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PM10-Emissionsfaktoren von Abriebspartikeln des Strassenverkehrs (APART)

PM10 emission factors of abrasion particles from road traffic

Facteurs d'émission des particules d'abrasion dues au trafic routier

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Forschungsauftrag ASTRA 2005/007 auf Antrag des Bundesamtes für Strassen (ASTRA)

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Table of Contents

Der Hauptbericht ist in englischer Sprache verfasst.

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1 Summary

1.1 Motivation

Particle emissions of road traffic are generally associated with fresh exhaust emissions. However, the preceding research project ASTRA2000/415 as well as several recent studies identified a clear contribution of non-exhaust emissions to the traffic related PM10 load of the ambient air. These emissions consist of particles produced by abrasion from brakes, road wear, tire wear, as well as vehicle induced resuspension of deposited road dust. For many urban environments, quantitative information about the contributions of the individual abrasion processes is still scarce. For effective PM10 reduction scenarios it is of particular interest to know whether road wear, resuspension or fresh abrasion from vehicles dominates the non-exhaust PM10 emissions.

1.2 Goal, concept and experiments

1.2.1 Main goals

The main scope of the project APART (Abrasion PArticles produced by Road Traffic) was to identify and quantify the non-exhaust fraction of traffic related PM10 for several road-side locations with characteristic traffic regimes.

Specific goals:

- To provide a reliable base for future PM10 reduction scenarios
- Determination of location-specific emission factors (mg/km/vehicle) for *trace elements* emitted by local road traffic.
- Calculation of location-specific emission factors (mg/km/vehicle) for individual *non-exhaust emission sources*.
- Separation of emission factor values for light duty vehicles (LDV) and heavy duty vehicles (HDV).
- Evaluation of the local mass contribution from individual non-exhaust sources (% of traffic related PM10).

Scope exclusion:

- The study focused on traffic related emissions and did not include a quantification of other PM10 sources.
- Exhaust related PM10 was quantified at the investigated locations to establish a mass balance of total traffic related PM10. An in-depth interpretation of the exhaust fraction is however subject of other studies and was not within the scope of the present investigation.

1.2.2 Concept

The selection of the investigated locations was based a) on their traffic and roadside characteristics being typical also for other real-world situations and b) on their experimental and conceptual applicability. To separate traffic related emissions from the total ambient PM10 load, representative background measurements were performed either upwind of the selected measuring location, or at a suitable background site (Figure 1.1). The identification of individual traffic related sources was based on specific elemental fingerprint signatures for the various sources. These fingerprints were obtained by hourly elemental mass concentration measurements in three size classes (2.5-10, 1-2.5 and 0.1-1 micrometers). A rotating drum impactor (RDI) was used as sampling device for this purpose. The collected samples were analyzed by synchrotron radiation X-ray fluorescence spectrometry (SR-XRF). The elemental fingerprint measurements were accompanied by additional aerosol, gas phase and meteorological measurements, and by traffic counting for light and heavy duty vehicles. The mathematical identification of the abrasion sources from the experimental data was performed by positive matrix factorization (PMF), a statistical method widely used for this purpose. The atmospheric dilution of the emissions from their point of emission to the point of sampling (10-20 m) was obtained by background corrected NO_x measurements and known NO_x emissions at the considered site. This dilution, along with the traffic counts, allowed for the calculation of vehicle specific emission factors for the measured tracer species and for the identified abrasion sources with help of a statistical model. To ensure a statistically significant calculation of emission factors, only time periods with distinctively high background corrected NO_x concentrations (ΔNO_x > 20 µg m^{-3}) were considered for analysis. The presented emission factors are independent of the exact measurement position along the road.

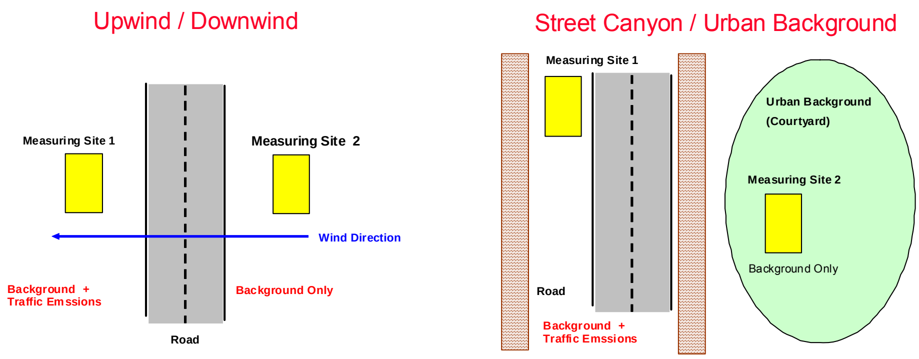

Fig. 1.1: Schematic illustration of the upwind-downwind concept (left) and the traffic vs. background concept (right). The sampling inlets of the measuring sites were located 4.5 m above ground, defined by experimental preconditions.

1.2.3 Measurements in Zürich at Weststrasse and Kaserne (February and March 2007)

The Zürich-Weststrasse site represented an urban street canyon with the following traffic characteristics:

- 'Stop-and-go traffic': Urban main road with traffic lights, strong disturbances (Category 'IO_HVS3' according to *Handbook of Emission Factors*, http://www.hbefa.net). Closed for transit traffic from 22:00 to 06:00.
- Pavement: Asphalt concrete (AB12), year of application: 1995/98
- Vehicle counting: <6m; (Light duty vehicles including 9% delivery vans), >6m (Heavy duty vehicles including motor coaches). Traffic counting was performed by Empa.
- Weekdays: 22000 vehicles per day (heavy duty vehicle fraction 12%)
- Saturdays: 21000 vehicles per day (heavy duty vehicle fraction 5%)
- Sundays: 19000 vehicles per day (heavy duty vehicle fraction 4%)

To quantify the local PM10 contributions at Zürich-Weststrasse, simultaneous measurements of the urban background were performed at Zürich-Kaserne (approximately 600 m distance from Zürich-Weststrasse). During the considered time periods, PM10 at Zürich-Kaserne was shown to also represent the urban background at Zürich-Weststrasse. It consisted of the accumulated contributions of all urban PM10 sources (both traffic and non-traffic related sources), as illustrated in Figure 1.2. Figure 1.3 shows the measured PM10 concentrations at both sites for a selected time period with a prevailing meteorological inversion.

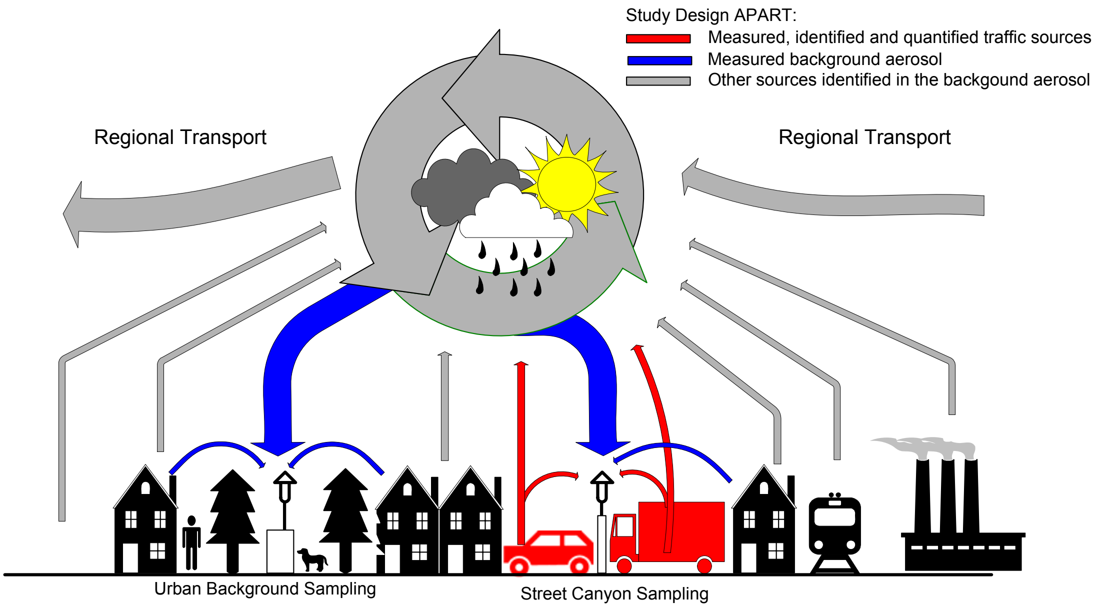

Fig. 1.2: Schematic view of relevant pollutant fluxes in an urban environment. To evaluate the local contribution of road traffic, all local background sources (also traffic emissions from other locations) as well as the meteorological dilution and chemical transformation have to be considered.

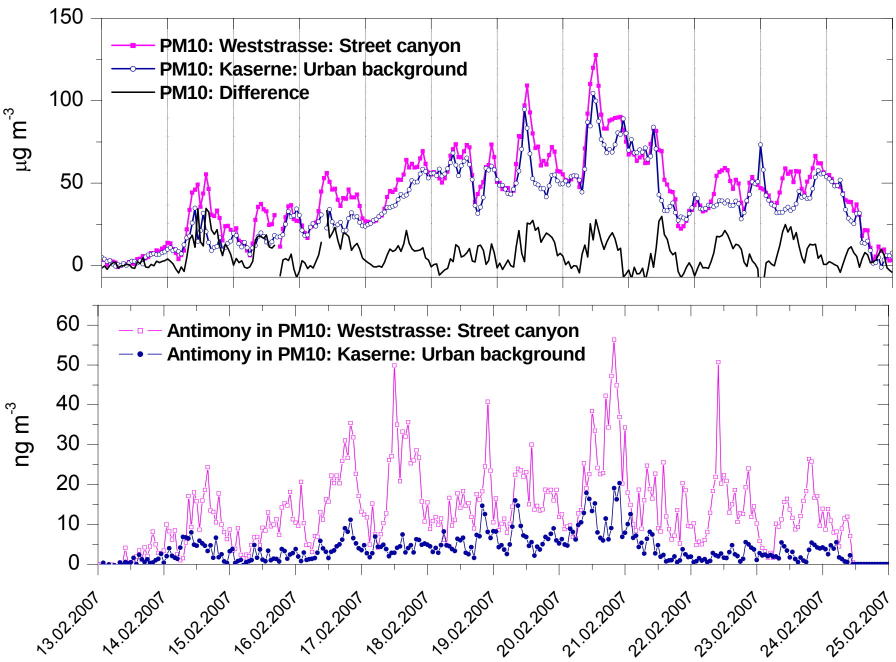

Fig. 1.3: Temporal evolution of PM10 and antimony in a street canyon in Zürich before, during and after a meteorological inversion situation (hourly values). Upper panel: The black line represents the difference between the street canyon and the background and thus represents the local traffic contribution to PM10 in the street canyon.

1.2.4 Measurements in Reiden (July – November 2007)

Measurements were performed in Reiden LU, along the national freeway A2 with the following traffic characteristics:

- Motorway with free-flowing traffic at 120 km h^{-1} (Category 'AB_120' according to *Handbook of Emission Factors,* http://www.hbefa.net)
- Pavement: Splitt-mastix asphalt (compact pavement comparable to asphalt concrete); direction Luzern SMA 11 B 80/100+NAF; direction Basel SMA 11 B55/70+NAF, year of application: 1999.
- Vehicle counting: Light duty vehicles (including 15% delivery vans) versus heavy duty vehicles (including motor coaches). Traffic counting was performed by ASTRA (lu_reiden-s-239)
- Weekdays: 49000 vehicles per day (heavy duty vehicle fraction 16%)
- Saturdays: 45000 vehicles per day (heavy duty vehicle fraction 7%)
- Sundays: 41000 vehicles per day (heavy duty vehicle fraction 2%, including coaches)

Measuring stations were placed at both sides of the freeway. For time periods with perpendicular wind, the upwind station measured the local background PM10 load, while the downwind station detected the background plus the local traffic PM10 emissions (Figure 1.1). Figure 1.4 shows the measured PM10 concentrations at both sites for a selected time period.

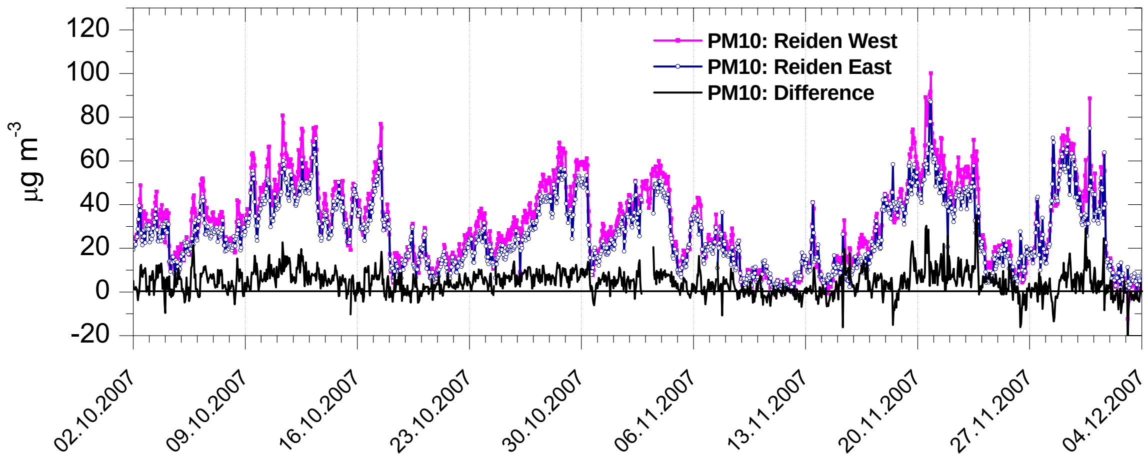

Fig. 1.4: Temporal evolution of PM10 in Reiden (hourly values). The solid black line represents the difference between the PM10 concentrations measured at both sides of the freeway, which was strongly dependent on the wind direction.

1.2.5 Complementing experiments

The road-side measurements provided a robust real-world data base, allowing for extensive data treatment and evaluations of PM10 related sources. To complete the overall results of the study, additional experiments were performed:

- **Resuspended road dust versus road wear:** A separation between road wear and resuspension of deposited dust can not easily be obtained from field measurements. Even with detailed chemical speciation these two sources can hardly be distinguished due to their similar elemental composition and highly correlated variation in time. A so-called "mobile load simulator" offered a possibility to tackle this issue. These devices are designed and used by road engineers to test the properties and durability of road pavements in the field. In this study emission rates for road wear were derived from measurements with two different types of mobile load simulators on different types of road pavement (asphalt concrete, porous asphalt). The experimental set-up allowed for a separate characterization of the emissions caused by fresh in-situ abrasion and by resuspension of previously deposited dust.

- **Deposited road dust:** Deposited PM10 collected from the surface of a road provides important information on the chemical composition of vehicle induced PM10 resuspension. A specialized instrument for the collection of road dust was used in a sampling campaign in Zurich in February 2008.

- **Mobile PM10 and PM1 measurements:** To investigate the spatial variation of individual particle size ranges within the city of Zürich, a series of mobile measurements was performed in Zürich in June 2007 using a mobile measurement platform.

1.3 Results

1.3.1 Traffic related PM10 emissions in Zürich-Weststrasse

1.3.1.1 Mass relevant PM10 traffic sources

For Zürich-Weststrasse, the following mass relevant traffic related PM10 sources were identified from the hourly measurements by the applied statistical method (positive matrix factorization):

- **Brake wear.** Brake wear was characterized by a specific pattern of Fe, Cu, Zn, Zr, Mo, Sn, Sb and Ba. These elements are widely used constituents of brake linings and are likely to be oxidized during the brake abrasion process.

- **Exhaust emissions:** Exhaust emissions predominantly consisted of organic and inorganic carbon species, expressed as total traffic related carbon. Trace elements originating from fuel additives were not specifically identified from the road side measurements, indicating that these contributions are low on a mass base and other emission sources of these elements are more relevant.

- **Vehicle induced resuspension of road dust:** Besides the large abundance of mineral elements in deposited and resuspended road dust, characteristic contributions of brake wear and exhaust particles (carbon) were clearly identified.

Road wear and tire wear were not identified as separate sources from the measurements at Zürich-Weststrasse, due to the absence of unique tracer species. With the applied approach of analysis, any unidentified contributions from road wear and tire wear were added to the other sources. However, the presented source apportionment is only minimally biased by undetermined contributions from these sources:

- **Road wear versus road dust resuspension:** The controlled experiments with a mobile load simulator showed that direct abrasion wear from the road surface is of minor importance for pavements in good condition. However, damaged pavement surfaces can cause quite significant PM10 emissions.

- **Tire wear:** Reliable information for PM10 emissions from tire wear can hardly be found in literature. Some older works report contributions up to 10% to urban PM10 concentrations. However, none of the applied methods was specific enough to be convincing. A new, still unpublished study at two urban traffic sites in Wiesbaden (Germany) for the first time uses a method that seems to be really specific (analysis of pyrolysis products of tire rubber) and find a mean contribution of tire wear of

0.5% to PM10. The same work shows that the earlier assumed contribution of up to 10% tire wear assumed earlier really exists, but in particle fractions >10 µm and not in PM10. This was also qualitatively confirmed by microscopic evidence. In agreement with these findings, PM10 tire wear emissions for the simulator experiments performed during APART were found to be negligible.

1.3.1.2 Emission factors for traffic related PM10 at Zürich-Weststrasse

Table 1.1 and Figure 1.5 show emission factors for the traffic related PM10 sources, with separate values for light and heavy duty vehicles, and for the average vehicle fleet. Emission factors were calculated from the hourly mass concentrations of the individual traffic sources. For the calculations, the atmospheric dilution of the emissions was taken into account, which was obtained from background corrected NO_x measurements and known NO_x emissions at the considered site. The applied calculation models also considered individual vehicle counts for light and heavy duty vehicles, which allowed for the calculation of separate emission factors for light and heavy duty vehicles. Table 1.1 shows that considerable uncertainties were introduced by splitting the fleet emission factors into vehicle type specific emission factors.

The calculated PM10 emission factors for **Zürich-Weststrasse** show the following characteristics:

- **Vehicle Fleet :** The average PM10 emission factor, related to a HDV fraction of 10%, was mainly caused by exhaust emissions (41%) and vehicle induced resuspension of road dust (38%), followed by brake wear (21%).
- **Light and heavy duty vehicles:** Exhaust (63%) and brake wear (33%) were the dominant PM10 emissions for **light duty vehicles**. In contrast, emissions from resuspension of road dust were estimated to be totally less than 5 % for light duty vehicles. Compared to light duty vehicles, the absolute emission factors for **heavy duty vehicles** were 15 times higher for total PM10 and 10 times higher for brake wear and the exhaust emissions. For heavy duty vehicles, the road dust resuspension capability of an individual heavy duty vehicle was estimated to be substantial. 53% of the PM10 emissions of an individual heavy duty vehicle were attributed to road dust resuspension. Exhaust emissions (31%) and brake wear (16%) are additional important contributions. In the heavily trafficked street canyon at Zürich-Weststrasse, the emissions from resuspension are likely to be limited by the amount of resuspendable dust. The available dust on the surface was resuspended and kept in suspended state mainly by the turbulence induced by the heavy duty vehicles, leaving only small amounts of dust to be resuspended by the light duty vehicles. From this finding at Weststrasse, however, it can not be concluded, that resuspension is generally not induced by LDV. In the case of little or no heavy duty vehicle traffic, the resuspension would also be induced by the light duty vehicle fleet.

While a strong correlation of brake wear and exhaust emissions with the hourly traffic frequencies was found, the diurnal pattern of vehicle induced resuspension was less correlated and characterized by a larger statistical variation. Therefore emission factors expressed as mg/km/vehicle are not appropriate for road dust resuspension. As a consequence, vehicle specific emission factors could not be calculated using the multilinear regression model, but could only be indirectly estimated with accordingly high absolute uncertainties. Since resuspension was found to be a relevant contributor to total traffic related PM10, the same applies to PM10.

Table 1.1: Emission factors for the individual sources contributing to traffic related PM10, valid for Zürich-Weststrasse (urban street canyon). LDV: Light duty vehicles (including 9% delivery vans), HDV: Heavy duty vehicles (including motor coaches). Brake wear was quantified assuming a brake dust antimony content of 1% and a copper content of 5%. Total traffic related carbon was estimated from black carbon measurements, using an experimentally determined ratio of 1.45 for traffic related carbon to emitted black carbon. Values are based on 12 days of measurements in February an March 2007, $\Delta NO_x > 20$ µg m^{-3}, dry time periods only) and are based on NO_x emission factors estimated for Zürich-Weststrasse (Year: 2007, $EF_{NOx}(LDV) = 286.8$ mg km^{-1}, $EF_{NOx}(HDV) = 10559$ mg km^{-1}, NO_x calculated as NO_2, *Handbook of Emission Factors, http://www.hbefa.net*) For comparison, emission factors for road wear and resuspension from mobile load simulator experiments are shown. The Table shows that considerable uncertainties were introduced by splitting the fleet emission factors into vehicle type specific emission factors.

Source	**Source quantification**	**Emission factor calculation**	**Zürich-Weststrasse**		
			Fleet 10% HDV[*1] mg/km/veh	**LDV [*2] mg/km/veh**	**HDV[*2] mg/km/veh**
Traffic related PM10	Measured (PM10-Difference: Street canyon - background	Estimated from mass balance	**71**	**24 ± 8**	**498 ± 86**
Brake wear	Statistical modelling[*3]	Multilinear regression	**15**	**8 ± 4**	**81 ± 39**
Exhaust (Total traffic related carbon species)	Statistical modelling[*3]	Multilinear regression	**29**	**15 ± 6**	**155 ± 67**
Road dust resuspension	Statistical modelling[*3]	Estimated from mass balance	**27**	**1 ± 11**	**262 ± 115**
Road Wear	Mobile load simulator experiments		-	(<3)[*a,d]	(7)[*a] (80[*b])
Resuspension[*d]			-	(5)[*d] (76)[*a]	(110)[*c] (660[*b])

[*1] Average heavy duty vehicle fraction during the entire field campaign in February and March 2007 (varies strongly within a day)

[*2] Multilinear model with individual consideration of hourly traffic composition

[*3] PMF (positive matrix factorization)

[*a] new asphalt concrete

[*b] asphalt concrete in poor condition

[*c] asphalt concrete in good condition

[*d] new porous asphalt

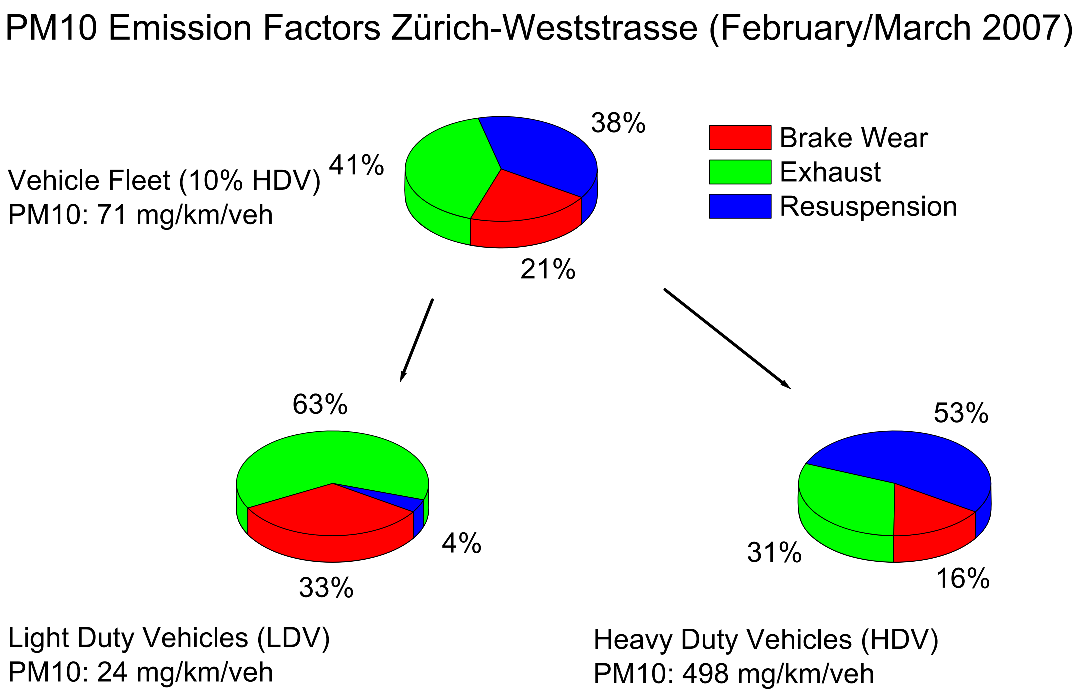

Fig. 1.5: Traffic PM10 emission factors determined for Zürich-Weststrasse and their composition. Considerable uncertainties were introduced by splitting the fleet emission factors into vehicle type specific emission factors.

1.3.2 Traffic related PM10 emissions in Reiden LU

1.3.2.1 Mass relevant PM10 traffic sources

For Reiden, the following mass relevant traffic related PM10 sources were identified from the hourly measurements by the applied statistical method (positive matrix factorization):

- **Brake wear:** Brake wear was characterized by a specific pattern of Fe, Cu, Zn, Zr, Mo, Sn, Sb and Ba. The pattern was very similar to the one found at Zürich-Weststrasse. These elements are widely used constituents of brake linings and are likely to be oxidized during the brake abrasion process.
- **Exhaust emissions:** The exhaust emissions were predominantly formed by organic and inorganic carbon species, expressed as total traffic related carbon. Like at Zürich-Weststrasse, trace elements originating from fuel additives were not specifically identified from the road side measurements, indicating that the contributions are low and other emission sources of these elements were more relevant on a mass base.

Contributions of mineral dust elements to traffic emissions were identified, pointing to vehicle induced road dust resuspension. A specific quantification for resuspension based on these contributions was however not possible, because no reliable composition profile was available for road dust deposited on the freeway.

1.3.2.2 Emission factors for traffic related PM10 at Reiden

Table 1.2 and Figure 1.6 show emission factors for the traffic related PM10 sources, with separate values for light and heavy duty vehicles, and for the average vehicle fleet. Emission factors were calculated from the hourly mass concentrations of the individual traffic sources. For the calculations, the atmospheric dilution of the emissions was taken into account, which was obtained from background corrected NO_x measurements and known NO_x emissions at the considered site. The applied calculation models also considered individual vehicle counts for light and heavy duty vehicles, which allowed for the calculation of separate emission factors for light and heavy duty vehicles. Table 1.2 shows that considerable uncertainties were introduced by splitting the fleet emission factors into vehicle type specific emission factors.

The calculated PM10 emission factors for **Reiden** show the following characteristics:

- **Vehicle fleet:** The average PM10 emission factor for Reiden (15% HDV fraction during the entire campaign) was caused by exhaust emissions (41%) and very low contributions from brake wear emissions (3.2%). The remaining 56% of the traffic emissions were not directly identified, but probably represented contributions from road dust resuspension (and minor contributions from tire wear and road wear).
- **LDV and HDV emission factors:** The PM10 emission factor for HDV was 5.8 times higher than for LDV. Because the mass contributions of both brake wear and traffic related carbon were extrapolated from the same traffic source identified by PMF, the resulting LDV and HDV emission factors showed virtually identical source contributions. An alternative calculation of LDV and HDV emission factors for brake wear and exhaust directly from measured concentration differences of specific marker species (Sb, BC) did not lead to statistically significant results. In contrast to Zürich-Weststrasse, the resuspended dust was removed laterally due to the perpendicular winds (upwind/downwind concept), rather than being kept in suspended state by the turbulence induced by heavy duty vehicles. Therefore a part of the resuspended road dust was also attributed to light duty vehicles.

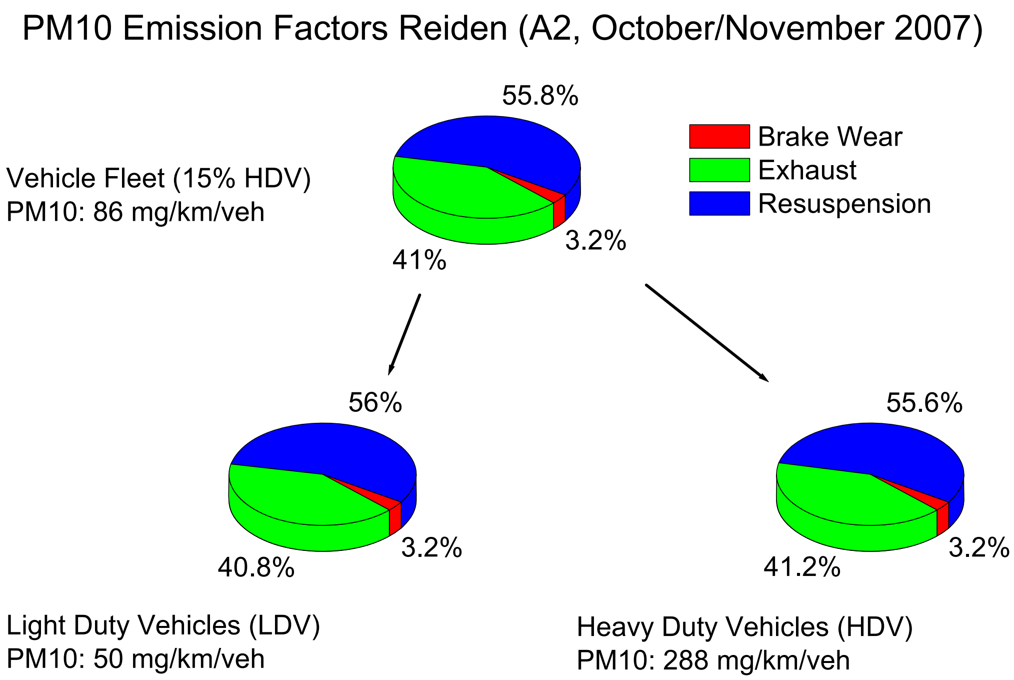

Fig. 1.6: Traffic PM10 emission factors determined for Reiden (A2) and their composition. Considerable uncertainties were introduced by splitting the fleet emission factors into vehicle type specific emission factors.

Table 1.2: Emission factors for the individual sources contributing to traffic related PM10, valid for Reiden LU (Autobahn). LDV: Light duty vehicles (including 15% delivery vans), HDV: Heavy duty vehicles (including motor coaches). Brake wear was quantified assuming a brake dust antimony content of 1% and a copper content of 5%. Total traffic related carbon was estimated from black carbon using the same empirical conversion factor of 1.45 as for Zürich-Weststrasse, due to the lack of a specific factor for Reiden. Values are based on 4 days of measurements in October and November 2007, dry time periods only) and are based on NO_x emission factors estimated for Reiden LU (Year: 2007, EF_{NOx}(LDV) = 448 mg km^{-1}, EF_{NOx}(HDV) = 5421 mg km^{-1}, NO_x calculated as NO_2, *Handbook of Emission Factors,* http://www.hbefa.net). The table shows that considerable uncertainties were introduced by splitting the fleet emission factors into vehicle type specific emission factors.

Source	Source quantification	Emission factor calculation	Reiden (LU) A2		
			Fleet 15% HDV[*1] mg/km/veh	**LDV[*2] mg/km/veh**	**HDV[*2] mg/km/veh**
Traffic related PM10	Measured (PM10-Difference: Downwind - Upwind	Multilinear regression	**86**	**50.0 ± 13**	**288 ± 72**
Brake Wear	Statistical modelling[*3]	Multilinear regression	**3**	**1.6 ± 1.1**	**9 ± 7**
Exhaust (Total traffic related carbon species)	Statistical modelling[*3]	Multilinear regression	**35**	**20.4 ± 7**	**119 ± 38**
Rest (Resuspension and minor sources[*4])	Estimated from mass balance		**48**	**28 ± 14**	**160 ± 82**

[*1] Average heavy duty vehicle fraction in October and November 2007 (varies strongly within a day)
[*2] Multilinear model with individual consideration of hourly traffic composition
[*3] PMF (positive matrix factorization)
[*4] Tire wear and road wear

1.3.3 Emission factor comparison with earlier research

The comparison of the traffic related PM10 emission factors for Zürich-Weststrasse and Reiden (A2) showed the following (values see Tables 1.1 and 1.2):

- The total PM10 fleet emission factor for Reiden (15% HDV, free-flowing traffic) was 20% higher than for Zürich-Weststrasse (10% HDV, heavily disturbed traffic), due to higher exhaust emissions and larger contributions from vehicle induced road dust resuspension.
- In contrast, the fleet emission factor for brake wear was found to be 5 times lower in Reiden compared to Weststrasse, due to the absence of relevant braking activity in the mainly free-flowing freeway traffic.

Table 1.3 compares the determined emission factors to values from earlier studies and emission inventory values for comparable locations in Switzerland:

- Temporal tendency: At Zürich-Weststrasse, a decrease in the PM10 fleet emission factors over time is observed. In contrast, the fleet emission value determined for Reiden is about equal to a value obtained for Birrhard in 2004, a site with a similar traffic regime.

- Exhaust emissions: The estimated values for exhaust emissions are in line with inventory values, considering the uncertainty of determination.
- Non-exhaust emissions and total traffic related PM10: These emission factors strongly depend on the influence of vehicle induced road dust resuspension during the time periods considered in the respective investigations. Therefore, differences rather reflect local conditions at the measurement sites (dirt load on the road surface, condition of pavement) than a reliable emission trend.

Table 1.3: Emission factors for exhaust and non-exhaust PM10 emissions determined at Zürich-Weststrasse, Zürich-Schimmelstrasse (heavily trafficked road intersection, 300 m from Zürich-Weststrasse), Reiden (LU, national freeway A2) and Birrhard (AG, national freeway A1). Generally, considerable uncertainties were introduced by splitting the fleet emission factors into vehicle type specific emission factors.

Parameter	**Study**	**Location**	**Year**	**Fleet ($mg\ km^{-1}$)**	**LDV ($mg\ km^{-1}$)**	**HDV ($mg\ km^{-1}$)**
PM10	NFP41[*1]	Zürich-Schimmelstrasse	1998/99	153	59	1420
	BUWAL/ASTRA 2004[*2]	Zürich-Weststrasse	2002/03	104	49	703
	APART	**Zürich-Weststrasse**	**2007**	**71**	**23.7 ± 7.5**	**498 ± 86**
Exhaust emissions	NFP41[*1]	Zürich-Schimmelstrasse	1998/99	48	14	507
	BUWAL/ASTRA 2003[*2]	Zürich-Weststrasse	2002/03	29	10	320
	HBEFA [*3]	IO_HVS3[*4]	2002/03	-	11	342
	APART	**Zürich-Weststrasse**	**2007**	**29**	**14.9 ± 6.3**	**155 ± 67**
	HBEFA [*3]	IO_HVS3[*4]	2007	-	12	286
Non-exhaust emissions (including resuspension)	NFP41[*1]	Zürich-Schimmelstrasse	1998/99	105	45	913
	BUWAL/ASTRA 2004[*2]	Zürich-Weststrasse	2002/03	75	39	383
	APART	**Zürich-Weststrasse**	**2007**	**42**	**9 ± 11**	**343 ± 122**

Parameter	**Study**	**Location**	**Year**	**Fleet ($mg\ km^{-1}$)**	**LDV ($mg\ km^{-1}$)**	**HDV ($mg\ km^{-1}$)**
PM10	BUWAL/ASTRA 2003[*2]	Birrhard	2003	83	63	267
	APART	**Reiden**	**2007**	**86**	**50.0 ± 12.6**	**288.0 ± 72**
Exhaust emissions	BUWAL/ASTRA 2003[*2]	Birrhard	2003	33	16	193
	HBEFA [*3]	AB_120[*5]	2002/03	-	17	176
	APART	**Reiden**	**2007**	**35**	**20.4 ± 6.6**	**119 ± 38**
	HBEFA [*3]	AB_120[*5]	2007	-	16	111
Non-exhaust emissions (including resuspension)	BUWAL/ASTRA 2003[*2]	Birrhard	2003	50	47	74
	APART	**Reiden**	**2007**	**51**	**30 ± 14**	**169 ± 82**

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

[*2] Verifikation von PM10-Emissionsfaktoren des Strassenverkehrs, Forschungsauftrag ASTRA/BUWAL 2000/415(52/00), Bern.

[*3] Based on: Handbuch Emissionsfaktoren des Strassenverkehrs, Version 2.1 / 2004, INFRAS im Auftrag BUWAL, Bern, http://www.hbefa.net.

[*4] IO_HVS3: Urban main road with traffic lights, strong disturbances.

[*5] Motorway with free-flowing traffic at 120 $km\ h^{-1}$.

1.3.4 Emission factors for brake wear related trace elements

Both at Zürich-Weststrasse and Reiden, brake wear was characterized by a characteristic pattern of Fe, Cu, Zn, Mo, Zr, Sn, Sb and Ba. This pattern is similar to real-world fleet brake wear compositions reported in other studies. In contrast, the respective pattern for individual brake linings is extremely inhomogeneous. Compared to older studies, the measured emission factors for brake wear related lead (Pb) were considerably lower, indicating that lead has in the mean time largely been replaced by other elements or substances in brake linings. Emission factors are shown in Figure 1.7 and Figure 1.8. Highest emission factors were found for Fe, Cu and Ba, followed by similar values for Zr, Mo, Sn and Sb. The average ratios between the emission factors for heavy and light duty vehicles were 9, 4 and 14 for the coarse, intermediate and submicron mode, respectively.

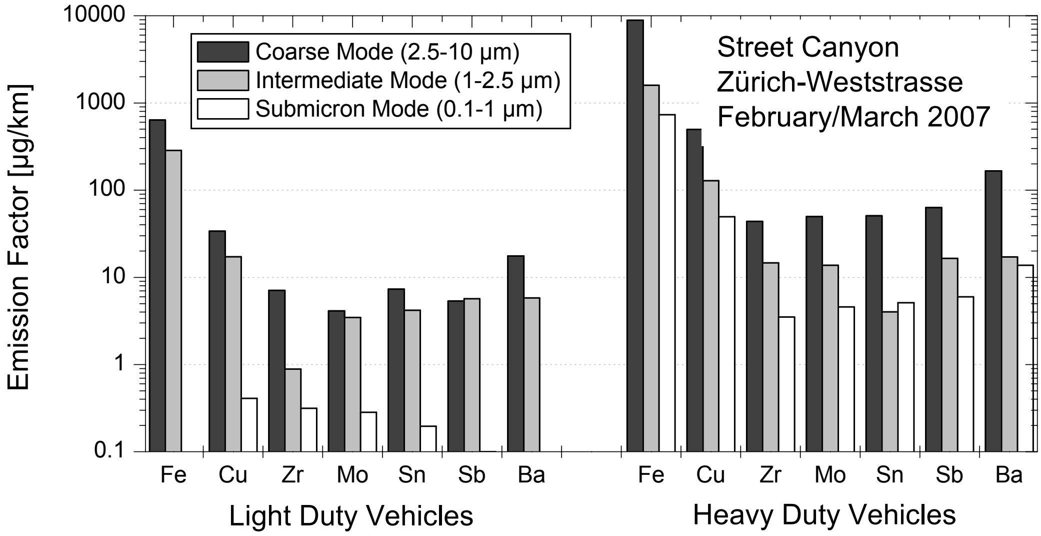

Fig. 1.7: Light duty vehicle (LDV) and heavy duty vehicle (HDV) emission factors (EF) for Zürich-Weststrasse (street canyon). The calculation was performed using 209 hourly values (~ 9 days, ΔNO_x > 20 µg m^{-3}, dry time periods only). For Zn no emission factors were calculated because the significant presence of other sources for this element did not allow for the determination of the contribution of local road traffic within the street canyon.

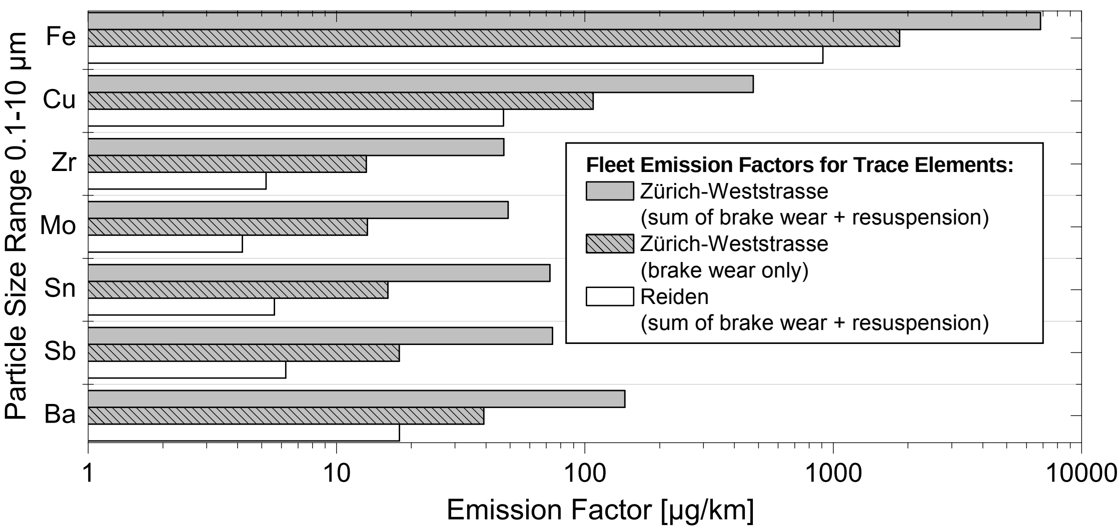

Fig. 1.8: Sum fleet emission factors (particle size range 0.1 - 10 µm) for Zürich-Weststrasse (10% HDV) and Reiden (15% HDV), for trace elements associated to brake wear. The values for Zürich-Weststrasse were calculated from experimental data from February and March 2007 (9 days, dry time periods only), while the values for Reiden refer to October 2007 (4 days, dry time periods only).

1.3.5 Particle size of non-exhaust emissions

Brake wear: Brake wear particles from light duty vehicles were distributed in the entire size range larger than 1 µm, while the contribution from the submicron mode was very low (Figure 1.9). In contrast, more than 75% of the brake wear particles from heavy duty vehicles were found in the coarse mode (2.5-10 µm). A comprehensive explanation of these different size distributions remains difficult, but is likely due to the strongly different design and operation conditions of LDV and HDV brake systems.

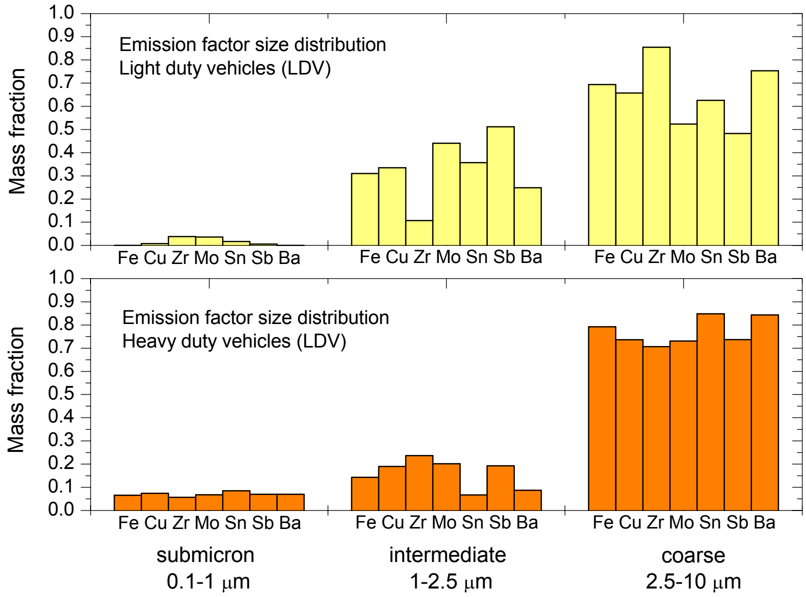

Fig. 1.9: Fractional size contribution for LDV and HDV emission factors determined for brake wear related trace elements and stop-and-go traffic in Zürich-Weststrasse (street canyon).

Road wear: The controlled mobile load simulator experiments showed that road wear was predominantly found in the coarse mode (Figure 1.10). The same also applied to resuspended particles.

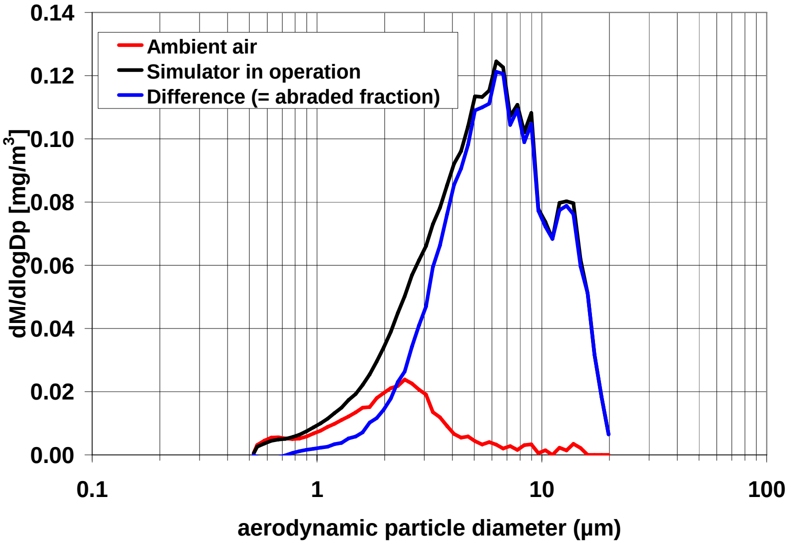

Fig 1.10: Typical particle size distribution obtained from an experiment with the mobile load simulator (measured size range 0.5-20 µm), during a measurement period with dominating abrasion (negligible resuspension). The size distribution of the abrasion particles is clearly shifted towards the coarse side compared to the ambient size distribution.

1.3.6 Spatial distribution and lifetime of urban PM10

1.3.6.1 Diurnal variation of pollutants in Zürich-Weststrasse

For a comprehensive description of the temporal variability of local emissions within the street canyon at Zürich-Weststrasse, normalized and background corrected diurnal variations of NO_x, CO_2, black carbon (BC) in PM1, PM10, size-segregated antimony and coarse mode silicon are shown in Figure 1.11, along with the vehicle frequencies for light and heavy duty vehicles.

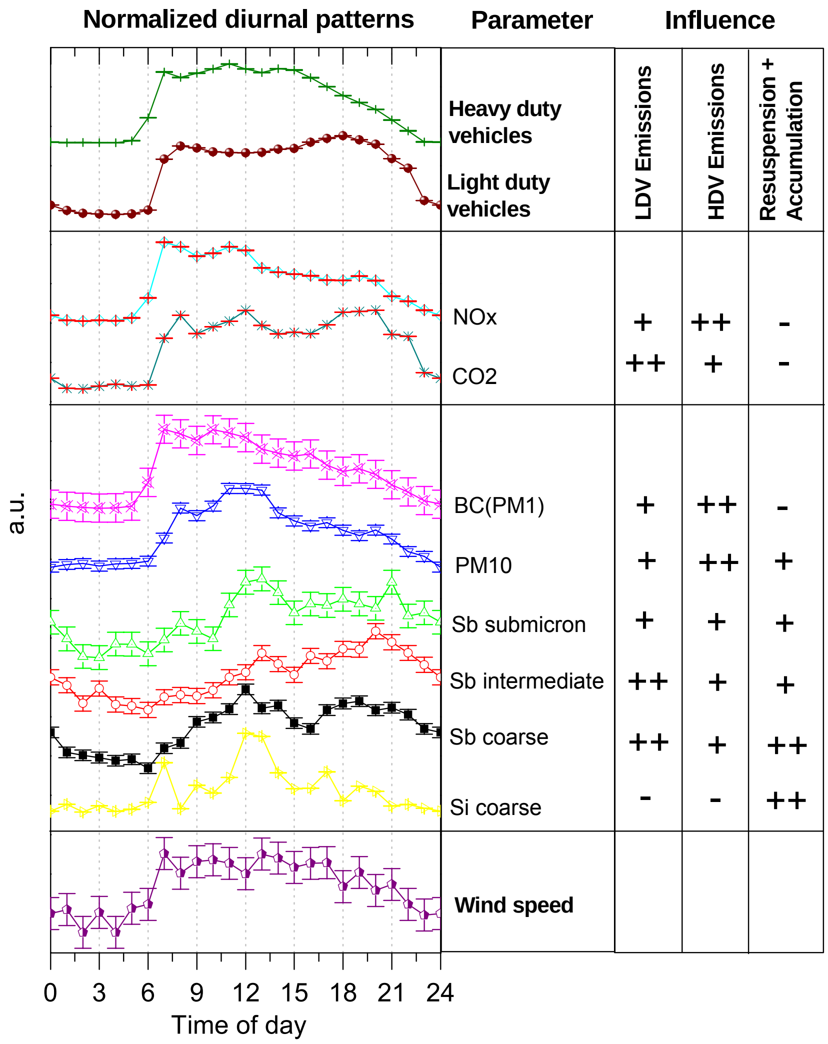

Fig. 1.11: Background corrected diurnal variations (Zürich-Weststrasse, 15 days in February and March 2007, weekdays and dry periods only). Diurnal variations were normalized to have comparable amplitudes. Error bars indicate the measurement precision. The meteorological conditions were comparable for the considered days (wintertime inversion layer).

The diurnal patterns for NOx and BC(PM1) were highly correlated to the diurnal pattern for heavy duty vehicles, indicating that their emissions by the traffic fleet (approx. 10% heavy duty vehicles) were mainly dominated by high emissions from heavy duty vehicles. On the other side, CO_2 showed a better correlation to the diurnal pattern of light duty vehicles, which accordingly implies a high net emission contribution from light duty vehicles. The slight concentration decrease from 14:00 until 16:00, observed for all gaseous and aerosol species, was partly attributed to meteorology.

In contrast, the diurnal patterns of PM10 and antimony showed no all-day correlation to traffic frequencies, but additionally exhibited a distinct midday maximum. A likely explanation for this midday maximum is an increased influence of wind speed induced resuspension of road dust, as well as the enrichment of fresh emissions and resuspended dust throughout the day within the street canyon. Coarse mode silicon, used as proxy for road dust resuspension in this context, was correlated to the wind speed within the street canyon and did not show any correlation to traffic numbers except for the initial traffic increase at 07:00. As seen from this distinct peak in wind speed with beginning morning traffic, the wind speed within the street canyon was not triggered by meteorology, but by the traffic fleet. Thus, resuspension has clearly to be assigned to traffic and not to natural wind movements.

Despite this distinct effect from road dust resuspension and emission enrichment within the street canyon, there were still clear indications for an influence of direct traffic emissions. In the afternoon and evening, the diurnal variations for PM10 and antimony showed a distinct correlation to light duty vehicle frequencies.

1.3.6.2 On-road PM10 mass concentrations

Mobile PM measurements in Zürich showed a complex variation with space and time (see Figure 1.12). For PM1 a correlation with traffic density could be discerned which hinted towards emissions of primary particles produced in combustion processes. Particles larger than 1 µm still showed a relationship with traffic density and hence can be attributed to abrasion processes and road dust resuspension. However, the pattern is spatially and temporally more inhomogeneous, such that other sources have to be taken into account. For example, the large variability of the concentrations at Badenerstrasse is probably due to the influence of the nearby construction site of the Letzigrund sport stadium with its HDV traffic.

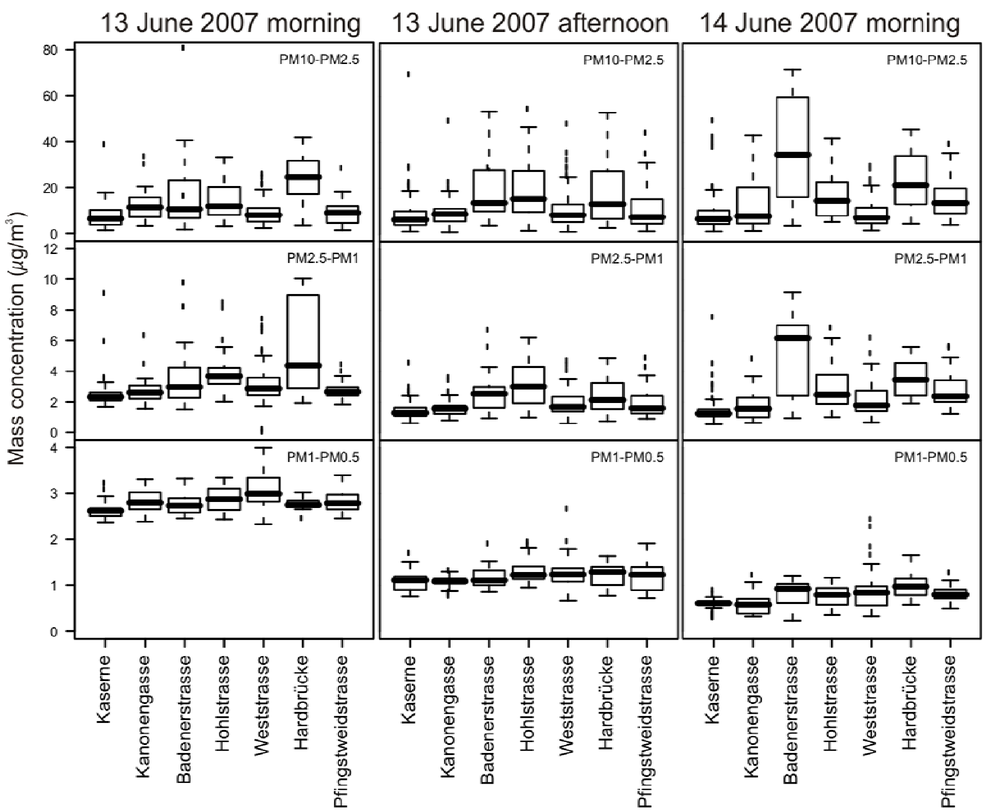

Fig. 1.12: Spatial variation of PM mass concentrations in µg m^{-3} in Zürich, determined by on-road experiments (assuming unit density for the collected particles). The sites are ordered according to increasing traffic density (averaged over 24 h), with Kaserne being the background site without traffic. For a better graphical representation 6 extreme outliers have been cropped on 13 June.

1.3.6.3 Composition of the PM10 fraction of deposited road dust

Zürich road dust consists mainly of silicate and carbonate compounds originating from mineral sources, building material and deposited traffic emissions. Fig. 1.13 shows the chemical profile or relative amount of the chemical constituents in a sample. The values of all road dust samples collected during the campaign in February 2008 were averaged to obtain a reference. Hence, on average 35% of a dust sample were silicate compounds (calculated as SiO_2), and further 35% of mass were organic matter (OM) and elemental carbon (EC).

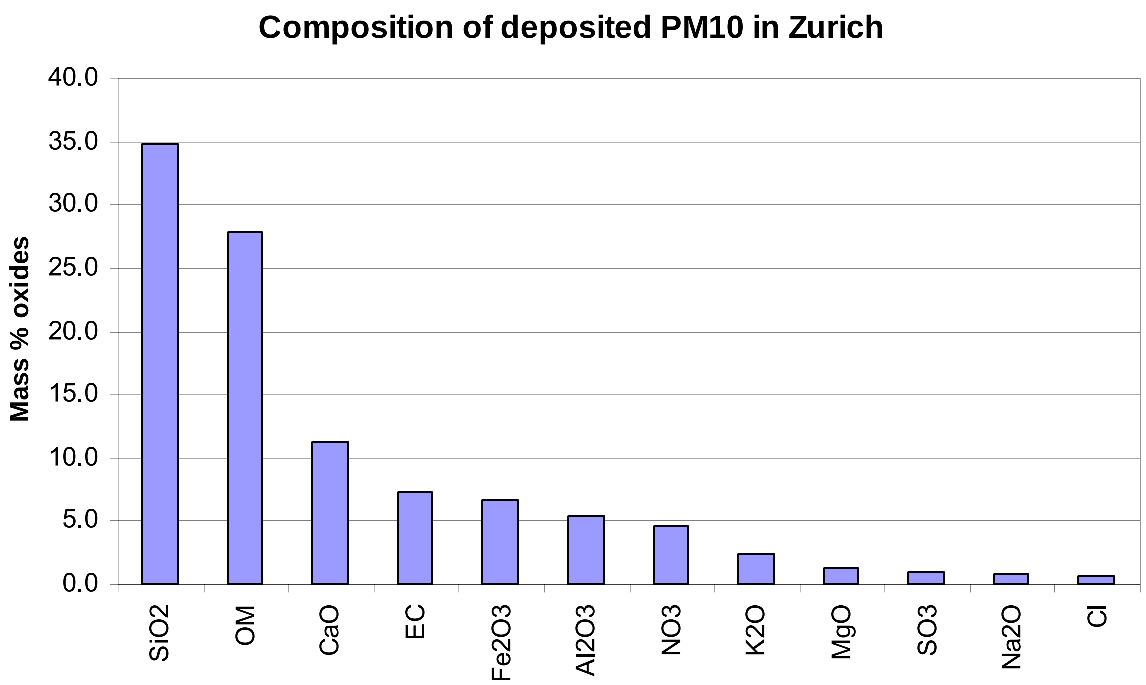

Fig. 1.13: Major element abundances of deposited PM10 collected from different roads in Zürich. Elements are shown in oxide form. OM = Organic matter, EC = elemental carbon.

1.4 Overall Conclusions and Outlook

The following statements are made based on the performed investigations and provide indications for future pollution abatement strategies:

- **Mass contribution of non-exhaust sources:** During the time periods considered for the measurements in the street canyon at Zürich-Weststrasse (February and March 2007) and along the national freeway A2 in Reiden LU (October and November 2007), the sum of direct abrasion sources and vehicle induced road dust resuspension made up 60% of the total traffic related PM10 emissions.

- **Brake wear:** Brake wear was characterized by a characteristic pattern of Fe, Cu, Zn, Mo, Zr, Sn, Sb and Ba, which is similar to real-world fleet emissions for brake wear reported in other studies. In contrast, the pattern of these elements in individual brake linings is extremely inhomogeneous. Compared to older studies, the measured emission factors for brake wear related lead (Pb) were considerably lower, indicating that lead has in the mean time largely been replaced in brake linings. At Zürich-Weststrasse, the heavily disturbed traffic flow resulted in brake wear emissions that made up 20% (15 mg/km/vehicle) of the total PM10 emissions from traffic. In contrast, brake wear emissions contributed less along the freeway in Reiden (3%, 3 mg/km/vehicle), due to the free-flowing traffic regime. For both locations the brake wear emissions from heavy duty vehicles were approximately 10 times higher than from light duty vehicles.

- **Traffic induced resuspension of road dust:** Generally, road dust resuspension is strongly influenced by available road dust and thus by the pollution of the road surface. In the street canyon at Zürich-Weststrasse, up to 40% of the traffic related PM10 emissions were assigned to resuspended road dust during the period of measurements in February and March 2007. Along the freeway in Reiden, the contribution of resuspended road dust to traffic related PM10 emissions was estimated to be higher than 50% in October and November 2007. In the heavily trafficked street canyon at Zürich-Weststrasse, the available dust on the surface was resuspended and kept in suspended state mainly by the turbulence induced by the heavy duty vehicles, leaving only small amounts of dust to be resuspended by the light duty vehicles.

- **Road wear and tire wear:** PM10 contributions from road wear and tire wear were not directly identified from the measurements at Zürich-Weststrasse and Reiden. Controlled experiments with a mobile load simulator showed that for intact pavements road wear is negligible compared to resuspension of deposited road dust, which shows a similar composition. Damaged pavements however led to significantly higher road wear emissions. Quantitative information for road wear under real-world traffic conditions has to be gained by further investigations. While not specifically investigated in this study, tire wear has been found by other investigations to be only relevant in the size range above 10 µm. Recent work indicates that certain pyrolytic products of rubber might be suitable tracers for tire wear.

- **Emission factors:** The presented emission factors are independent of the exact measurement position along the road, because the emissions were corrected for their atmospheric dilution. However, for road dust resuspension at Zürich-Weststrasse emissions were only insufficiently described in terms of mg/km/vehicle, because there was no strictly linear relation with hourly traffic counts due to the complex mechanisms of these emissions. As a consequence, vehicle specific emission factors could only be indirectly estimated with high absolute uncertainties. Since resuspension of road dust was found to be a relevant contributor to total traffic related PM10, the same applied to PM10. Future work will have to address this problem and define refined models for emission inventories.

- **Particle size of non-exhaust emissions:** The investigated particle size ranged from 0.1 to 10 µm. Mass relevant contributions from abrasion related particles and resuspended road dust to traffic related PM10 were mainly found for particles larger than 1 µm.
- **Exhaust:** Although not in the scope of APART, exhaust emissions were estimated from black carbon measurements to complete the mass balance for traffic related PM10. These emissions were assigned to the particle size range below 1 µm. Trace elements originating from fuel additives (Zn, Ca, S, P) were not specifically identified from the road side measurements, indicating that other emission sources of these elements are more relevant on a mass base. Zn and P show a relative enrichment in the submicron particle fraction which was however not attributed to traffic.
- **Comparison of results to earlier investigations:** At Zürich-Weststrasse, a net decrease in the PM10 fleet emission factors over the last 10 years was observed. In contrast, the fleet emission value determined for Reiden is about equal to a value for a comparable freeway location near Birrhard in 2004. Generally, the emission factors for non-exhaust emissions and total traffic related PM10 strongly depend on the influence of vehicle induced road dust resuspension during the time periods considered in the respective investigations. Therefore, differences rather reflect local conditions at the measurement sites (dirt load on the road surface, condition of pavement) than a reliable emission trend.
- **Comparison of PM10 from non-exhaust sources to general urban PM10:** The locations selected for this study exhibited a different local topography (street canyon at Zürich-Weststrasse versus the open-field situation in Reiden), which strongly influenced the dilution of emitted PM10 and consequently the total local PM10 concentration. Mobile measurements in Zürich showed that the spatial mass concentration variation in the particle size range 0.5 - 1 µm was influenced by local traffic emissions on the days selected for measurements. In contrast, the traffic related emissions in the PM10-PM1 fraction were not dominant compared to emissions from other urban emission sources in this size range (e.g. construction sites). While the coarse mode contribution of the urban background aerosol is dominated by mineral dust elements, the coarse mode of the traffic related emissions contributes trace elements (Fe, Cu, Zn, Mo, Zr, Sn, Sb and Ba) produced by brake wear.