In-field verification of PM10 emission factors of road traffic

Robert Gehrig, Matz Hill, Brigitte Buchmann, Swiss Federal Laboratories for Materials Testing and Research, CH-8600 Dübendorf
David Imhof, Ernest Weingartner, Urs Baltensperger, Paul Scherrer Institute, CH-5232 Villigen

Conference paper STRC 2004

STRC 4th Swiss Transport Research Conference
Monte Verità / Ascona, March 25-26, 2004

In-field verification of PM10 emission factors of road traffic

Robert Gehrig
Laboratory for Air Pollution/Environmental Technology
Swiss Federal Laboratories for Materials Testing and Research
CH-8600 Dübendorf

Phone: 01 823 42 34
Fax: 01 821 62 44
e-Mail: robert.gehrig@empa.ch

Abstract

Little is known about the the relevance of mechanically produced particles of road traffic from abrasion and resuspension processes in relation to the exhaust pipe particles. In a project, which was jointly realised by EMPA and PSI, concentration measurements of particles and nitrogen oxides (NO_x) in ambient air were performed on both sides of busy roads. During meteorological conditions with winds across the street it is possible to determine the contribution of the local traffic from upwind-downwind differences. Alternatively, these contributions can also be obtained from differences between kerbside sites and nearby background sites.

Emission factors of PM10 and PM1 for light and heavy-duty vehicles were derived for different representative traffic regimes. It was shown that the emissions from abrasion and resuspension processes are considerable in relation to the exhaust pipe particles. Given the fact, that the emissions from abrasion and resuspension processes represent roughly half or even more of the total primary particle emissions of road traffic, the question of possible impacts of these emissions has to be raised. Though quantitatively highly significant, these contributions have a completely different particle size distribution and chemical composition than exhaust pipe emissions. While the latter consist mainly of fine soot and organic particles (partly known as cancerogenic), abrasion and resuspension predominantly leads to coarse mineral and metallic particles. The current knowledge of the mechanisms, which are responsible for adverse effects of fine particles, does not allow a conclusive judgement concerning the relative importance of the emissions stemming from exhaust pipe as compared to abrasion and resuspension.

Keywords

PM10, particles, emission – 4th Swiss Transport Research Conference – STRC 2004 – Monte Verità

1. Introduction

Several epidemiological studies show a clear connection of the incidence of cardiovascular and pulmonary disease with the concentrations of fine particles (PM10 = particulate matter with aerodynamic diameter < 10 μm) in ambient air (AckermannLiebrich et al., 1997; Braun-Fahrlander et al., 1997; Dockery and Pope, 1994; Kunzli et al., 2000; Pope et al., 2002). Therefore, limit values for PM10 have been introduced into the Swiss clean air legislation (Luftreinhalteverordnung) in 1998. At present, the concentrations of PM10 in urban and sub-urban areas often exceed these limit values of 20 $\mu g/m^3$ (annual means) and 50 $\mu g/m^3$ (daily means) respectively (BUWAL, 2002). The formation processes of atmospheric fine particles (emissions of primary particles, formation of secondary particles from precursor gases) are extremely complex and knowledge is still insufficient.

The emissions of primary particles of road traffic are not only caused by fuel combustion (exhaust pipe emissions) but also by mechanical abrasion and resuspension processes. The direct exhaust pipe emissions of vehicles can be measured on test benches under well-defined conditions with a limited number of vehicles and with a defined test cycle. However, it remains an open question how well these laboratory experiments represent the real conditions on the roads concerning age, types and maintenance of the vehicles. It is well known that in particular the particle emissions of diesel vehicles can vary widely depending on the actual condition of the vehicle.

The current knowledge about particles, which are emitted (in addition to the exhaust) by mechanical abrasion processes from tyres, brakes, clutches and road surfaces, is still very scarce. There is also very little information about resuspension processes. For Switzerland only a very preliminary first estimation for a specific urban traffic situation is available (Hüglin, 2000). For US and Sweden some empirical estimation procedures for the contributions of abrasion and resuspension were proposed, which, however, could never be sufficiently be validated by measurements. A discussion of these attempts can be found in (Lohmeyer and Düring, 2001). This paper discusses the results of an extensive Swiss field study, which aimed at closing this knowledge gap. The method employed provided not only information about the exhaust pipe emissions of the actually circulating vehicle fleet, but also about emissions from abrasion and resuspension processes, which are not available from test bench measurements. In addition it was possible to obtain these information for different important traffic situations.

2. Goals of the project and experimental concept

The primary particle emissions of road traffic consist of a fraction stemming from fuel combustion (exhaust emissions) and a fraction from abrasion and resuspension processes. From test bench measurements good information about direct exhaust pipe emissions is already available (BUWAL, 2000; INFRAS, 1999). But it remains open, how well they represent the actually circulating vehicle fleet concerning types, age and maintenance. Still little is known about the additional emissions from mechanical abrasion of tyres, brakes, clutches and road surfaces and from resuspension of particles previously deposited on the streets. This knowledge gap was addressed in this project. The main goals were:

- The determination of total PM10 emission factors for different traffic situations,
- Quantitative information about the apportionment of the total PM10 emissions to exhaust pipe emissions and to abrasion/resuspension emissions,
- Quantitative information about the contribution of light and heavy-duty vehicles to exhaust pipe emissions and to abrasion/resuspension emissions.

Concentration measurements of particles (PM10, PM1) and nitrogen oxides (NO_x) in ambient air were performed on both sides of busy roads. During meteorological conditions with winds across the street it is possible to determine the contribution of the local traffic from downwind-upwind differences (Fig. 1). Alternatively, these contributions can also be obtained from differences between kerbside sites and nearby background sites.

Beta-ray absorption monitors (FH62 I-R) were used for the measurements of hourly values of PM10 and PM1 and chemiluminescence monitors (ML 8841) for NOx. Hourly dilution factors were calculated from the measured concentration differences of nitrogen oxides (NOx), the number of vehicles, and published NO_x emission factors. For NOx monitors shorter averaging times would have been possible, however, the limiting factor for only hourly time resolution was the relatively high noise of the PM monitors.

$$d = \frac{EF_{LDV,NOx} \cdot n_{LDV} + EF_{HDV,NOx} \cdot n_{HDV}}{\Delta NOx} \qquad (1)$$

The emission factors for particles were then calculated from the measured concentration differences, assuming that these undergo the same dilution as nitrogen oxides. Two vehicle categories were distinguished: LDV (light-duty vehicles < 6 m, i.e. petrol and diesel passenger cars, vans, motor cycles) and HDV (heavy-duty vehicles > 6 m, i.e. lorries, coaches and busses). In order to distinguish between exhaust pipe emissions and emissions from abrasion and resuspension the PM10 and PM1 fractions were measured separately. PM1 was interpreted as direct exhaust pipe emissions, and PM10 as total fine particle emissions. The difference PM10-PM1 thus represents the emissions from abrasion and resuspension. Additional size distribution measurements confirmed that PM10 and PM1 are well suited to distinguish between emissions from exhaust pipes and abrasion/resuspension processes (Gehrig et al., 2003).

$$\Delta PM1 = \frac{EF_{LDV,PM1}}{d} \cdot n_{LDV} + \frac{EF_{HDV,PM1}}{d} \cdot n_{HDV} \quad (2)$$

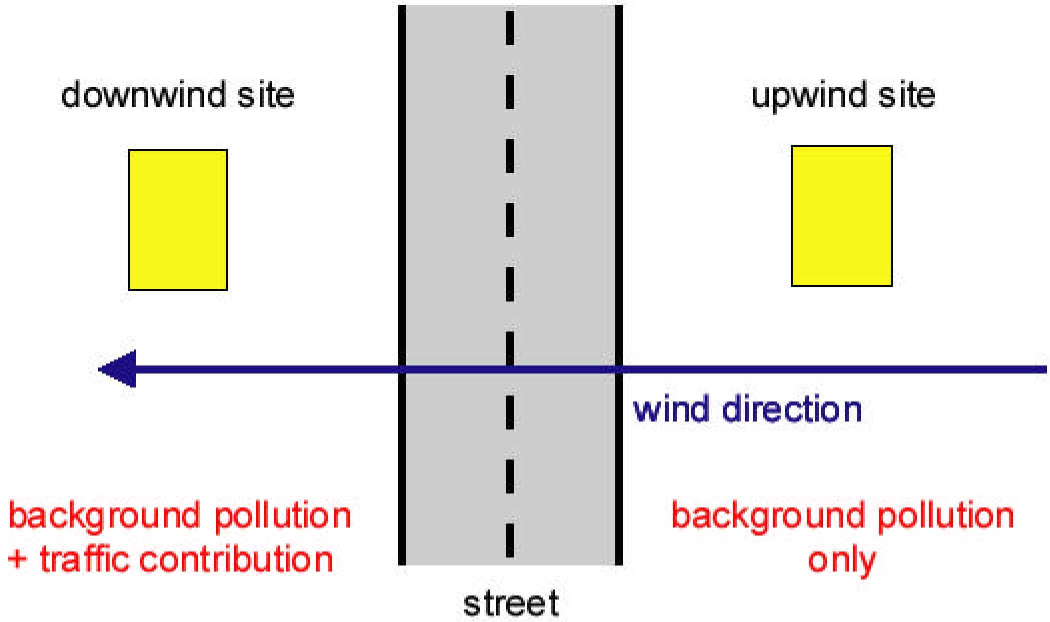
$$\Delta PM10 = \frac{EF_{LDV,PM10.}}{d} \cdot n_{LDV} + \frac{EF_{HDV,PM10.}}{d} \cdot n_{HDV} \quad (3)$$

Where

- $EF_{LDV,NOx}$ emission factor LDV for nitrogen oxides (as NO_2) [µg/m] = [mg/km]
- $EF_{HDV,NOx}$ emission factor HDV for nitrogen oxides (as NO_2) [µg/m] = [mg/km]
- $EF_{LDV,PM1}$ emission factor LDV for PM1 [µg/m] = [mg/km]
- $EF_{HDV,PM1}$ emission factor HDV for PM1 [µg/m] = [mg/km]
- $EF_{LDV,PM10}$ emission factor LDV for PM10 [µg/m] = [mg/km]
- $EF_{HDV,PM10}$ emission factor HDV for PM10 [µg/m] = [mg/km]
- ΔNOx concentration difference nitrogen oxides (as NO_2) downwind-upwind or kerbside-background [µg/m^3]
- $\Delta PM1$ concentration difference PM1 downwind-upwind or kerbside-background [µg/m^3]
- $\Delta PM10$ concentration difference PM10 downwind-upwind or kerbside-background [µg/m^3]
- d dilution [m^2/h]
- n_{LDV} LDV frequency [1/h]
- n_{HDV} HDV frequency [1/h]

From a sufficient number of measurements the PM emission factors can then be obtained by regression analysis.

Figure 1 Schematic view of the measurement concept



3. Measurement sites and investigated traffic situations

Tab. 1: Traffic situation at the investigated measurement sites

Site Traffic situation	LDV/h	HDV/h	total vehic./h	% HDV	speed (km/h) LDV/HDV*)
Aathal (Outside built-up area)	1102	71	1173	6.1	50/50
Birrhard (Motorway)	2495	265	2760	9.6	120/85
Humlikon (Motorway)	1471	210	1681	12.5	85/75
Rosengartenstrasse (Built-up area, slope 8%)	2741	168	2909	5.8	50/40
Schimmelstrasse (Built-up area, directly at traffic lights)	1074	80	1154	6.9	0-50/0-50
Weststrasse (Built-up area, 50 m distance from traffic lights)	1014	66	1080	6.1	0-50/0-50

*) The on-site speed measurements did not differentiate between LDV and HDV. The indicated values were estimated from observed speed distributions and HDV speed limits.

Tab. 2: Emission factors (mg/km) for the different sites for exhaust particles and NOx as estimated by BUWAL based on the "Handbook" (BUWAL, 2000; BUWAL, 2001; INFRAS, 1999; Jenk, 2003; UBA, 2003).

	exhaust particles	exhaust particles	NOx as NO_2	NOx as NO_2
	LDV	HDV	LDV	HDV
Aathal	13.5	283	290	9088
Birrhard	16.6	176	589	8662
Humlikon A4	10.0	187	361	8194
Zürich, Schimmelstrasse	12.1	449	394	13378
Zürich, Rosengartenstrasse (uphill)	34.0	491	714	24207
Zürich, Rosengartenstrasse (downhill)	10.7	272	69	5622
Zürich, Weststrasse	10.9	342	353	12332

4. Results

Tab 3 shows an overview of the PM10, PM1 and NOx concentration differences at the investigated sites. The measured differences between downwind and upwind side of the streets (resp. between kerbside and background) for NOx were at most times high enough to allow for a reliable calculation of the dilution according to equation (1).

Tab. 3: Mean measured concentration differences (downwind-upwind resp. kerbside-background) for PM10, PM1 and NOx (calculated as NO_2)

	ΔPM10 [µg/m³]	ΔPM1 [µg/m³]	ΔNOx [µg/m³]
Aathal/Seegräben	7.1	2.3	86
Birrhard	4.1	1.8	66
Humlikon	3.4	1.5	68
Rosengartenstrasse/ Zeughaushof	3.9	2.3	87
Schimmelstrasse/ Zeughaushof	12.1	--	85
Weststrasse/ Zeughaushof	10.9	3.2	121

For the PM measurements the contributions from the local traffic in relation to the background concentrations was much smaller than for NOx. This resulted in relatively high measurement uncertainties for the PM differences. The evaluation model described in equation (1)-(3) therefore produced reliable results only for the site Weststrasse with the highest PM differences. At the other sites the model did not provide a reliable differentiation for LDV and HDV. However, it was possible to calculate emission factors for PM10 and PM1 per vehicle (without differentiation between LDV and HDV) from hourly concentration differences according to the following simple equations:

$$\Delta PM10 = \frac{EF_{PM10}}{d} \cdot n_{total} \quad \rightarrow \quad EF_{PM10} = \frac{\Delta PM10 \cdot d}{n_{total}} \qquad (4)$$

$$\Delta PM1 = \frac{EF_{PM1}}{d} \cdot n_{total} \quad \rightarrow \quad EF_{PM1} = \frac{\Delta PM1 \cdot d}{n_{total}} \qquad (5)$$

Where

d dilution calculated according to equation (1)

n_{total} total vehicle frequency (LDV + HDV per h)

Table 4 shows the emission factors per vehicle calculated according to equations (4) and (5). EF(PM10) represent the total emission of fine particle emissions, EF(PM1) the direct exhaust pipe emissions, and. EF(PM10-PM1) thus represents the emissions from abrasion and resuspension processes. Though the corresponding statistical uncertainties (Table 5) seem quite high, they agree for PM1 very well with the expected values given in the handbook. As already mentioned, it was extremely difficult to get reliable results with the evaluation differentiating between LDV and HDV according to equations (1) – (3). This approach was only successful for the site Weststrasse. Nevertheless, a rough apportionment of the emission factors to LDV and HDV could be obtained based on more robust mean values for weekdays, Saturdays and Sundays instead of hourly values. The emission factors are given in Table 6. However, a quantitative estimation of the measurement uncertainty was not possible.

Tab. 4: Mean emission factors (mg/km) per vehicle (in parenthesis: PM1 emission factors calculated from handbook values for the actual LDV-HDV mix at each site)

	EF (PM10) [mg/km]	EF (PM1) [mg/km]	EF (PM10-PM1) [mg/km]
Aathal	67	23 (30)	44
Birrhard	83	33 (32)	50
Humlikon	71	34 (32)	37
Rosengartenstrasse	56	34 (43)	22
Schimmelstrasse	184	*42*)*	142
Weststrasse	104	29 (31)	75

*) No PM1-measurement available at this site; EF(PM1) taken from handbook.

Tab. 5: Measurement uncertainties in percent (95% confidence interval) of the emission factors

	EF (PM10)	EF (PM1)	EF (PM10-PM1)
Aathal	22	70	73
Birrhard	17	45	48
Humlikon	18	47	50
Rosengartenstrasse	39	70	80
Schimmelstrasse	14		
Weststrasse	14	50	52

Tab. 6: Estimations of the emission factors (mg/km) for LDV and HDV based on hourly measurements (Weststrasse) and on weekday/weekend means for the other sites.

		EF (PM10) [mg/km]	EF (PM1) [mg/km]	EF(PM10-PM1) [mg/km]
Aathal	LDV	46	13	33
	HDV	394	187	207
Birrhard	LDV	63	16	47
	HDV	267	193	74
Humlikon	LDV	33	11	22
	HDV	344	200	144
Rosengartenstrasse	LDV	30	13	17
	HDV	496	381	115
Schimmelstrasse 2002 *)	LDV	104	12	92
	HDV	1268	449	819
Weststrasse	LDV	49	10	39
	HDV	703	320	383

*) No PM1-measurement available at this site; EF(PM1) taken from handbook.

5. Conclusions

Abrasion and resuspension processes represent a significant part of the total primary PM10 emissions of road traffic. At sites with relatively undisturbed traffic flow (Aathal, Birrhard, Humlikon, Rosengartenstrasse) they are in the same range as the exhaust pipe emissions. At sites with disturbed traffic flow (Schimmelstrasse, Weststrasse) emissions from abrasion/resuspension are even higher than those from the exhaust. German studies showed similar results, and, furthermore, indicated a pronounced impact of the paving condition (Lohmeyer and Düring, 2001). In one case the emissions on a road with damaged paving and dusty roadsides were by factors higher than those from roads with intact paving and roadsides with no uncovered dusty surfaces.

An assessment of the potential hazard of the mechanically produced particles as compared to the exhaust particles would be of interest. There are important differences concerning size distribution as well as chemical composition. While exhaust particles consist primarily of finest soot and organic compounds (partly known as cancerogenic) relatively coarse mineral and metallic particles dominate the fraction of the mechanically produced particles. The current knowledge of the mechanisms, which are responsible for adverse effects of fine particles, does not allow a conclusive judgement concerning the relative importance of the emissions stemming from exhaust pipe as compared to abrasion and resuspension. Further studies should attempt to close this significant gap.

Based on the new information from this project, the total primary PM10 particle emissions of road traffic in Switzerland were recalculated (Gehrig et al., 2003). For the year 2000 they were roughly 25% lower than estimated in an earlier publication in 2001 (BUWAL, 2001). Consequently road traffic contributes approximately 20% to the total primary PM10 emissions in Switzerland. The PM1 emission factors at the different sites correspond very well with the respective values of the Handbook, which are based on dynamometric test bench measurements.

Within the scope of this project it was possible to obtain quantitative information about emissions factors for fine particle mass from road traffic. However, some limitations of the evaluation concept have to be kept in mind. The concept assumes e.g. that the NOx emission factors, which are needed for the calculation of the actual dilution conditions, are known. Therefore the newest available knowledge about NOx emissions was used. Changes in the NOx emissions factors would have a direct impact on the emission factors of PM10 and PM1 as calculated in this project. However, in this case only calculative corrections would be necessary without a need for new measurements.

An important limitation is the still unsatisfactory state of the art for particle mass measurements with high time resolution. The monitors used for the PM10 and PM1 measurements allowed a time resolution of only 1 hour, and even this with a still considerable statistical noise of the signal. Moreover the local traffic contributions to PM10 and PM1 are generally small compared with the background concentrations. This resulted in considerable measurement uncertainties for the differentiation between LDV and HVD emission factors, which cannot exactly be quantified..

Concerning the emission factors for particles from abrasion and resuspension processes the concept of a defined emission per vehicle and km is questionable. In the case of a road in an open surrounding with wind across the street the concept is plausible because the mechanically produced particles are continuously transported off the street and no accumulation of these particles on the street is to be expected. Therefore, resuspension should be of minor importance in this situation. However, without wind or in a street canyon sedimentation of the produced abrasion particles on the street surface with subsequent resuspension is possible. It seems plausible, that this portion of the particles can be kept in suspension already by a small number of passing vehicles and is not increased much if more vehicles pass. The emissions by resuspension would then not be proportional to the traffic frequency. In addition it has to be kept in mind that the emissions from abrasion depend strongly on the local condition of the pavement.

This study shows the importance of the so far neglected particle emissions from abrasion and resuspension processes. Further research should concentrate on a quantitative apportionment of these emissions to the involved processes (abrasion of road surface, tyre wear, brake wear, clutch wear). This information is strongly needed for the development of efficient measures for emission reductions.

6. References

AckermannLiebrich, U., Leuenberger, P., Schwartz, J., Schindler, C., Monn, C., Bolognini, C., Bongard, J.P., Brandli, O., Domenighetti, G., Elsasser, S., Grize, L., Karrer, W., Keller, R., KellerWossidlo, H., Kunzli, N., Martin, B.W., Medici, T.C., Perruchoud, A.P., Schoni, M.H., Tschopp, J.M., Villiger, B., Wuthrich, B., Zellweger, J.P., and Zemp, E., 1997. Lung function and long term exposure to air pollutants in Switzerland, American Journal of Respiratory and Critical Care Medicine 155(1), 122-129.

BraunFahrlander, C., Vuille, J.C., Sennhauser, F.H., Neu, U., Kunzle, T., Grize, L., Gassner, M., Minder, C., Schindler, C., Varonier, H.S., and Wuthrich, B., 1997. Respiratory health and long-term exposure to air pollutants in Swiss schoolchildren, American Journal of Respiratory and Critical Care Medicine 155(3), 1042-1049.

BUWAL, 2000. Luftschadstoff-Emissionen des Strassenverkehrs 1950-2020, Nachtrag; Schriftenreihe Umwelt Nr. 255, Luft, pp. 83, BUWAL, Bern.

BUWAL, 2001. Massnahmen zur Reduktion der PM10-Emissionen, pp. 112, Electrowatt Engineering AG, R. Kropf, Swiss Federal Office for Environment, Forest and Landscape, Bern.

BUWAL, 2002. NABEL, Luftbelastung 2001; Schriftenreihe Umwelt Nr. 343, Luft, pp. 217, BUWAL, Bern.

Dockery, D.W., and Pope, C.A., 1994. Acute Respiratory Effects of Particulate Air-Pollution, Annual Review of Public Health 15(107-132.

Gehrig, R., Hill, M., Buchmann, B., Imhof, D., Weingartner, E., and Baltensperger, U., 2003. Verifikation von PM10-Emissionsfaktoren des Strassenverkehrs, pp. 203, Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation/Bundesamt für Strassen, Bern.
Available on Internet: http://www.empa.ch/plugin/template/empa/700/5750/---/l=1

Hüglin, C., 2000. Anteil des Strassenverkehrs an den PM10- und PM2.5-Immissionen; Chemische Zusammensetzung des Feinstaubs und Quellenzuordnung mit einem Rezeptormodell, pp. 161, Nationales Forschungsprogramm NFP41 Verkehr und Umwelt, Bericht C4, Bern.

INFRAS, 1999. Handbuch Emissionsfaktoren des Strassenverkehrs, Version 1.2 (CD-ROM); im Auftrag des BUWAL, Bern/Berlin.

Jenk, H., 2003. Persönliche Mitteilung.

Kunzli, N., Kaiser, R., Medina, S., Studnicka, M., Chanel, O., Filliger, P., Herry, M., Horak, F., Puybonnieux-Texier, V., Quenel, P., Schneider, J., Seethaler, R., Vergnaud, J.C., and Sommer, H., 2000. Public-health impact of outdoor and traffic-related air pollution: a European assessment, Lancet 356(9232), 795-801.

Lohmeyer, A., and Düring, I., 2001. Validierung von PM10-Immissionsberechnungen im Nahbereich von Strassen und Quantifizierung der Feinstaubbildung von Strassen, pp. 80, Senatsverwaltung für Stadtentwicklung Berlin, Sächsisches Landesamt für Umwelt und Geologie Dresden, Radebeul.

Pope, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., and Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, Jama-Journal of the American Medical Association 287(9), 1132-1141.

UBA, 2003. Emission functions for heavy duty vehicles; Update of the emission functions for heavy duty vecicles in the handbook emission factors for road traffic; Bericht BE-223; Umweltbundesamt GmbH, Wien.