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Exposure to Particulate Matter in Vehicle Cabins of Private Cars

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ABSTRACT

A growing number of studies indicate the significance of short-term exposures to airborne particulate matter, such as those occurring in a vehicle cabin. In this study, PM_{10}, $PM_{2.5}$, PM_1 concentrations were measured using optical particle counters in eighteen tobacco smoke-free private cars in movement. The average concentrations were 48.6 μg/m^3, 26.9 μg/m^3 and 22.6 μg/m^3 for $PM_{10,}$ $PM_{2.5}$ and for $PM_{1,}$ respectively. These levels were found to depend directly on the ambient air PM concentration and the choice of ventilation used inside the cars. The average number of particles with a diameter > 0.3 μm measured in the cabins of the cars was 185,723 particles/L. The average number of particles with a diameter between 0.02–1 μm was 16,391 particles/cm^3. Concentrations were found to partly exceed the established limit values for ambient air. Thus, the time spent driving a vehicle might significantly contribute to the daily overall exposure to particulate matter, especially in the case of some groups of professional workers.

Keywords: PM_{10}; $PM_{2.5}$; PM_1; Ultrafine particles; In-vehicle exposure.

INTRODUCTION

Exposure to airborne particulate matter (PM) is of increasing concern to the general public. Several studies conducted over the last decades have revealed that chronic exposure to high levels of respirable particulate matter is closely linked to an increase in respiratory problems, hospital admissions and mortality (Ostro, 1993; Dockery and Pope, 1994; Tony, 1995; Verhoeff *et al*., 1996; Tsang *et al*., 2008).

Short-term exposure (e.g. while driving) to peak particle concentrations may also be associated with adverse health affects (Katsouyanni *et al*.; 1997; Delfino *et al*., 1998; Michaels and Kleinman, 2000; Peters *et al*., 2001). The vehicle cabin represents a confined space where passengers are exposed to particulate matter concentrations for variable periods of time.

Exposure to pollutants (VOCs, particles) inside car cabins is often very high, compared to other outdoor or indoor micro-environments (Geiss *et al*., 2009). Praml and Schierl (2000) investigated PM_{10} exposure in buses and trams in Munich, Germany: the results indicated that particulate concentrations inside vehicles originated from external sources, e.g. road traffic. Moreover, the PM concentrations inside the vehicles exceeded outdoor concentration values by 3–5 times, when measurements were compared to sampling stations located near the roadside. Alm *et al*. (1999) found that the PM levels inside vehicles were slightly affected by the number of stops at traffic lights along the travelling route. Chan *et al*. (2002) examined passenger exposure to respirable suspended particulate matter while commuting in public transport in the city of Hong Kong and measured concentrations of PM_{10} up to 175 μg/m^3 on a tram. They concluded that the in-vehicle particulate exposure level is greatly affected by the choice of transport systems and the mode of in-vehicle ventilation applied. Similar studies have been carried out in several European cities. They all report high levels of particle concentrations inside public means of transport (Pfeiffer *et al*., 1999; Kaur *et al*., 2005). Gulliver *et al*. (2004) measured exposure to particulate air pollution (PM_{10}, $PM_{2.5}$, PM_1) simultaneously in pedestrians and in cars in Northampton, UK. They reported concentrations in the car cabin of 38.2 μg/m^3 for PM_{10}, 15.1 μg/m^3 for $PM_{2.5}$ and 7.1 μg/m^3 for PM_1. They concluded that exposures to PM experienced in cars and during walking were similar.

The current study was carried out with the intent to determine PM_{10}, $PM_{2.5}$, PM_1 and ultrafine particles (d = 0.02–1 μm) in the interior of 18 used, private cars during parking and while driving. It differentiates from most other studies in that the cars were driven in a rural area with low traffic. In addition, particle concentrations both inside and outside a car were recorded simultaneously (in parallel) while driving, to evaluate the impact of outdoor PM concentrations and the influence of in-car ventilation on the PM concentrations inside the vehicle cabin.

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MATERIALS AND METHODS

Vehicles under Study

The vehicles under investigation belong to colleagues who volunteered to take part in this study. This approach led to a set of cars of different origin and manufacturing year (1989–2009). All participants live within a maximum of 20 km from the place of work (Ispra located in the province of Varese, Northern-Italy) and none of the volunteers live in a city. None of the participants smoke in their cars. Volunteers were asked to keep the window closed while driving. Each measurement was done on a different day, but all measurements were concluded within 3 weeks of time. Participants declared to spend an average of 30 ± 18 minutes driving during working days.

Instrumentation

Real-time laser photometers (Optical Particle Counters, OPCs) were used for all particle measurements. This kind of instrumentation allowed the measurement of short term concentration profiles during driving time. OPC monitors have been used in previous studies for the determination of mass concentrations in vehicles (Chan *et al*., 2002; Leutwyler *et al*., 2002) and proved to work well.

Measurement of Particles with the Optical Equivalent Particle Size Range of > 0.3 μm

The instruments used were GRIMM model 1.108 portable aerosol spectrometers (GRIMM Aerosol Technik GmbH & Co. KG, Ainring, Germany). The GRIMM instruments were calibrated against Arizona Test Dust (ISO 12103-1) by the manufacturer. Data points were collected every minute. The cars were equipped with two identical optical particle counters. The OPCs were placed on the back seat of the vehicles and were running in parallel, one giving the output as number of particles/m^3 of air and the other one transforming the information on the amount of particles/m^3 of air into mass concentration. The instruments were placed in the car cabin approximately 0.5–3 hours before driving, thus allowing the acquisition of stationary particle concentration. The average driving time was between 15 and 30 minutes, resulting in 15–30 data points. Mass concentration was measured for the fractions PM_{10}, $PM_{2.5}$ and PM_1.

Measurement of Particles with the Optical Equivalent Particle Size Range of 0.02–1 μm

Ultra fine particle counts were measured using a P-Trak® Ultrafine Particle Counter (TSI Model 8525, TSI Incorporated, Shoreview, MN, USA) for particles in the size range 0.02–1 μm. The instrument was calibrated by the manufacturer against the PortaCount Bench 1 calibration standard.

The P-Trak is based on the condensation particle counting technique using isopropyl alcohol. Westerdahl *et al*. (2005) reported that the instrument can underestimate particle concentrations at levels exceeding 100,000 particles/mL (particles per cubic centimetre). Since the concentrations measured in the frame of this study did not reach those levels, it was decided not to apply any correction to the values. Matson *et al*. (2004) found the P-Trak's precision not significantly different from a more sophisticated instrument.

Each car was equipped with a P-Trak ultrafine particle counter placed on the back-seat (on different days). The instrument was placed in the car cabin approximately 0.5–3 hours before driving, thus allowing the acquisition of the stationary particle concentration. The average driving time lasted between 15 and 30 minutes.

RESULTS AND DISCUSSION

Mass Concentration Measurements of Particles with an Optical Equivalent Particle Size Range from 0.3 to10 μm

Fig. 1 shows the changes in PM concentrations (PM_{10}, $PM_{2.5}$ and PM_1) in relation to the day-time during parking and while driving. In the example given in Fig. 1, the car was moved twice; the first time during the lunch break and a second time in the evening. The vertical lines mark the sections in which the average parking and driving concentrations were calculated. PM_{10} levels measured inside cars were higher when the car was in movement compared to the parking position. The complete data set of coarse and fine particle concentrations found inside all 18 cars under study, both in movement and in parking position, are reported in Tables 1 and 2.

The results show that PM concentrations inside the vehicles in movement exceed those measured during parking by (on average) 9.2 times for PM_{10}, 3.8 times for $PM_{2.5}$ and 3.4 times for PM_1. Particle mass concentrations inside the moving vehicles ranged from 0.9–332.3 μg/m^3 for PM_{10} (avrg. 48.6 μg/m^3), 0.9–94.4 μg/m^3 for $PM_{2.5}$ (avrg. 26.9 μg/m^3) and 0.8–82.9 μg/m^3 for PM_1 (avrg. 22.6 μg/m^3).

The wide variability of PM concentrations among the 18 cars while driving can be attributed to the different routes travelled by the volunteers and differences in the traffic density along the route, in addition to the differences of particulate matter concentrations in the ambient air on the measurement day.

In the absence of indoor air legislation for particulate matter, the values found in this study can only be compared to limit values for ambient air. In regard to the PM_{10} limit values proposed by WHO (WHO, 2005) and established by the European Parliament and the Council (EU Directive 2008/50/EC), 9 out of 18 values (50%) measured while driving exceed the limit of 50 μg/m^3 (24 hour mean). The limit for PM_{10} of 150 μg/m^3 (24 h mean) proposed by EPA (EPA, 2006) was not reached in any of the measurements.

The value proposed by WHO of 25 μg/m^3 (24 h mean) for $PM_{2.5}$ is exceeded in 10 cases out of 18 (55%). The European Parliament and the Council set the limit at the same value for an average period of one calendar year. The value of 35 μg/m^3 (24 h mean) proposed by EPA is exceeded 5 times out of 18.

The comparison is rather indicative because only a few drivers spend more than a couple of hours inside the vehicle.

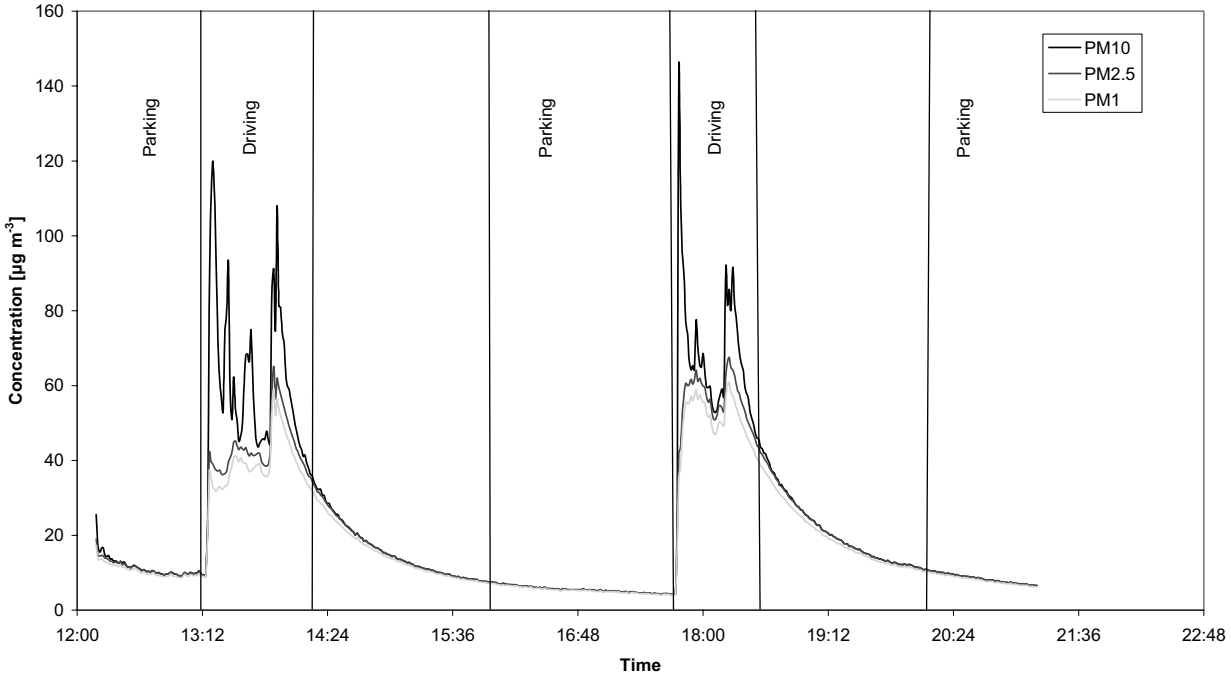

Fig. 1. Trend of particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) concentrations over time inside a car while driving and while parking

Table 1. Concentration of PM_{10}, $PM_{2.5}$ and PM_1 while driving ($\mu g/m^3$).

Driving												
ID Car	PM_{10}				$PM_{2.5}$				PM_1			
	Average	*MIN*	*MAX*	*SD*	*Average*	*MIN*	*MAX*	*SD*	*Average*	*MIN*	*MAX*	*SD*
1	61.0	37.7	92.8	12.8	49.6	16	85	12.3	42.5	43.7	70.8	10.2
2	68.0	24.7	332.3	42.8	34.1	20.8	56.5	1.3	16.0	14.5	18.7	1.2
3	59.6	10.5	217.2	41.9	7.9	3.4	17.3	3.8	4.8	2.2	12.2	2.3
4	75.9	19.6	145.3	29.0	25.8	13.0	42.3	10.1	20.9	9.1	37.0	9.7
5	38.8	21.3	67.0	11.0	28.0	17.5	36.7	5.1	24.5	13.9	32.7	4.6
6	21.5	7.7	48.1	8.8	18.1	5.9	32.6	6.6	16.5	5.1	29.6	6.1
7	39.8	13.9	103.7	22.7	11.4	4.8	15.5	2.6	9.3	3.4	12.5	2.1
8	77.8	44.1	134.1	21.9	46.7	29.1	59.5	8.0	39.7	25.7	51.3	6.4
9	46.8	21.6	78.5	14.6	32.9	16	41.3	5.5	29.4	14.6	36.7	4.7
10	37.4	16.2	106.4	29.1	20.4	16.1	30.3	5.0	17.9	15.1	24.7	3.4
11	24.0	4.1	42.5	8.5	11.5	3.8	13.6	2.0	9.8	3.5	11.2	1.6
12	40.2	8.6	263.7	39.9	17.8	6.7	32.5	7.4	14.2	5.7	28.0	6.3
13	61.4	29.8	87.8	17.9	27.3	22.5	31.8	3.7	23.7	18.8	28.1	4.0
14	13.0	0.9	56	11.6	3.1	0.9	8.6	1.2	2.6	0.8	4.8	2.6
15	56.9	26.5	178.4	30.1	45.7	26.2	94.4	14.6	41.1	24.3	82.9	12.6
16	14.9	3.2	51.4	10.9	4.0	2.0	8.4	1.6	3.2	1.6	6.3	1.4
17	65.3	25.0	120	17.9	49.5	22.1	67.6	9.3	45.1	20.3	60.9	8.7
18	72.1	52.5	105.2	14.6	50.2	18.2	63.7	11.5	44.7	15.2	56.6	10.7

The $PM_{2.5}$ mass concentrations were substracted from PM_{10} leaving a concentration with a range of average particle diameters from 2.5 to 10 µm. A concentration value is gained for a range from 1 to 2.5 µm by subtracting PM_1 from $PM_{2.5}$.

These new values allow ranges of particle diameters to be compared while parking and while driving, as illustrated in Fig. 2.

The results show that the portion of larger particles increases while driving. The reason for the almost complete absence of larger particles in the air while parking can be attributed to fast deposition of these coarse particles in the vehicle cabin in the absence of air movement. The average ratio of $PM_{2.5}/PM_{10}$ while driving is 0.53; whereas while parking this ratio is 0.98.

The day-to-day variability of PM_{10} concentrations inside

Table 2. Concentration of PM_{10}, $PM_{2.5}$ and PM_1 while stationary ($\mu g/m^3$).

Parking												
ID Car	PM_{10}				$PM_{2.5}$				PM_1			
	Average	*MIN*	*MAX*	*SD*	*Average*	*MIN*	*MAX*	*SD*	*Average*	*MIN*	*MAX*	*SD*
1	15.0	12.8	17.5	1.4	15.0	12.8	17.5	1.4	14.2	12.2	16.5	1.2
2	16.9	15.1	19.9	1.4	16.9	15.1	19.8	1.3	16.0	14.5	18.7	1.2
3	2.2	1.5	4.6	0.8	1.8	1.4	2.4	0.3	1.5	1.2	1.7	0.1
4	5.5	4.5	6.9	0.7	5.1	4.3	6.2	0.5	4.6	4.0	5.4	0.4
5	4.3	3.9	5.0	0.2	4.3	3.9	4.9	0.2	4.1	3.7	4.5	0.1
6	5.0	4.3	5.6	0.3	5.0	4.3	5.5	0.3	4.8	4.2	5.3	0.2
7	2.5	1.8	3.8	0.5	2.5	1.8	3.7	0.5	2.4	1.7	3.6	0.4
8	20.4	19.2	22.0	0.8	20.3	19.2	21.9	0.7	19.1	18.1	20.7	0.7
9	10.9	10	12.6	0.8	10.9	10	12.6	0.8	10.4	9.6	12	0.7
10	14.9	11.4	19.9	2.4	14.8	11.4	19.9	2.4	14.2	11.0	19	2.2
11	4.3	3.1	6.1	0.8	4.3	3.1	6.1	0.8	4.2	3.0	5.9	0.8
12	3.1	2.2	4.2	0.6	3.1	2.2	4.1	0.5	2.9	2.1	3.7	0.5
13	15.5	14.4	16.7	0.8	15.3	14.3	16.3	0.7	14.5	13.6	15.5	0.6
14	0.6	0.4	0.9	0.1	0.6	0.6	0.9	0.1	0.6	0.4	0.9	0.1
15	8.5	6.9	10.7	1.1	8.5	6.9	10.7	1.1	8.1	6.5	10.2	1.1
16	0.9	0.5	1.2	0.2	0.9	0.5	1.2	0.2	0.9	0.5	1.2	0.2
17	10.1	6.6	33.6	3.4	10.1	6.5	15.5	2.5	9.6	6.2	14.7	2.3
18	18.0	13.8	25.7	3.1	17.9	13.7	25.6	3.1	17.1	13.1	24.3	2.9

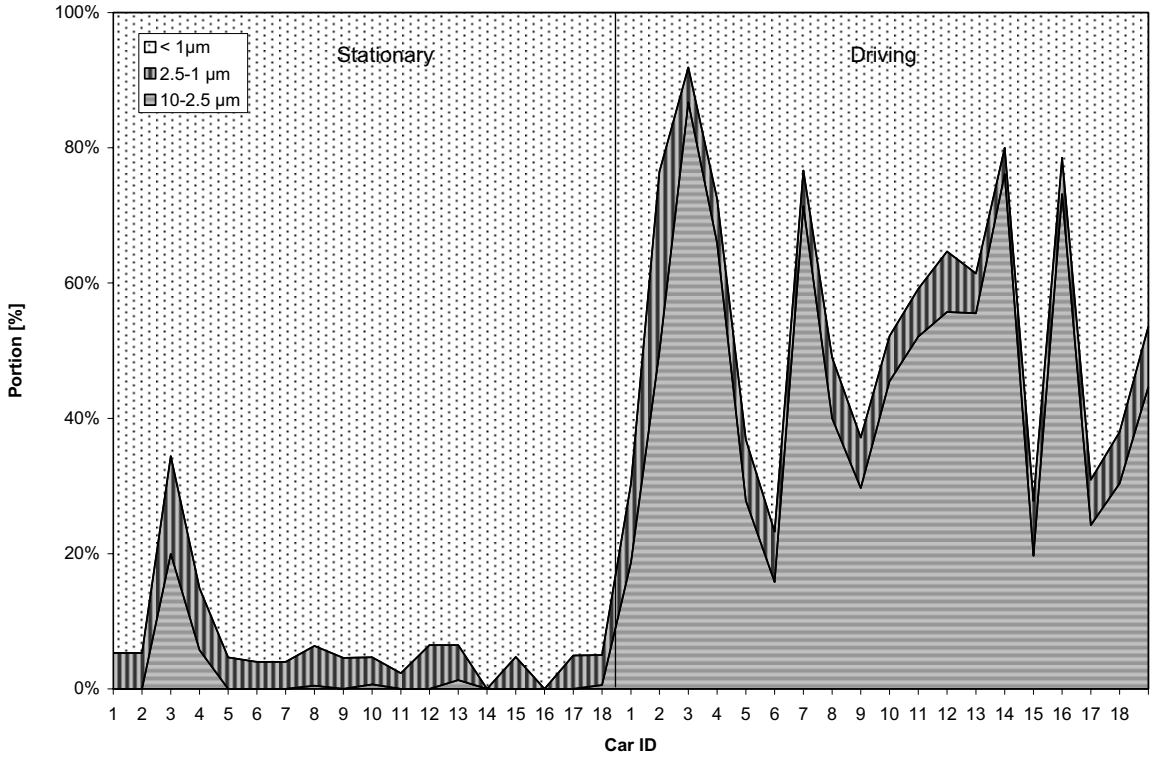

Fig. 2. Portions of different particle-size ranges while parking and while driving.

a vehicle cabin and the impact of ambient PM_{10} levels on the PM concentrations inside the car were investigated by repeating measurements (for ten consecutive days) during a driving time of approximately 30 minutes (Fig. 3). Ambient outdoor concentration data of PM_{10} measured at the nearest air quality network station (e.g. at the JRC-Ispra GAW Regional Station EMEP Station IT04) were collected. The EMEP station was chosen because it is located very close to the area where all the cars involved were parked during working hours. The comparability of

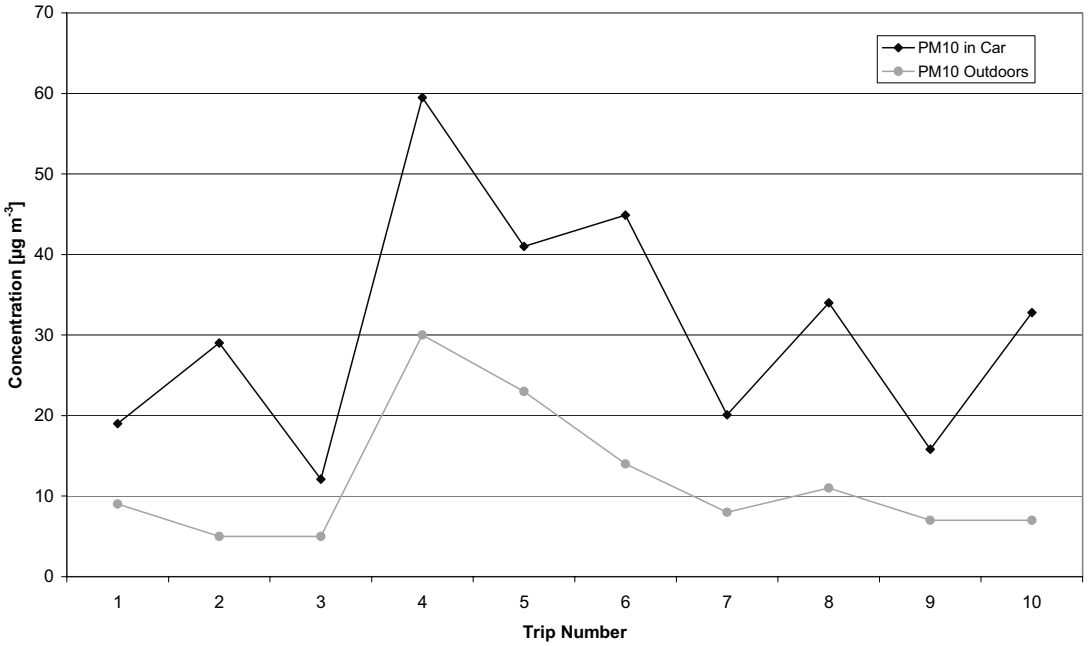

Fig. 3. Concentrations of PM_{10} measured in the cabin of Car ID 5 (while driving) on 10 different days compared to outdoor concentrations (measured at a stationary measurement statio.

the OPC used in the vehicle and the instrument used at the EMEP station was tested by co-locating both instruments, with a resulting agreement of values.

The concentration patterns are similar for both the measurements inside the vehicles and for the ambient measurement at the EMEP station. This suggests that there is a relationship between the outdoor PM_{10} concentration and the concentration measured inside the vehicle cabin. The expectation was to find the in-cabin concentration to be similar to the concentration measured outdoors. However, the air monitoring station only supplies data on its precise location; it does not read the additional particle load whirled up by cars passing on the road. In order to gather more information on the PM indoor/outdoor relationship, an additional experimental set up was therefore prepared. The car under investigation was equipped with two GRIMM OPCs. One sampled air directly inside the car and the second one in parallel aspirated air from outside the car through an antistatic tube while driving. This set up allowed a direct comparison between the concentrations of PM_{10} inside and outside while driving. This experiment was repeated 10 times on 10 different days always with the same car driving along the same route. Fig. 4 summarises the outcome of these measurements (the same pattern was observed for all 10 repetitions).

While the car is in movement with the fresh air mode selected, the PM_{10} concentration inside the car reaches levels almost as high as the ambient air levels. But in air re-circulation mode, with exception of the initial and final concentration peaks (when doors are opened and closed) the overall PM_{10} concentrations are lower inside than outside. This indicates that particles with a diameter < 10 µm are not retained by the air filtering system and do penetrate into the cabin. The observation that the in-vehicle concentration does not exceed the outside concentration demonstrates that re-suspension of particles already present in the car cabin only plays a secondary role.

Measurement of Particles with an Optical Equivalent Particle Size Range of > 0.3 µm–Particle Count

In addition to the mass concentration measurement (section 3.1), the particle count per volume of air was measured. Table 3 lists the concentration (particles/litre) for all particles in this size range. In this case the variability on different days due to fluctuating concentrations outside the vehicle was not considered.

The concentration of particles inside the moving vehicles exceeds those measured in parking conditions by an average of 3.3 times. Particle concentrations inside the moving vehicles ranged from 21,540 to 403,090 particles/L (avrg. 185,723 particles/L).

Measurement of Particles with an Optical Equivalent Particle Size Range of 0.02–1 µm–Particle Count

Table 3 lists concentrations of ultrafine particles inside cars during parking and while driving. In this case the variability on different days due to fluctuating concentrations outside the vehicle was not considered.

The study shows that the concentration of ultrafine particles inside the moving vehicles exceeds those measured in parking conditions by an average of 9.8 times. Particle concentrations inside the moving vehicles ranged from 5,933–29,921 particles/cm^3 (avrg. 16,392 particles/cm^3). Wallace and Ott (2010) measured ultrafine particles (with a comparable instrument to the one used in this study, measuring in the same diameter range) in two cars during 17 different drives. The in-traffic mean concentrations ranged from 17,600 to 48,100 particles/cm^3. Kaur *et al.* (2006) found similar concentrations inside cars driving around London (avrg. 36,821 particles/cm^3). The differences

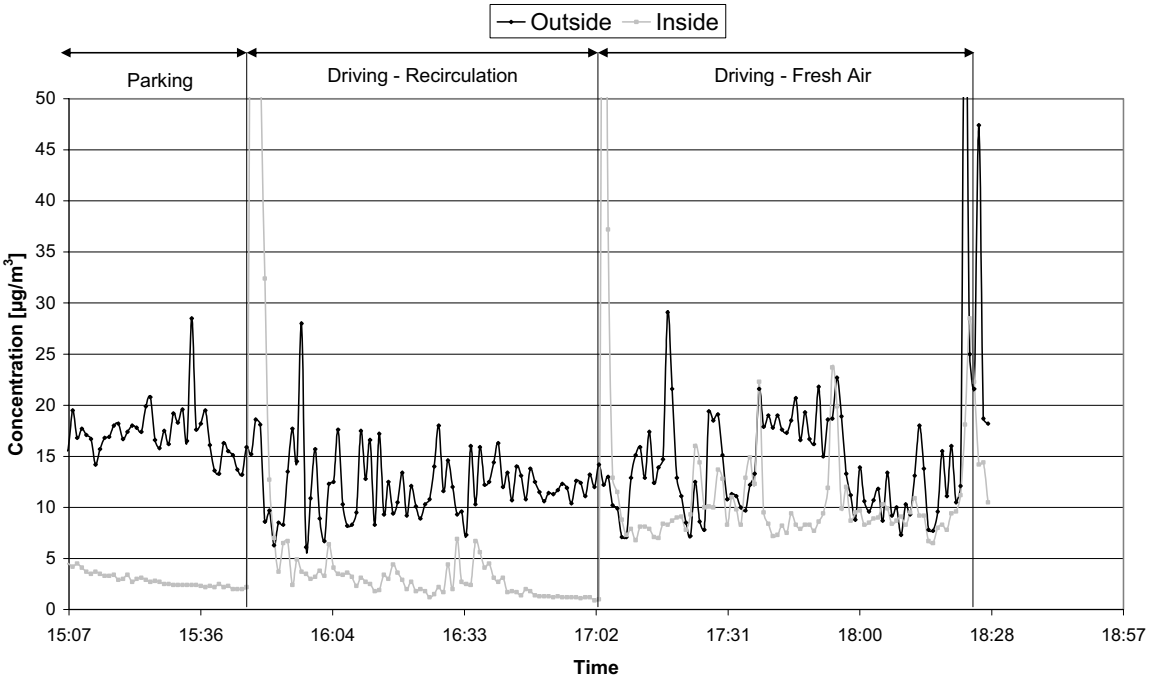

Fig. 4. Concentrations of PM_{10} inside and outside the vehicle cabin while driving, running two different ventilation modes (recirculation and fresh-air).

Table 3. Concentration (particles/L) for particles with a diameter > 0.3 μm and 0.02–1 μm while parking and while driving.

Car ID	Particles with diameter > 0.3 μm			Particles with diameter 0.02–1 μm		
	Parking (pt/L)	Driving (pt/L)	Ratio (D/P)	Parking (pt/mL)	Driving (pt/mL)	Ratio (P/D)
1	104942	241589	2.3		no data available	
2	218579	232885	1.1	1219	12413	4.7
3	11099	36575	3.3			
4	74094	171537	2.3	3042	27161	8.9
5	34281	224790	6.6	1581	21558	13.6
6	28608	137869	4.8		no data available	
7	12737	73210	5.7		no data available	
8	158856	328447	2.1		no data available	
9	88183	255882	2.9	1559	7713	4.9
10	113017	285580	2.5	2667	29921	11.2
11	31823	81319	2.6	295	7895	26.8
12	14926	109747	7.4	2237	13043	5.8
13	102122	180296	1.8	1682	26471	15.7
14	8564	21540	2.5	901	5933	6.6
15	145746	344938	2.4	3175	12509	3.9
16	8772	27997	3.2		no data available	
17		no data available		2605	15690	6.0
18	148344	403090	2.7		no data available	
Average	76747	185723	3.3	2033	16391	9.8
STDEV	64843	117437	1.8	911	8525	6.8

found between these two studies and ours may be attributed to the fact that the Wallace and Ott study was conducted in dense traffic on highways, and Kaur *et al.* studied the centre of London, whereas the volunteers in our study drove on country roads with low traffic.

CONCLUSIONS

The present study gives an insight into the levels of particulate matter concentrations inside the cabin of private cars while driving. The resultant concentrations exceed the

limit values set for ambient air in 50% of measured PM_{10} and 55% of measured $PM_{2.5}$ values. Thus, the time spent driving may in some cases significantly contribute to the daily overall body burden, especially in some groups of professional workers. The values found inside the vehicle cabins are furthermore significantly higher than those measured at fixed ambient background monitoring stations, a fact which underlines the need to assess personal exposure by acquiring data directly in the microenvironments where people spend their time.

The information provided during this study may contribute to a better understanding of human exposure to particulate matter and the processes governing the accumulation of particles in both private vehicles and public means of transport. It also draws attention to the need to develop more efficient filtering systems capable of retaining particles with an optical equivalent particle size of < 10 μm.

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