NEW METHODS OF DETERMINATION OF AVERAGE PARTICLE EMISSION FACTORS FOR TWO GROUPS OF VEHICLES ON A BUSY ROAD

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ABSTRACT

In this paper, two new methods are developed for the determination of the average emission factors of fine and ultra-fine particles for different groups of vehicles on a busy road. The values of these emission factors for heavy-duty trucks and light-duty cars are calculated, discussed, and compared with the previous results obtained mainly in laboratory conditions.

Key words: Ultra-fine particles; Average emission factor; Busy road; Light cars, Diesel trucks.

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1. Introduction

During the last decade, aerosols of fine and ultra-fine particles, emitted from combustion sources, have been of an increased concern in relation to human health in urban areas. Therefore, busy roads, being the main source of fine particles in the urban environment, are of a particular interest in aerosol science. As a result, accurate determination of average emission factors for vehicles on a road is of major importance for the evaluation of the impact of road pollution on human health and the environment.

Recently, the CALINE4 model, designed for calculation of concentrations of carbon monoxide near a busy road (Benson, 1992), has been adapted for the analysis of aerosols of fine and ultra-fine particles (Gramotnev *et al*, 2003). A scaling procedure for this model has been developed and justified. A new method for the determination of emission factor for the average fleet on the road has also been developed, based on the experimental values of the total number concentration at some distance from the road (Gramotnev *et al*, 2003).

However, the developed methods (Gramotnev *et al*, 2003) are not applicable for the determination of the emission factors of different types (groups) of vehicles on the road, for example, heavy-duty trucks and light cars. This information may be vital for the ability to effectively forecast aerosol pollution from busy roads. At the same time, the values of the emission factors obtained under laboratory conditions for different types of vehicles differ by up to ~ 3 orders of magnitude (Graskow et al, 1998, Watson et al, 1998, Ristovski et al, 1998, Cadle et al, 2001), and lie within the intervals between $\sim 10^{12}$ to $\sim 10^{14}$ particles/vehicle/kilometre for gasoline (light-duty) vehicles, and $\sim 10^{14}$ to $\sim 10^{15}$ particles/vehicle/kilometre for diesel trucks. Gross et al (2000) also estimated during on-road measurements that the ratio of the average emission factors for trucks and cars is ~ 48. However, the actual values for the emission factors have not been determined.

Thus there is a strong need to develop reliable methods for the determination of average emission factors for different types of vehicles on a busy road. Therefore, the aim of this paper is to develop new simple methods for the determination of average emission factors for two different groups of vehicles on a road. These methods are based on the experimental measurements of the total number concentration near the road. As an example, on-road emission factors for heavy-duty trucks and cars are determined.

2. Emission factors for two different groups of vehicles

The measurements were taken near the Gateway Motorway (Brisbane, Australia) at different traffic conditions: 18.1% of heavy-duty trucks on 30 July 2002 (weekday) and 2.7% of heavy-duty trucks on 24 November 2002 (weekend). The total number concentration of fine and ultra-fine particles in the range from 14 nm to 710 nm was measured at the distance of 15 m from the kerb at 2 m height above the ground by a scanning mobility particle sizer (SMPS-3071) and a condensation particle counter (CPC-3010). The concentrations were measured in 110 equal intervals (channels) of Δlog(Dp), where Dp is the particle diameter in nanometers. Five and ten scans were taken on the weekday and weekend, respectively, and the average total number concentration was determined. The time intervals within which SMPS took the concentration measurements in one channel were $\tau_1 \approx 2.73$ s for the weekday, and $\tau_2 \approx 1.36$ s for the weekend. The meteorological parameters (wind speed, wind direction, temperature and humidity) were measured every 20 seconds by a weather station. Standard deviations of the wind speed and direction, their one hour averages, and other meteorological and traffic parameters with their standard deviations of the mean values are presented in Table 1. Traffic flow for each type of vehicles (light duty vehicles, light trucks and heavy duty vehicles) has been calculated within 5 min intervals eight times during the period of measurements of 40 min. Then the average traffic flows were calculated – see Table 1 (the resultant standard deviation are ~ 6% – 7%). These small standard deviations clearly indicate the high stability of the traffic. It is also worth mentioning that the average speed on the motorway was approximately the same for the period of measurements on both the days (100 km/h).

Using the concentrations, meteorological and traffic parameters from Table 1, the values of the emission factors E_f for the average fleet on the road were calculated by means of the CALINE4 model (Gramotnev et al, 2003) – see the last row of Table 1.

Let us now assume that there are two groups of vehicles on the road – heavy-duty trucks and cars. The light trucks (Table 1) are included in the car group. In this case the emission factors for the average fleet for the weekday (index 1) and weekend (index 2) can be written as

$$E_{f1} = w_{t1}n_{t1}e_t + w_{c1}(1 - n_{t1})e_c, \quad (1)$$

$$E_{f2} = w_{t2}n_{t2}e_t + w_{c2}(1 - n_{t2})e_c. \quad (2)$$

Here, n_{t1} and n_{t2} are the fractions of heavy-duty trucks in the traffic flow, e_c and e_t are the emission factors for cars and heavy-duty trucks (to be determined), $w_{t1,2}$ and $w_{c1,2}$ are the correction factors that are introduced to compensate for the discreteness of the traffic flow (breach of the line source approximation). The reasons for using these factors can be understood from the following.

The concentration measurements were taken in 110 size channels in sequence within the time intervals τ_1 and τ_2 per one channel. Let $N_{t1,2}$ and $N_{c1,2}$ be the numbers of trucks (index t) and cars (index c) passing by within the time interval that takes for a measurement within one channel on the weekday (index 1) and weekend (index 2). If, for example, $N_{t2} < 1$, then the particle concentration will be affected by the passing trucks only in a fraction of channels that equals N. Table 1 gives $N_{t2} = 0.04$. Therefore, only one out of ~ 25 channels in one scan "feels" the presence of a heavy truck. This effectively reduces the contribution of e_t to E_{f2} by a factor 0.04. Therefore the values of $e_{t,c}$ in Eqs. (1) and (2) are multiplied by the additional correction factors $w_{t1,2} = \min\{1,N_{t1,2},\}$, and $w_{c1,2} = \min\{1,N_{c1,2}\}$. It follows from the traffic data (Table 1) that in our experiments, $w_{c1,2} = 1$, $w_{t1} \approx 0.6$, and $w_{t2} \approx 0.04$.

Eqs. (1), (2) can be solved with respect to e_t and e_c. The theory of variance (Larsen and Marx, 1986) gives that if ΔE_{f1} and ΔE_{f2} are the standard deviations of E_{f1} and E_{f2}, then the standard deviations of e_t and e_c are

$$\Delta e_t = [w_{c2}^2(1 - n_{t2})^2\Delta E_{f2}^2 + w_{c1}^2(1 - n_{t1})^2\Delta E_{f1}^2]^{1/2}/D_0, \qquad (3)$$

$$\Delta e_c = [w_{t1}^2 n_{t1}^2\Delta E_{f2}^2 + w_{t2}n_{t2}^2\Delta E_{f1}^2]^{1/2}/D_0, \qquad (4)$$

where

$$D_0 = |n_{t1}w_{t1}w_{c2}(1 - n_{t2}) - n_{t2}w_{t2}w_{c1}(1 - n_{t1})|.$$

For example, for the values of $E_{f1,2}$ presented in Table 1, we obtain:

$$e_t = (25 \pm 6)\times 10^{14} \text{ particle/vehicle/km},$$

$$e_c = (0.21 \pm 0.06)\times 10^{14} \text{ particle/vehicle/km}. \qquad (5)$$

Note that another possible source of error of the obtained results is related to the possibility of different contributions of the light trucks to the overall flow of cars on the weekday and weekend. To evaluate the upper limit of this error, we take the difference between the flow of the light trucks on weekday and weekend (i.e. 165 vehicles/hour) and include it into the number of heavy-duty trucks. Thus we assume that the average emission factor of 165 light trucks/hour on the weekday is equal to that of heavy-duty trucks (which is an obvious exaggeration). The resultant emission factor for heavy trucks is different from that given by Eq. (4) by $\approx 30\%$, while for the cars, this difference is $\approx 4\%$, which gives the upper (exaggerated) limit for the possible error due to differences in the flow of the light trucks on weekday and weekend.

3. Constrained optimization

The same results can be obtained from Eqs. (1), (2) by means of the method of constrained optimization (Kreyszig, 1999, Wolfram, 1999). In this method, e_t, e_c, E_{f1}, and E_{f2} are regarded as four variables. The average emission factors for the average fleet $E_{f1,2}$ lie within the intervals given by the standard deviations of these parameters (Table 1). These two intervals and Eqs. (1), (2) represent four constraints for the considered variables. Analytical (Kreyszig, 1999) or numerical (Wolfram, 1999) solution of this problem with the considered parameters (Table 1) gives the intervals (in particle/vehicle/km):

$$18.3\times10^{14} \le e_t \le 31.4\times10^{14}, \qquad 0.14\times10^{14} \le e_c \le 0.27\times10^{14} \tag{6}$$

that are hardly different from (5).

Note however, that though in the considered example the method with constraints is equivalent to the direct solution of Eqs. (1) and (2), it may be very important for the determination of the emission factors when the traffic conditions during the two sets of measurements are similar: $n_{t1} \approx n_{t2}$. In this case, the slopes of the two lines, given by Eqs. (1), (2) in the (e_t, e_c) space, may be too close, and the point of intersection of these lines (the solution to (1), (2)) is highly sensitive to experimental errors. As a result, the obtained values of e_t and e_c suffer from substantial errors (increasing when $n_{t1} \rightarrow n_{t2}$) – see Eqs. (3), (4).

In this case, using the method of constrained optimization (Kreyszig, 1999, Wolfram, 1999), we can determine the average emission factors for two groups of vehicles from only one set of measurements and the typical ratios for the emission factors determined in the laboratory conditions: $e_t/e_c \approx 36$ (Watson et all, 1998), and $e_t/e_c \approx 377$ (Ristovski et all, 1998). The on-road value of $e_t/e_c \approx 48$ was estimated by Gross *et al* (2000). The inconsistency of these results is obvious. However, they determine the constraint $36 < e_t/e_c < 377$.

Suppose that we have only one set of measurements on the weekday (30 July 2002). Thus the second constraint is given by Eq. (1), while the third is again obtained from the standard deviation of E_{f1} (Table 1): $2.2\times10^{14} \le E_{f1} \le 3.4\times10^{14}$. The solution of this problem with constraints (Wolfram, 1999) gives in particle/vehicle/km: $17\times10^{14} \le e_t \le 32\times10^{14}$, and $0.06\times10^{14} \le e_c \le 0.75\times10^{14}$.

If we take the other set of measurements, then Eq. (2) is the second constraint, whereas the third is $0.17\times10^{14} \le E_{f2} \le 0.29\times10^{14}$ (Table 1). In this case, $6.2\times10^{14} \le e_t \le 78.9\times10^{14}$, and $0.13\times10^{14} \le e_c \le 0.28\times10^{14}$ (in particle/vehicle/km). Note however, that in this case the accuracy of e_t and e_c is lower than in Eq. (5). This is due to the fairly loose constraint on the laboratory results for e_t/e_c.

Note that the considered second method automatically gives the comparison of the determined emission factors with the previously obtained results from the measurements mainly in laboratory conditions (Watson et all, 1998, Ristovski et all, 1998, Gross *et al*, 2000).

4. Conclusions

In this paper, two new methods have been developed for the determination of the average emission factors of fine and ultra-fine particles for two groups of vehicles (heavy-duty trucks and cars) on a busy road. The first method requires experimental measurements of particle concentrations at different traffic conditions (e.g., on a weekday and on a weekend), whereas the second method is applicable when the traffic conditions are not changing. However, the second method requires some knowledge (typical range of variation) of the ratio of the average emission factors for heavy-duty trucks and cars (e.g., from the literature). The values of the emission factors have been determined during the on-road measurements. Both the methods have been shown to yield very similar results, which clearly demonstrates the advantage of the proposed methods compared to the laboratory approaches giving strongly dispersed results.

The correction factors compensating for the discreteness of the traffic flow (i.e., for the breach of the line source approximation) have also been introduced.

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Table 1

	30 July (weekday)	24 November (weekend)
Concentration at 15 m, cm^{-3}	20.3×10^3 (±16%)	2.2×10^3 (±13%)
Background concentration, cm^{-3}	2.3×10^3 (±4%)	0.74×10^3 (±9%)
Traffic flow, vehicle/hr	4295 (±2%)	3694 (±2.2%)
Heavy-duty trucks, vehicle/hr	776 (±2.3%)	100 (±15%)
Cars, vehicle/hr	3097 (±2.3%)	3337 (±2.3%)
Light trucks, vehicle/hr	422 (±9%)	257 (±9%)
Wind direction, ^{o} to the North	142 (Std. Dev. = 48)	28.54 (Std. Dev. = 39.43)
Wind speed, m/s	2.3 (Std. Dev. = 8)	2.2 (Std. Dev. = 0.7)
Temperature, °C	22	27
Humidity, %	33	35
Emission factor, particle/vehicle/km	2.8×10^{14} (±23%)	0.23×10^{14} (±24%)