m^{-3})	11.7	(3.3)	14.0	(3.9)
Traffic volume (num. of vehicles)	895.7	(313.7)	873.6	(298.7)
Temperature (°C)	29.5	(6.3)	31.4	(5.2)
Humidity (%)	28.9	(13.5)	27.1	(9.6)
Wind direction (angles)	173.8	(65.4)	174.9	(50.3)
Wind velocity (ms^{-3})	1.7	(0.5)	1.4	(0.3)

overcome the lack of $PM_{2.5}$ background measurements we decided to use multivariate regression analysis as a complementary tool to examine the influence of street washing activities. In this study we have examined $PM_{2.5}$ concentrations with respect to the variability of meteorology, traffic volume and also of the street-washing programme.

Table 1 provides the hourly average values of the $PM_{2.5}$ concentrations at Maldonado site, traffic volume, ambient temperature, relative humidity, wind direction and velocity between StW and no StW days. However, their mean values did not differ substantially between StW days and no StW days. For these two periods these parameters presented similar variability.

The dependence of continuous measurements of $PM_{2.5}$ levels on washing days, meteorological parameters and traffic flow was firstly examined using simple linear regression models controlling by time trends and residual autocorrelation. For all the regression models, the logarithms of $PM_{2.5}$ concentrations were used since $PM_{2.5}$concentrations were non-normally distributed. The regression coefficients (β) and its standard errors (se) are given in Table 2. The results showed a reduction of around 16% for $PM_{2.5}$concentrations caused by street washing activities, although this was not statistically significant. For an increase of the number of vehicles by 1000, $PM_{2.5}$ levels were increased by 29%, being statistically significant ($p < 0.05$). For an increase of 1 °C of ambient temperature levels of $PM_{2.5}$ increased by 1.3% ($p < 0.05$). It is possible that the increase of the temperature (that also represents the increase in the solar radiation during the day) stimulates the production of secondary particles. On the other hand, relative humidity had no effect in the $PM_{2.5}$ concentrations although it is well known that humidity influences significantly the properties of aerosol particles. Finally, wind direction and velocity were related to $PM_{2.5}$ concentrations, showing a decrease of <1% and 7.2%, respectively when the wind direction was shifting (by 10 angles) from northern to southern and the wind speed was increasing by 1 ms^{-1}, although both were not statistically significant.

When adjusting simultaneously all variables into a multiple linear regression model the coefficients did not vary substantially, although traffic flow was the only variable that remained statistically significant ($p < 0.05$). Thus, the obtained results show that traffic flow is the most important factor that controls the variability of the $PM_{2.5}$ hourly concentrations at Maldonado site.

Table 2
Regression coefficients (β) and its standard errors (se) from simple and multiple linear regression models of the potential explanatory factors for the $PM_{2.5}$ concentrations (log-transformed) at Maldonado site. Statistical significant values are highlighted in bold.

	Simple linear regression			Multiple linear regression		
	β	(se)	p-value	β	(se)	p-value
Street washing	−0.1607	(0.1261)	0.243	0.2551	(0.167)	0.187
Traffic volume	**0.2926**	**(0.0570)**	**0.001**	**0.2213**	**(0.0619)**	**0.016**
Temperature	**0.0132**	**(0.0032)**	**0.005**	0.0126	(0.0098)	0.255
Humidity	0.0015	(0.0022)	0.522	0.0038	(0.0049)	0.465
Wind Direction	−0.0002	(0.0003)	0.520	−0.0002	(0.0003)	0.528
Wind Velocity	−0.0723	(0.0393)	0.125	−0.0756	(0.0466)	0.166

4. Conclusions

A study has been undertaken with the purpose to investigate any effect of street washing activities on the levels of fine particles, $PM_{2.5}$. The continuous $PM_{2.5}$ data indicate a reduction during the morning hours after street washing was implemented but exactly the opposite trend was observed during the afternoon-evening hours. With the lack of $PM_{2.5}$ background concentrations multivariate regression analysis was used to examine the effect (if any) of street washing on fine particle levels. Continuous $PM_{2.5}$ concentrations were analysed with respect to the meteorological parameters, the traffic volume and also of the street-washing programme. The obtained results show that traffic flow is the only important factor that controls $PM_{2.5}$ hourly concentrations.

Taking into account that we have reported a signal in the coarse fraction following street washing activities (Karanasiou et al., 2011) and considering the documented size distribution of resuspendable particles on the road surface that has mass in sizes smaller than 2.5 μm, it cannot be ruled out that street washing influences the street surface $PM_{2.5}$ emissions. But since there are other potentially more dominant $PM_{2.5}$ emission sources in the road environment, e.g., vehicle exhaust particles, no signal was observed following the street washing activities. Therefore street washing cannot be considered an efficient method for controlling the $PM_{2.5}$ concentrations.

An implication for public policy is that local authorities should reconsider the street washing activities. In our previous work (Karanasiou et al., 2011) we have found that street washing has a short lived (3–5 h) effect on PM_{10}. With this complementary analysis we show that this method has no effect on fine particles. Hence, street washing could reduce the ambient levels of coarse particles if it is employed just before the traffic peak hours. Again for more health relevant aerosol particles like $PM_{2.5}$ this method has no effect.

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