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Miniature diffusion size classifiers (miniDiSC) are novel handheld devices to measure ultrafine particles (UFP). UFP have been linked to the development of cardiovascular and pulmonary diseases; thus, detection and quantification of these particles are important for evaluating their potential health hazards. As part of the UFP exposure assessments of highway maintenance workers in western Switzerland, we compared a miniDiSC with a portable condensation particle counter (P-TRAK). In addition, we performed stationary measurements with a miniDiSC and a scanning mobility particle sizer (SMPS) at a site immediately adjacent to a highway. Measurements with miniDiSC and P-TRAK correlated well (correlation of $r = 0.84$) but average particle numbers of the miniDiSC were 30%–60% higher. This difference was significantly increased for mean particle diameters below 40 nm. The correlation between the miniDiSC and the SMPS during stationary measurements was very high ($r = 0.98$) although particle numbers from the miniDiSC were 30% lower. Differences between the three devices were attributed to the different cutoff diameters for detection. Correction for this size dependent effect led to very similar results across all counters. We did not observe any significant influence of other particle characteristics. Our results suggest that the miniDiSC provides accurate particle number concentrations and geometric mean diameters at traffic-influenced sites, making it a useful tool for personal exposure assessment in such settings.

[Supplementary materials are available for this article. Go to the publisher's online edition of *Aerosol Science and Technology* to view the free supplementary files.]

INTRODUCTION

Exposure to particulate matter (PM) is associated with adverse cardiovascular and pulmonary health effects (Pope et al. 1995; Brook et al. 2010). Traffic emissions are an important source of PM and traffic exposure has been directly linked to adverse health outcomes (Peters et al. 2004; Riediker et al. 2004). Recent publications suggest that ultrafine particles (UFP) play a critical role in triggering oxidative stress and inflammatory processes that provoke atherogenic and thrombotic effects and influence the autonomous nervous system (Schmid et al. 2009; Schneider et al. 2010; Peters et al. 2011). Detection and quantification of these particles is important and a first step to characterizing potential health hazards. UFP are usually measured in number-concentrations, as they do not contain significant mass for gravimetric quantification. State of the art UFP measurements are performed with condensation particle counters (CPCs) (Bricard et al. 1976). The basic working principle of a CPC is to condensate alcohol or water vapor on particles and to detect these droplets by light scattering. Miniaturized portable CPC devices, such as the P-TRAK, are used to measure UFP under real-world conditions in industry or environmental research. Recently, a miniature diffusion size classifier (miniDiSC) has been developed at the University of Applied Sciences Northwestern Switzerland. The working principle of this new handheld device is to label particles in an standard positive unipolar charger and to detect them in two electrometer stages: in a diffusion stage and a filter stage where the particles induce an electrical current (Fierz et al. 2011). In addition to number counts, the two detection stages allow an estimation of the geometric mean particle diameter. A laboratory comparison (Dahl et al. 2009) suggested that the miniDiSC correlates well to an SMPS; however, no studies compared these devices under real world conditions such as personal exposure campaigns.

With this comparative study, we wanted to assess how measurements of this new generation device correspond to the widely used CPCs and how useful they are for personal exposure assessment. Although the working principle differs from a CPC we expected to measure similar particle numbers. To compare UFP numbers of a miniDiSC with conventional UFP counters, we made simultaneous measurements with (1) a miniDiSC and a P-TRAK while following highway maintenance workers in western Switzerland; and (2) a miniDiSC, a P-TRAK

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and a Grimm SMPS+C at a stationary site next to a highway in southwestern Switzerland.

METHODS

Measurement Setup

For nonstationary UFP measurements during highway maintenance work, a miniDiSC and a P-TRAK were fixed on a hand cart that was taken to different workplaces on highways in western Switzerland. Measurements were performed during six randomly selected work shifts. Maintenance activities included signalization, electric maintenance, guardrail repair, mowing, collection of foliage and litter, as well as preparation at the maintenance center, loading material, and driving to the work sites. Work locations were distinguished into indoor, garage at the maintenance center, inside car/truck, roadside and off-road. None of the observed maintenance tasks included work in tunnels. Table S1 (see the online supplemental information) contains a detailed description of each activity and corresponding locations.

Stationary measurements using a miniDiSC, a P-TRAK, and an SMPS were performed next to the highway maintenance center at the highway A9 in Rennaz, Switzerland, on two randomly chosen nonconsecutive days. All three devices were connected to a passive mixing chamber with a volume of 10 l in order to buffer the influence of short-term UFP peaks and to achieve stable conditions over SMPS cycles.

Application of UFP-Counters

During highway maintenance work two handheld UFP counters were compared: (1) the P-TRAK 8525 (TSI Incorporated, Shoreview, MN, USA) and (2) the miniDiSC developed at the University of Applied Sciences Northwestern Switzerland, which is now commercially available as DiSCmini (Matter Aerosol AG, Wohlen, Switzerland). The P-TRAK is a handheld condensation particle counter designed to measure UFPs in a size range from 20 to 1,000 nm and a concentration range from 0 to 500,000 particles/cm^3. The miniDiSC was calibrated to measure UFP in a size range from 10 to 300 nm and a concentration range from 1,000 to 1,000,000 particles/cm^3. For simultaneous measurement during highway maintenance work, we fixed the UFP counters on a handcart. Both devices were placed in a plastic box in order to protect them from direct sunlight and rain. Sampling tubes were fixed onto the cart-handle at about 1 m above ground. Sampling with the P-TRAK was performed with the standard inlet screen and the sample tube provided with the instrument. For the miniDiSC, we used Nalgene® 180 clear plastic tubing in combination with the 0.8 μm-cutoff impactor. The miniDiSC sampled in 1 s intervals. P-TRAK sampling interval was set to 1 min. Because of instrument failure caused by tilt during continuous movement, logging of the P-TRAK had to be restarted repeatedly during all work shifts.

During stationary measurements the miniDiSC and P-TRAK were compared with a Grimm SMPS+C. The SMPS consisted of a Differential Mobility Analyzer (model 55-40-26 long U-DMA) and a CPC (model 5.403) to measure particles in a size range from 10 to 1,110 nm and in concentrations up to 10,000,000 particles/cm^3. The SMPS was set to fast scan mode with measurement cycles of 3.5 min. MiniDiSC sampling was performed in intervals of 1 s; the P-TRAK sampled in intervals of 10 s. Nalgene® 180 clear plastic tubing was used to connect all three devices to the single outlet of the mixing chamber. During these stationary measurements, we did not use the 0.8-μm-cutoff impactor for the miniDiSC.

Treatment of Raw-Data

P-TRAK data were exported into a text file using TSI software TrakPro™. Data from miniDiSC were exported into a text file using the miniDiSC data conversion tool version 1.13 (the option for induction correction was not used). For measurements during highway maintenance, we used the data conversion tool to average miniDiSC data over 1 min. In a second step, data of the miniDiSC were synchronized with P-TRAK data using STATA 12. Synchronization of UFP counters was based on recording time; fine adjustments were made using distinctive particle peaks. For stationary measurements, we used the data conversion tool to average miniDiSC data over 10 s. In a second step, we used STATA 12 to synchronize and average the 10 s means of miniDiSC and P-TRAK over 3.5 min and to fit them to SMPS cycles. Data points with missing values of the alternative particle counter were excluded from the comparison. The SMPS only measures one particle size range at a time and, depending on the time point at which a peak occurs, the total particle counts may be too low or too high. A peak of small particles at the beginning of a cycle leads to an underestimation, while a peak at the end leads to an overestimation. In consequence, data from stationary measurements were only considered if particle counts were stable over a full SMPS cycle. Cycles were classified as stable if continuous miniDiSC-counts within a cycle varied less than $\pm 10\%$ of the cycle mean. SMPS data were stratified into the size-range corresponding to the miniDiSC and the P-TRAK. This was done by converting the exported SMPS normalized particle counts (dN/dln[dp]/cm^3) to actual particle numbers per size range using the manufacturer's reported size range for each channel. The particle counts of the relevant channels were used to calculate the geometric mean diameter of the size ranges corresponding to the handheld counters.

Statistical Analysis

Stata 12 (Stata Statistical Software, Release 12, StataCorp., College Station, TX, USA) was used for statistical analysis and graphic visualization. Particle numbers were log10-transformed for linear regression models. Models were calculated with the xtmixed-function. We grouped data into clusters of measurements on the same day and used the first order auto regression option to correct for first order autocorrelation. We apportioned

TABLE 1
Summary statistics for measurements during highway maintenance work. Detailed description for location specific measurements as well as for mowing. All correlations are highly significant ($p < .001$)

	Observations #	miniDiSC particles/cm³ (SD)	P-TRAK particles/cm³ (SD)	Size[b] nm (SD)	Correlation r	Linear regression (ac1)[c] Slope	Intercept
All locations[a]	2,597	34,576 (59,406)	23,491 (31,320)	49.5 (14.9)	0.84	0.99	0.17
Indoor	539	9,540 (6,780)	8,000 (6,162)	56.3 (12.8)	0.91	0.61	1.59
Indoor[d]	536	9,536 (6,797)	7,959 (6,111)	56.3 (12.8)	0.92	0.82	0.77
Garage	388	44,039 (43,605)	34,743 (31,473)	52.2 (15.5)	0.96	0.92	0.41
Off-road	153	10,460 (13,830)	8,320 (11,097)	59.2 (12.9)	0.93	0.97	0.20
Car/Truck	1,010	44,371 (68,471)	28,402 (34,125)	45.9 (13.8)	0.80	0.98	0.20
Road side[a]	507	41,716 (77,729)	26,145 (37,338)	44.3 (14.6)	0.87	1.03	0.02
Mowing[e]	*197*	*699,008 (1,267,327)*	*74,145 (98,791)*	*36.2 (23.9)*	*0.86*	*1.26*	*–0.56*

[a]Data collected during mowing excluded. [b]Geometric mean diameter measured by miniDiSC. [c]Model corrected for first order autocorrelation. [d]Exclusion of three unexplained outliers. [e]Overrange, not considered for general comparison.

data collected during maintenance work into corresponding clusters to analyze location or activity specific patterns. Direct comparisons of particle counts and diameters were tested with paired t-tests; location and activity specific differences were tested with unpaired t-tests.

RESULTS

Nonstationary Measurements During Highway Maintenance

Measurements were conducted for the duration of 6 work shifts and lasted for 7.5–9 h. This resulted in a total of 2,999 (100%) observations (means over 1 min). Excluded were 203 values because one of the instruments did not record the particle number (P-TRAK stopped logging because of tilt: 6%, miniDiSC was measuring zero-offsets: 1%). Analyzed separately were 197 observations (7%) because they occurred during mowing with brush cutters which caused very high particle numbers that frequently overloaded the UFP-counters. Two additional observations were excluded from the comparison because of very high particle numbers caused by metallic friction and heat during the use of an angle grinder to cut guard rails. Thus, a total of 2,597 observations (87%) could be used for the comparison of the miniDiSC and the P-TRAK.

MiniDiSC particle counts during highway maintenance work ranged from common background concentrations in office buildings or off-road (means around 10,000 particles/cm^3) to elevated concentrations on road sites (41,716 particles/cm^3) and high concentrations during particular work tasks such as signalization (82,303 particles/cm$^{3)}$ and mowing (699,008 particles/cm^3). Mean particle diameters ranged from 36.2 nm during mowing to 56.3 nm for indoor locations. Summary statistics for measurements during highway maintenance work is shown in Table 1. Data of both UFP counters were auto correlated due to the high temporal resolution. Partial autocorrelation was significant for lag 1 and linear regression models were therefore corrected for first order autocorrelation (ac1). Ac1 for log10-transformed particle numbers was ac1 = 0.88 for the miniDiSC and ac1 = 0.86 for the P-TRAK. Throughout all 6 work shifts (mowing excluded) the miniDiSC and the P-TRAK measured consistently particle numbers with the very same peak episodes (Figure S1 in the online supplemental information). Correlation during all work shifts was $r = 0.84$. However, when comparing average particle numbers over full work shifts miniDiSC values were significantly higher (30%–60%). The linear regression-model (corrected for ac1) for log10-transformed particle numbers of the two counters had a slope of 0.99 with an intercept of 0.17 (Figure 1a). Comparing the number ratio P-TRAK/miniDiSC with the geometric mean particle diameter from the miniDiSC showed that the difference between the two counters increased with decreasing particle diameter (Figure 1b). The ratio was stable between 0.8 and 1 for diameters between 40 and 100 nm but decreased rapidly for diameters below 40 nm, reaching 0.23 for mean diameters between 12 and 14 nm.

Location and Work Activity Dependent Comparison of miniDiSC and P-TRAK

The conditions under which particles are generated (i.e., location and activity which are described in detail in Table S1) may affect particle characteristics such that the UFP are measured differently by the miniDiSC and P-TRAK. Therefore, data collected under different conditions were analyzed separately. The miniDiSC measured averaged particle counts that varied from 9,540 particles/cm^3 indoor to 44,371 particles/cm^3 in the car/truck. Average particle diameters ranged from 44.3 (roadside) to 59.2 nm (off-road). Summary statistics of location specific data as well as for mowing are provided in Table 1. All activity specific data are provided in the Table S2. The mean

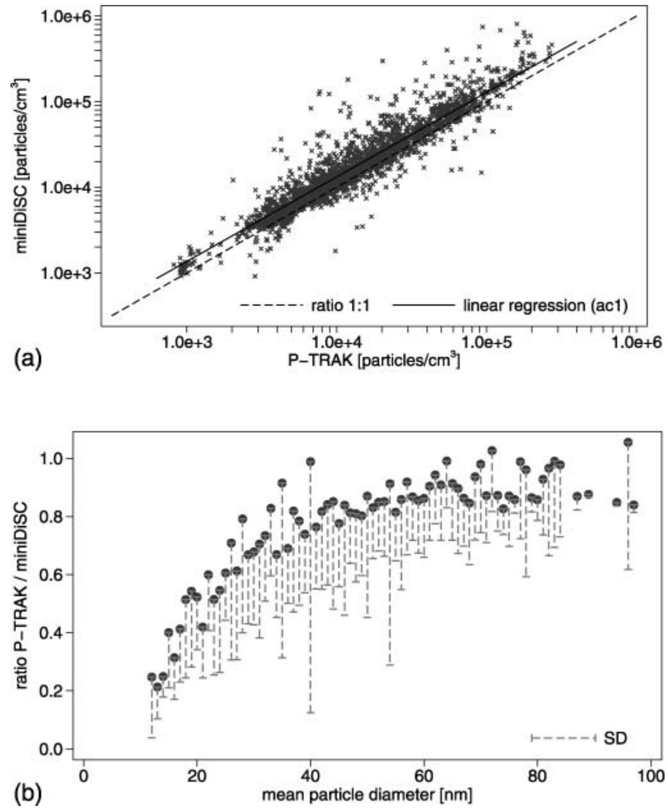

FIG. 1. (a) Linear regression model for log10-transformed particle number concentration measurements with a miniDiSC and a P-TRAK during highway maintenance work (mowing excluded, corrected for first order autocorrelation). (b) Ratio of particle number concentrations measured with the miniDiSC and the P-TRAK as a function of the mean particle size measured by the miniDiSC. Data from measurements during highway maintenance work (mowing excluded).

numbers reported by the miniDiSC were significantly higher under all conditions ($p < .001$) except for the short period of truck loading off-road when values did not differ significantly ($p = .32$). Linear regression models for log10-transformed particle numbers showed a uniform relationship for most conditions; location and activity specific slopes were between 0.61 (indoor) and 1.26 (mowing). Location specific slopes for traffic-influenced sites (car/roadside) were slightly steeper than for other locations; indoor data had the lowest slope. Activity specific slopes were generally higher for activities in car/on roadside but did not differ significantly, except for mowing with a significantly steeper slope than all other activities. The model for indoor data was not very robust as the exclusion of three unexplained outliers shifted the slope from 0.61 to 0.82—which is still lower than slopes of all other locations. The model for the activity "loading truck" is not very robust either as it is based on only 27 data points. All location and activity dependent regression models are shown in Figures S2 and S3.

Comparison of miniDiSC and P-TRAK During Mowing

During mowing, we encountered very high particle numbers that exceeded repeatedly the measurement range of the UFP-counters. Under these extreme conditions, the particle counts of the two counters drifted widely apart. The correlation was still high ($r = 0.86$) but mean particle counts of the miniDiSC were almost ten times higher than P-TRAK counts. Mean particle number measured with the miniDiSC was 699,008 particles/cm^3 while short term peaks reached up to several million particles/cm^3. Under the same conditions, the P-TRAK measured a mean of 74,145 particles/cm^3 with peaks up to 420,000 particles/cm^3. The mean particle size during mowing was low; the miniDiSC measured a mean diameter of 36.2 nm (SD 23.9). Data collected during mowing are summarized in Table 1.

Stationary Comparison of miniDiSC, P-TRAK, and SMPS

From a total of 194 SMPS cycles conducted during stationary measurements, we excluded data of 112 cycles (58%) because particle numbers within these cycles were unstable (continuous miniDiSC particle counts drifted by more than 10% of the mean during the corresponding time period). The other 82 cycles were used to compare the miniDiSC and the SMPS. Only 69 cycles were used for the comparison with the P-TRAK, because we had to exclude P-TRAK data due to low isopropanol levels (P-TRAK reported error).

During the stationary measurements, particle numbers were about 50% lower than the average during maintenance work; the mean number indicated by the miniDiSC was 18,282 particles/cm^3 and the average particle size 41.6 nm. Although the exclusion of unstable cycles led to a decreased autocorrelation, it was still significant (ac1 = 0.56 for the miniDiSC, ac1 = 0.59 for the P-TRAK and ac1 = 0.53 for the SMPS). The miniDiSC and the P-TRAK correlated well ($r = 0.89$) but numbers obtained from the P-TRAK were 55% lower than miniDiSC numbers. The linear regression model for log10-transformed data had a slope of 1.02 and an intercept of 0.22 (corrected for first order autocorrelation, Figure 2b). Comparison of the miniDiSC with the SMPS in its full size range from 10 to 1,110 nm showed that particle counts by the SMPS were on average 46% higher. Compared to the P-TRAK, the SMPS counts were on average 2.6 fold higher (Table 2a). To evaluate the effect of the cutoff diameter, we calculated the particle numbers counted by the SMPS using different cutoffs. We found that particle number concentrations in the size range of 16–311 nm corresponded best to the miniDiSC, while the size range of 36–1,110 nm matched to the P-TRAK. Particles with diameters from 311 to 1,110 nm represented only 0.25% of the total number and had a negligible influence on these results. The upper limits of 311 and 1,110 nm were chosen as they are the upper limit of the closest SMPS channels that correspond to the indicated measurement range of the handheld counters. Correlation of the miniDiSC with the SMPS in the adapted size range was $r = 0.95$; correlation of the P-TRAK with the SMPS in the adapted size range $r = 0.89$ (Table 2b). The linear regression model for log10-transformed data of the miniDiSC and the SMPS had a slope of 1.01 with an intercept of −0.04; the model for P-TRAK and SMPS had a slope of 0.83 with an intercept of 0.61 (Table 2b; Figures 2a and c). We also calculated the regression model

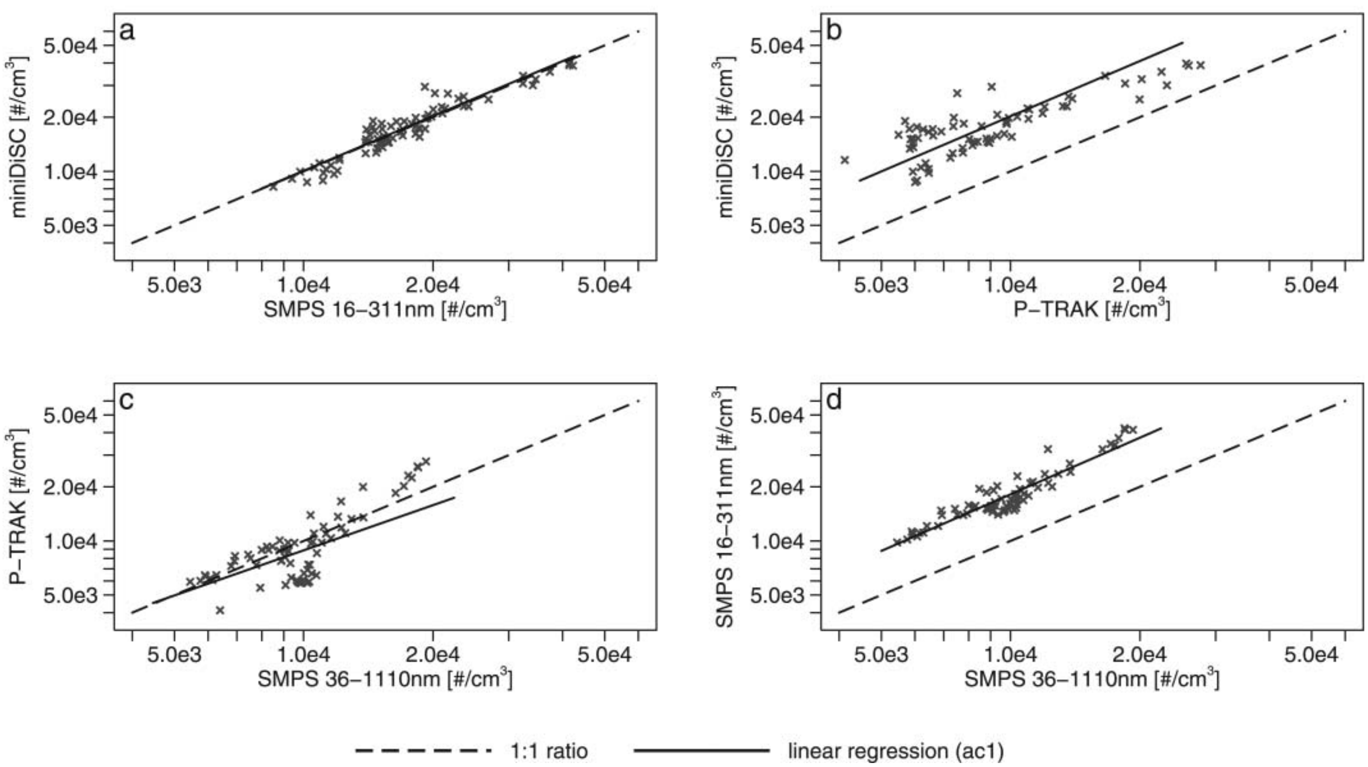

FIG. 2. Linear regression models for log10-transformed particle number concentrations of miniDiSC, P-TRAK, and SMPS during stationary measurements next to a highway (corrected for first order autocorrelation).

for the two SMPS size-ranges and saw that the slopes were very close to the model comparing the miniDiSC and the P-TRAK. Its slope was 1.04 and the intercept at 0.07 (Table 2b and Figure 2d). Summary statistics for stationary measurements are shown in Table 2a; correlations and model parameters in Table 2b.

The correlation of the geometric mean diameters measured by the miniDiSC and the SMPS was high ($r = 0.85$), but mean diameters measured by the miniDiSC were consistently between 4.8 and 13.2 nm (mean 8.6 nm) higher than mean diameters measured by the SMPS in the full size range (Table 2a; Figure 3a). The linear regression model for the two diameters had a slope of 1.02 with an intercept of −9.42 (Table 2b). We calculated the geometric mean particle diameters for different cutoffs and saw that the mean diameters of the SMPS size range from 13 to 311 nm corresponded to the miniDiSC (Table 2a; Figure 3a). The linear regression model using the diameters in the corresponding SMPS size range had a slope of 0.91 with an intercept of 4.87 (Table 2b; Figure 3b).

DISCUSSION

We demonstrate that UFP measurements of a miniDiSC under real world conditions are very well correlated to a conventional handheld CPC as well as to an SMPS. This, combined with their small size and weight, suggest that these devices are very useful for personal exposure assessment to UFP. The comparison of the P-TRAK and the miniDiSC during nonstationary highway maintenance showed that both devices measured similar particle numbers with a high time resolution, which allowed both devices identifying the very same peak episodes. However, particle counts of the P-TRAK were typically lower and the difference increased with decreasing particle diameters.

TABLE 2A
Summary statistics for stationary measurements next to a highway

		miniDiSC	P-TRAK	$SMPS_{10–1110}$[a]	$SMPS_{13–311}$	$SMPS_{16–311}$	$SMPS_{36–1,110}$
Cycles	#	82	69	82	82	82	69
Particle counts	Particles/cm^3	18,282	10,052	26,642	20,442	18,226	10,202
	(SD)	(7,234)	(5,365)	(10,562)	(8,165)	(7,273)	(3,221)
Size[b]	nm (SD)	41.6 (3.6)	–	33.0 (4.0)	42.8 (4.0)	47.8 (3.9)	77.2 (2.6)

[a]Full SMPS size range. [b]Geometric mean diameter.

TABLE 2B
Correlations and parameters of linear regression models of log10-transformed particle number concentrations from stationary measurements next to a highway. All correlations are highly significant ($p < 0.001$)

	Correlation r	Linear regression (ac1)[a] Slope	Intercept
miniDiSC P-TRAK	0.89	1.02	0.22
miniDiSC $SMPS_{10–1,110}$	0.98	0.90	0.29
miniDiSC $SMPS_{16–311}$	0.95	1.01	−0.04
P-TRAK $SMPS_{10–1,110}$	0.85	0.66	1.05
P-TRAK $SMPS_{36–1,110}$	0.89	0.83	0.61
$SMPS_{16–311}$ $SMPS_{36–1,110}$	0.95	1.04	0.07
$size_{miniDiSC}$ $size_{SMPS10–1,110}$	0.85	1.02	−9.42
$size_{miniDiSC}$ $size_{SMPS13–311}$	0.86	0.91	4.87
$size_{miniDiSC}$ $size_{SMPS16–311}$	0.76	0.77	15.93

[a]Model corrected for first order autocorrelation

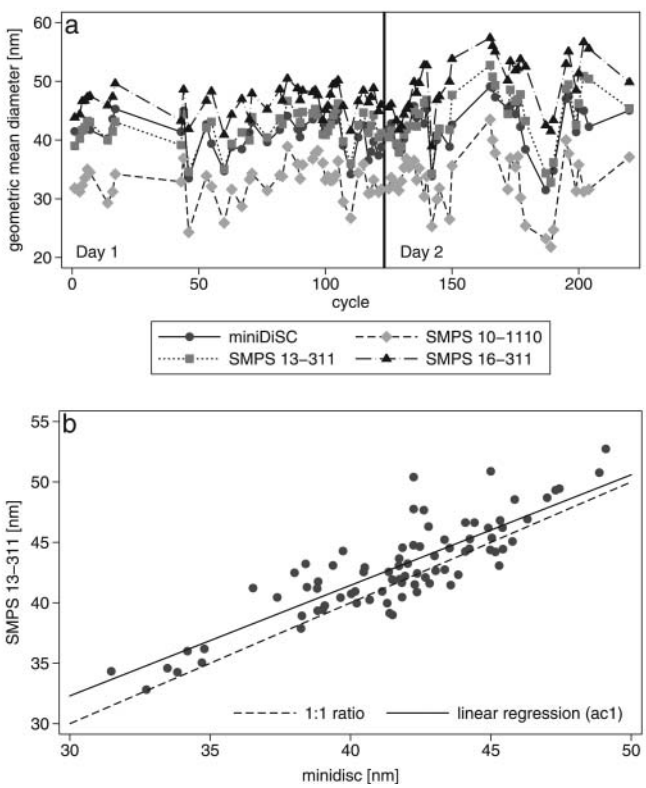

FIG. 3. (a) Geometric mean particle diameters from the miniDiSC and the SMPS size ranges 10–1,110 nm, 13–311 nm, and 16–311 nm during stationary measurements next to a highway. Mean particle size from cycles with stable particle numbers within the respective SMPS cycles. (b) Linear regression model for geometric mean diameters from the miniDiSC and the SMPS in the size range 13–311 nm during stationary measurements next to a highway (corrected for first order autocorrelation).

This is not very surprising as the miniDiSC is designed to detect smaller particles than the P-TRAK (Matson et al. 2004; Fierz et al. 2011). We saw that the underestimation became most pronounced once the geometric mean particle diameter, measured by the miniDiSC, fell below 40 nm. While above this point, the P-TRAK measured constantly more than 80% of what the miniDiSC measured, this percentage dropped rapidly down to 20% for mean diameters around 15 nm. Similar percentages have been described earlier when the P-TRAK was compared to a CPC (Zhu et al. 2006). The effect has been explained by the size dependent efficiency of the P-TRAK and it has been hypothesized that volatile compounds of freshly emitted particles are not effectively detected by the P-TRAK (Zhu et al. 2006).

The stationary comparison of the miniDiSC and the P-TRAK confirmed the findings of the mobile measurements during maintenance work. The correlation as well as the parameters of the regression model were similar to the values obtained during nonstationary measurements. The comparison of the handheld counters with the SMPS showed that the particle numbers from the SMPS were 46% higher than numbers from the miniDiSC and 2.6 fold higher than numbers from the P-TRAK. By setting the cutoff from the SMPS at 16 nm, we obtained particle numbers that corresponded to the miniDiSC and by setting it at 36 nm we obtained counts that were similar to the P-TRAK. This suggests that the effect of the particle size is the main reason for discrepancies between the UFP counters. According to our measurements, the critical particle diameter for the P-TRAK is around 36 nm what explains the increasing difference between the miniDiSC and the P-TRAK for geometric mean particle diameters below this size. For the miniDiSC particle number concentrations, we have found the critical diameter to be at 16 nm what corresponds to the estimated d_{50} cutoff of the miniDiSC at 14 nm reported by Fierz et al. (2011). This, in comparison to the SMPS, elevated cutoff is also the reason for the higher geometric mean particle diameters of the miniDiSC. The SMPS includes high numbers of particles below the cutoff of the miniDiSC and calculates therefore a significantly lower mean diameter. We have seen that the SMPS size range from 13–311 nm corresponded very well to the miniDiSC. This slightly lower cutoff, compared to cutoff for corresponding particle number concentrations, is likely to be a consequence of the difference between the encountered particle size distribution and the one that was used for the miniDiSC calibration. To further evaluate the differences between the miniDiSC and the P-TRAK, we looked at the two SMPS size ranges corresponding to the handheld counters and could see that the regression model for the two size ranges was very similar to the model from the miniDiSC and the P-TRAK. Hence, by correcting for the size dependent effect, we obtained very similar results of all devices.

Varying locations and maintenances activities during nonstationary UFP measurements led to slight variations in the regression models for the two handheld counters. They did not change significantly but we observed steeper slopes for traffic related locations and activities. Slopes were less steep on locations without direct traffic influence where mean particle diameters were significantly higher (indoor, off-road, and garage, $p < .001$). The particles that we encountered during maintenance work must have originated from traffic emissions (vehicular exhaust, brake, tire, and road wear) or from the environmental background. The main difference between locations and activities was the mixing ratio of the smaller traffic particles and the bigger particles from the environmental background which explains the differences between the location and activity specific regression models. Although in theory other particle properties could have influenced the measurements, we did not see any indications for such effects. A special case was mowing where very high numbers of UFP were generated by the mowers' two stroke engines. It seems plausible that the main cause for the unequal measurements is the differing upper limit of detection of the devices, which becomes particularly relevant when measuring in close proximity of the exhaust pipes of the mowing equipment. The P-TRAK measures up to 500,000 particles/cm^3 and the miniDiSC is calibrated for up to 1,000,000 particles/cm^3 (although it also indicates higher numbers). Particle numbers concentrations in the vicinity of two stroke engines are usually much higher (Ålander et al. 2005) and exceed the measurement range of both counters. Hence, the overload of the devices led to inaccurate measurements, characterized by a significant underestimation by the P-TRAK and a potential measurement-error in the miniDiSC. In theory, the charging efficiency of the miniDiSC could have been influenced by increased particle charge in proximity to exhaust pipes or due to specific fuel additives that increase charge of exhaust particles (Jung and Kittelson 2005). But neither the measurements during highway maintenance work nor the stationary measurements showed any indications of such an effect being of practical relevance.

To compare studies using different UFP counters it can be useful to apply device specific correction factors. Because of the high correlation coefficients between the miniDiSC and the P-TRAK, a correction according to the location specific regression models should provide reasonable results. The same is true for the comparison of the two handheld counters with the SMPS under highway conditions. However, these correction factors depend on the particle size distribution at the measurement site as well as on the device calibration and should therefore not be applied without assessing their validity. Another factor that can influence the results is the temporal resolution of an UFP measurement which can be important to describe the particle environment. The SMPS measured particle size distributions in cycles of more than 3 min. This may not give an accurate picture of situation if short-term peaks occur, as is the case adjacent to the highway where vehicles leave a cloud of particles behind as they pass. For measurements of UFP number concentrations, it is therefore important to use appropriate devices according to the relevant situation and to critically evaluate the measured size range and the temporal resolution. Comparison between different studies is otherwise seriously hampered.

We found that particle numbers and average particle size measured by the miniDiSC were highly correlated with data from the P-TRAK as well as from the SMPS. However, we have seen that total particle counts of the three counters differed significantly. The miniDiSC measured significantly more particles than the P-TRAK and significantly less than the SMPS in its full size range. Our data suggests that the instrument specific cutoffs were the main reason for the different particle counts. Correcting for this size effect led to very similar results and we did not observe an influence of other particle specific effects. However, we tested the measurement devices under environmental and highway conditions. Further studies will be needed to confirm that this holds also for industrial settings where engineered nanoparticles could influence the performance of these counters differently. We conclude that the miniDiSC was found to be a useful tool to assess personal exposure under field conditions, including worksites characterized by combustion sources.

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