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INFLUENCE OF VEHICLE DYNAMICS ON THE NON-EXHAUST PM-EMISSION PROCESS

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Abstract: We have studied the influence of vehicle speed and meteorological variables on the detected non-exhaust particulate signals by a mobile monitoring system called the Sniffer in the measurement campaign during 2006-2009, in Helsinki. PM10 particulates are decomposed into coarse and fine fractions. The functional forms based on the statistically analyzed data, reveal the dependency of emission factors on vehicle speed and meteorological variables. A clear dependence of the coarse fraction on vehicle velocity is observed and the threshold velocity for the change of slopes of the emission factors and for the relative coarse fraction is suggested.

Key words: *Non-exhaust particulate emission, PM_{10}, coarse fraction, fine fraction*

INTRODUCTION

The development of engines and fuels has moved the target of traffic induced particulate emissions from exhaust to non-exhaust emissions, for which new monitoring methods are needed. The Sniffer system (Pirjola et al., 2004; 2009; 2010) collects data with a constant volume rate (volume/time) from which the analyzer takes samples with a lower constant volume rate. The averaging time is 10 s during which location and velocity are also detected allowing the computation of mean acceleration and distance. The location of the collector is behind the left rear tire and measured PM signal includes both urban and traffic influenced background concentrations and also unknown amount from other tires. Instead of these limitations, the observed signal and the correspondingly determined emission factor are obviously associated with the emission factor of the vehicle including turbulence, brakes and the interaction between tires and the road surface.

EMISSION FACTOR VERSUS OBSERVED PM SIGNAL

The volume rate of the main collector in the Sniffer system is $\dot{V}_C$ from which the analyzer takes samples with volume rate $\dot{V}_S$. The corresponding collected masses during the averaging time T_{ave} are denoted by m_C and m_S, when the detected PM concentration can be written as a function of distance x and vehicle speed v is

$$PM = m_S/\dot{V}_S T_{ave} = m_S v/\dot{V}_S x \tag{1a}$$

Assuming that all particles behind the rear tire are collected the ratio of $m_C/m_S = \dot{V}_C/\dot{V}_S$, by substitution we obtain

$$PM = m_C v/\dot{V}_C x \tag{1b}$$

Because the emission factor (mass/length) is defined as EF = m_C/x, we can perform it as a function of the detected signal PM, vehicle speed v and the constant volume rate $\dot{V}_C$. We emphasize that also EF should to be treated as a signal from the total vehicle induced EF.

$$EF = \dot{V}_C PM/v \tag{2}$$

METHODS

PM measurements were conducted with a mobile laboratory Sniffer equipped with versatile air quality and meteorology measuring devices (Pirjola et al., 2004; 2009; 2010). Sniffer (VW LT 35) collects dust sample behind the left rear tyre, approximately 5 cm from the tyre through a conical inlet with a surface area of 0.20 m x 0.22 m into a vertical tube with a diameter of 0.1 m. An electric engine located on the roof of the vehicle produces a constant flow rate of approximately 2000 lpm, see details in Pirjola et al. (2009). A sampling air branch-off was constructed into the particle mass monitors TEOM (Tapered Element Oscillating Microbalance; series 1400A, Rupprecht & Patashnick) and ELPI (Electrical Low-pressure Impactor; Dekati Ltd.) with the total flow rate of 13 lpm. TEOM saved a 30-s running average mass concentration every 10 s whereas ELPI saved the particle size distribution in 1 s time resolution. Since measuring is done very close to the street surface and source, it is expected that the sample has no time to dilute. The other ELPI measured background PM in front of the van.

During the KAPU-project in 2006-2011 (Kupiainen et al., 2011) the road dust measurements by Sniffer were conducted in the city centre of Helsinki on a special 20 km route as often as the weather was favorable. The objective was to measure before the wintertime when accumulation of dust begun, during the dust accumulation period in winter, in the spring before any street cleaning activities were started, during different stages of springtime street cleaning, and after the springtime cleaning period, until the amount of dust emissions stopped going down. For this work we selected the data in 2006-2009 concerning three main streets with a criterion that near these streets the meteorological parameters were monitored by FMI.
Meteorological variables were measured at Testbed weather station at Sörnäinen locating SE from Helsinki city centre and 0.5-1 km NW from the study site (Sörnäisten rantatie). All parameters are measured by Vaisala Weather Transmitter

WXT510 on the roof of 3-4 m high building at 23 m height above the sea level. Road surface wetness is not accounted in this study.

The statistical methods used in this work are described e.g. by Martinez and Martinez (2008) in Chs. 8-13 and Tabachnick and Fidel (2001) in Ch.4. MATLAB vs. R2010b software package with Statistics Toolbox vs.7.5 (the Mathworks, Inc.) and SYSTAT 13 software package (Systat Software, Inc.) were applied to the analysis of the data.

RESULTS

Because the monitored Sniffer data and meteorological data have different averaging times, the Sniffer data were firstly rearranged into hourly data including 988 separate 10 second test cases during 78 hours on Sörnäisten rantatie in South-Eastern part of Helsinki during years 2006-2009 (Kupiainen et al., 2011). PM10 and PM2.5 concentrations were detected, from which coarse (2.5 μm < $D_p \leq 10$ μm) and fine ($D_p \leq 2.5$ μm) emission factor fractions were determined according to equation (2).

For determining the influence of vehicle velocity on emission factor, transformed data was formed on the basis of moving average of monitored vehicle speed. The preliminary analysis revealed that only relative humidity RH(%), temperature T(C) and wind speed WS(ms^{-1}) of the meteorological variables were correlated to the computed emission factors.

Dependence of emission factor on vehicle speed

Moving average procedure is a filtering process smoothing the variability of the data, where window size plays a key role. The used window size of the vehicle speed 1 kmh^{-1} is based on the criterion that the information of the regression trees of the initial and filtered data keeps essentially unchanged, which requires rather small window size.

The mean and median of the running averaged EF for the coarse and fine fractions of particulates indicate slightly skewed distributions of EF over the vehicle speed. The fractions are highly correlated and the fine fraction is relatively high. Recall that only one tire is considered and the observed values include also both the influence of the background and vehicle wake effects.

The running means of coarse and fine EF values are fitted against velocity v according to $c_0 v^{c1}$. The R-squares of coarse and fine fittings are 0-0.663 and 0.763 and the constants c_0 and c_1 are presented in Table 1. The decreasing EF against vehicle velocity according to Table 1 is physically surprising, because positive slope for the emission from tires is expected. An explanation may be that the signal EF is decomposed from differently behaving components. The background component includes the urban background (practically constant during a test) and traffic induced background including exhaust, the turbulence induced concentrations and influence of brakes. The traffic induced concentration dilutes effectively by the vehicle wake. Consequently, we may assume the mean EFs consist of the decreasing traffic wake induced component and increasing tire-road surface interaction component.

Dependence of emission factor on meteorological variables

Yearly and monthly variation of coarse and fine EF fractions was firstly compared. Strong skewness is characteristic for the raw data. Observed outliers are obviously responsible on the cleaning operations, which may change between years and are concentrated in spring time period from March to May in Helsinki. The mean yearly change is only moderate, but the monthly change is significant both for coarse and fine fractions of PM_{10}. The behavior of coarse and fine fractions is roughly similar.

The dependence of EF on meteorological variables was tested by several standard methods. Only relative humidity, temperature and wind speed appeared to be potential predictors for the fractions of emission factors. Downwind/upwind side flow direction doesn't contribute to the measured signals in this study.

Fitting of emission factors against meteorological variables

The fitted running mean EFs are firstly subtracted from EF values (988 cases) to remove the velocity dependence from the data. The meteorological fitting is limited to the coarse EF ≤ 20 μg/m and fine EF ≤ 10 μg/m. The models for fitting are denoted e.g. by (M1). According to traditional fitting procedures, the negative minimums of response variables were first subtracted from responses and then for linearization purposes a logarithm was taken. Logarithmically transformed response variables were fitted with robust linear regression against meteorological variables using SYSTAT 13 software package. The criterion for selecting independent variables was, that the 95 % confidence level doesn't include zero. The reverse process yields equations for the predicted coarse and fine EFs including vehicle speed and meteorology (M2), where meteorological variables for coarse EF are temperature and wind speed, while in case of fine EF temperature and wind speed were selected. Consequently, the fitting of PM10 particulates against meteorological variables requires decomposition of the data into separate coarse and fine fractions. Adjusted squared correlation is poor: 0.256 for the coarse and 0.166 for the fine fraction. Constants crmin and brmin are minimum residual values in Table 1.

The signs of the meteorological constants in Table 1 refer to the average effects. According to equation (M1) increasing relative humidity and wind speed decreases emission factors. Wind speed affects as a removal factor for coarse particles from the road surface, while relative humidity is present only in the fine fraction. Temperature is a seasonal indicator, because below zero Celsius degrees emission factors increase and above zero they decrease. This is consistent with the monthly distributions of the observed EFs. According to equation (M1) variations of the emission factors depend only on the vehicle speed during constant meteorological conditions.

Table 1. Values of the fitted constants.

Coarse fraction						Fine fraction					
c_0	c_1	cm_0	cm_1	cm_2	crmin	b_0	b_1	bm_0	bm_1	bm_2	brmin
24.21	-0.437	2.84	-179E-4	-0.027	-15.8	9.15	-0.483	1.55	-276E-5	-162E-4	-3.98

$$EF_c^p = c_0 v^{c1} + exp(cm_0 + cm_1 T + cm_2 WS) + crmin \quad \text{(M1a)}$$

$$EF_f^p = b_0 v^{b1} + exp(bm_0 + bm_1 RH + bm_2 T) + brmin \quad \text{(M1b)}$$

The variation is large in both fractions, but also a systematic underestimation is observed. To reduce variance, we firstly sort the above used data in ascending order with new indexes. Secondly, we formulate a running means for the sorted observed and predicted data in window size 7 according to (M2), which still yieds systematic errors in slope and also a clear change of slope in case of coarse particulates above 6 μgm^{-1}. Obviously, the presented model (M2a) is unable to predict episodic coarse EF values.

$$MEF_c^p(j) = \frac{1}{2n+1} \sum_{j-n}^{j+n} EF_c^p(j) \text{ , where n= 3} \quad \text{(M2a)}$$

$$MEF_f^p(j) = \frac{1}{2n+1} \sum_{i=j-n}^{j+n} EF_f^p(i) \text{ , where n= 3} \quad \text{(M2b)}$$

For correcting the slope and shift a new robust linear regression is applied to the results computed by (M2). The robust constant values in (M3) are cr_0= -2.817, cr_1= 1.902, br_0= -1.880 and br_1= 2.303. The results are presented in Figure 1, where number of robust cases for coarse EF is 709 and for fine EF 883. Adjusted R-squares for robust fitting of coarse EF is 0.719 and for fine EF 0.641. The variation of predicted values has increased, because the robust slope decreased. Observed coarse values > 6 μg/m are interpreted as outliers. However, they are outliers only for the current model, which doesn't include factors for treating sanding, salting, studded tires and cleaning operations. From the physical view negative predicted values are interpreted as zeroes.

$$RMEF_c^p = cr_0 + cr_1 MEF_c^p \quad \text{(M3a)}$$

$$RMEF_f^p = br_0 + br_1 MEF_f^p \quad \text{(M3b)}$$

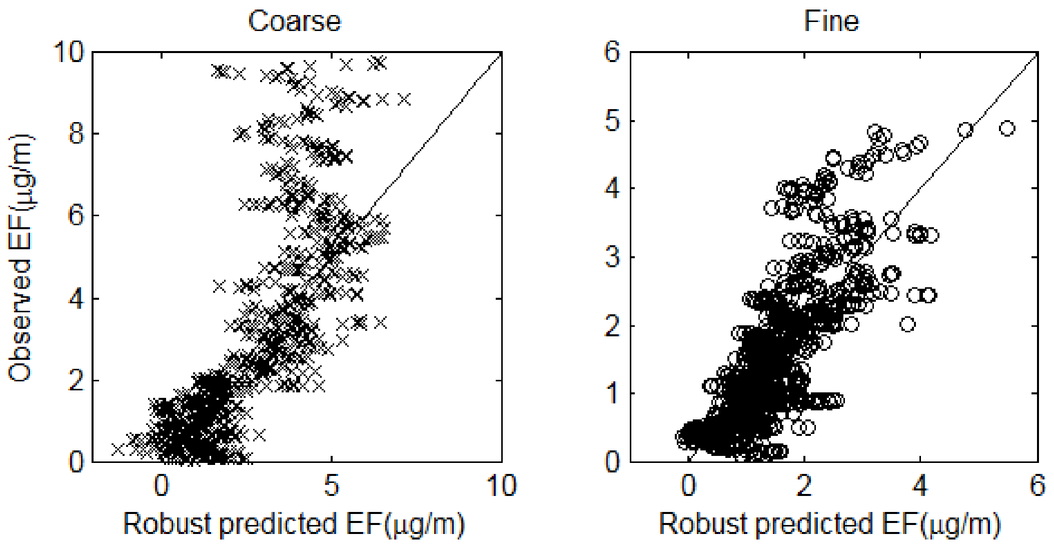

Figure 1. Running means of observed versus robust predictions of coarse and fine particulate EF(μgm^{-1}) . Number of cases in coarse and fine fractions is 709 and 883 correspondingly.

Equations (M3) and Figure 1 suggest that the window size including 7 cases is a reasonable choice. Because averaging time is 10 s, the window includes about one minute monitoring (if continuous) representing the average distance roughly 0.5 km with vehicle speed 30 kmh^{-1}. This distance changes linearly with vehicle speed, which should be remembered in interpreting the separate running mean EF values.

Emission factors of particle size below 10 μm

The superposition of coarse and fine running means of emission factors including the particle size range 0-10 μm is denoted by EF10. EF10 represents measurements behind the right hand side rear tire of the mobile monitoring system Sniffer. The dependence of the observed versus robust predicted EF10 is presented in the upper left panel of Figure 2. The relative amount of the observed coarse EF to observed EF10 is shown in the upper right panel, which indicates that fine fraction dominates in small EF values. In most cases coarse fraction dominates, but never more than 80 % of the emitted mass. Recall that the emissions and coarse-ratio include also the influence of dilution by the vehicle wake, which may affect differently to the fractions.

The previous averaging procedure associated with vehicle speed is applied to the EF10 and to the ratio of coarse EF to EF10, when the window size is 1 km/h in the vehicle speed range 3.5-60.5 kmh^{-1}. Vehicle speed is indexed correspondingly with the sorted EF10. The dependencies are plotted in the lower panels of figure 2 (including possible outliers), where in the left EF10 firstly decreases and has the minimum value at about 20 km/h. The values are smoothed with the robust loess (robust locally weighted regression excludes outliers) routine by Martinez and Martinez (2008). Moving averages of the upper panels represent 7 cases in the window, while the lower panels additionally are averaged in the vehicle speed window of 1 kmh^{-1}. This indicates the difference between Figures 1 and 4c and the different scales in Figures 2a and 2c. Gustafson et al. (2009) reports increasing pavement wear above vehicle speed 30 km/h in laboratory experiments. The right lower panel suggests a relative increase of the coarse fraction in EF10.

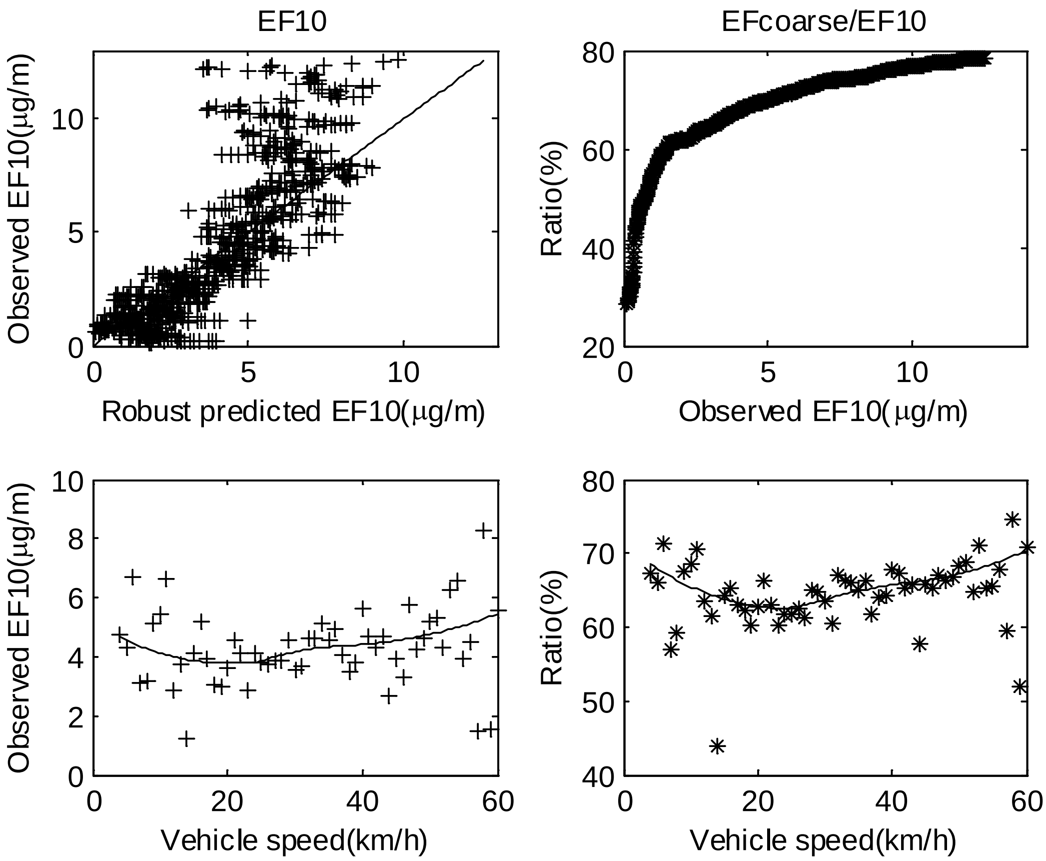

Figure 2. Observed vs. robust predicted emission factors EF10(μgm^{-1}) in the size range 0-10 μm is presented in the upper left panel and the ratio of coarse fraction in the same size range in the right panel. The lower panels present mean EF10 and coarse-ratio against vehicle speed within window size 1kmh^{-1}, where the solid line illustrates the robust loess smoothing. Number of cases in the upper and lower panels is 772 and 56, correspondingly.

CONCLUSIONS

The vehicle induced non-exhaust emission process is studied theoretically and statistically using the observed data of the Sniffer system and meteorological mast measurements in Helsinki during 2006-2009. The focus of the work is in the dynamics of mobile system and the interactions between meteorological variables. The results show that the most important factors of the Sniffer system, collecting particulates behind the rear tire, are the vehicle speed and meteorological variables, relative humidity, temperature and wind speed.

Correlation between observed and predicted emission factors is also reasonable in the particle size range $D_p \leq 10$ μm, but prediction underestimates in high values as also in case of coarse fraction. Fine particulate fraction dominates only within low EF10 values, but is always between 20-70 % of the emitted mass according to the results. The average slope of EF10 and coarse-ratio against vehicle speed increases after 20 km/h, but decreases below it.

The results suggest that emission factors for the coarse and fine fractions of PM_{10} particulates can be converted from the signals (concentrations) of the Sniffer system. However, the relation between the total emission factor of the vehicle and monitored value behind one rear tire is still unknown. The emission factors composed of differently behaving components against vehicle speed is also unknown.

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