Ground–fixed and on–board measurements of nanoparticles in the wake of a moving vehicle

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Abstract

An integrated experimental methodology has been applied to measure number and size distributions of particles in the 5–560 nm size range in the wake of a diesel car running at different speeds. Measurements were made at both ground–fixed (0.10 and 0.25 m above the ground level) and on–board (in 12 different sampling locations behind the moving car) measurement configurations using a fast response differential mobility spectrometer (Cambustion DMS50) with a sampling frequency up to 10 Hz. Results from both the experimental campaigns were analysed to understand the dynamics, dispersion and transport of nanoparticle emissions in the wake of a moving vehicle. Temporal changes in results were divided into three main stages (pre–evolution, evolution and post–evolution) after the release of exhaust emissions from the tailpipe. Evolution stage is of most interest where all the changes to particle number and size distribution occurred. Up to four evolution sub–stages were observed, each showing distinct evolution patterns of particle size distributions, depending on the particular experimental run. In agreement with previous studies, dilution was found to be the dominant process throughout all the evolution stages. The first evolution sub–stage was common to all the measurements, and consisted of an initial particle number concentrations and distributions change due to rapid (less than 1 s) nucleation followed by a rapid increase of accumulation mode particle number concentrations. After this first sub–stage the presence of vehicle wake with recirculating particles and the possible influence of other transformation processes lead to complex interactions. Results from the two experimental data sets clearly confirm the presence of two separate groups of particles: (i) new particles, which are freshly emitted and come directly from the tailpipe and (ii) relatively aged particles, which are entrained within the recirculation vortices of the vehicle wake and reside there for a longer time. The two groups have different characteristics and interact with each other. This interaction has often been overlooked in past studies about local scale dispersion of nanoparticle from moving vehicles.

Keywords: Fast response measurements; Nanoparticles dispersion; Number concentrations; Size distribution; Ultrafine particles; Vehicle wake

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1. Introduction

Nanoparticles in the atmosphere are responsible for a number of adverse effects on human health and the environment (Davidson et al., 2005; Strawa et al., 2010). Road vehicles are the dominant source of particles by number (Kumar et al., 2011a). Particles below 300 nm (referring here as nanoparticles to describe particle number concentrations, PNCs, throughout this article) can contribute up to 99% of total PNC in the urban environment (Kumar et al., 2008b; Kumar et al., 2009a). Measuring and characterising emissions from individual vehicles under operational driving and dilution conditions is an important area of research. However, studying nanoparticle dispersion at fine spatial and temporal scales (e.g. in a vehicle wake) becomes a complex task, mainly because of the limited time response of most available instrumentation (Kumar et al., 2010). Our recent review summarised studies on field measurements and dispersion modelling of nanoparticles in vehicle wakes (Carpentieri et al., 2011). The review highlighted very short time scales associated with nanoparticle transformations in the earliest stages of emission. These transformations strongly interact with the flow and turbulence field immediately behind the emitting vehicle; hence, there is a need for characterising in detail the mixing processes in the wake, especially in the near wake.

A recent review by Kumar et al. (2010) reported that several field measurement studies of number and size distributions of nanoparticles in urban areas have been made using instruments such as scanning mobility particle sizers (SMPS), condensation particle counters (CPC), electrical low pressure impactors, alone or in combination. Most of these instruments have lower sampling frequencies relative to that required to characterise nanoparticle dispersion phenomena in vehicle wakes, hence an instrument with a fast response is required (Kumar et al., 2009c).

Field experiments purposely designed for measuring nanoparticle evolution in the wakes of vehicles are rare. Ambient measurements, while providing an integral view of the population exposure levels, cover both primary emitted and secondary formed particles, thus they cannot be reliably used to derive detailed source–receptor relationships (Wehner et al., 2009) or to investigate the first stages of the particle evolution within the wake (Carpentieri et al., 2011). Most of the previous
studies on nanoparticle emissions from single vehicles in real driving conditions (as opposed to
direct laboratory measurements using chassis dynamometers) are based on on-road measurements
with so-called chasing methods (Wehner et al., 2009). In these experiments, mobile laboratories
equipped with measurement instruments follow the car to be investigated and measure the particle
and gas emissions; for example, see Vogt et al. (2003), Giechaskiel et al. (2005) and Kittelson et al.
(2006). The main limitation of these methods is the minimum distance between the two vehicles
(i.e. chasing and experimental) which cannot be smaller than 10–15 m for safety reasons (Wehner et
al., 2009), making the technique unsuitable to investigate nanoparticle transformations in the near
wake, especially in the very first stages from emission.

New techniques have recently been developed to measure closer to the tailpipe. For instance,
Morawska et al. (2007) used a plume capture trailer to sample the naturally diluted air within 1–3 m
behind the tailpipe of a moving diesel car. However, the vehicle wake was heavily distorted due to
the presence of the trailer and the samples were taken offline, making impossible a realistic analysis
of the evolution process. Wehner et al. (2009) overcame this problem by using on-board
measurements. They mounted samplers for measuring meteorological parameters (ambient
temperature and relative humidity), PNCs in the 7–400 nm size range and gas (NOx and CO2)
concentrations, upon a bicycle rack on the back of a moving car. Using this experimental setup, they
measured number and size distributions of particles between 0.45 and 0.90 m away from the
tailpipe and derived particle number emission factors under different driving conditions. This
experimental setup reduced the disturbance on the wake flow generated by the mounted
instrumentation to acceptable levels. However, the number of measuring devices deployed, while
being very useful for the post-processing and interpretation phases still produced a non-negligible
modification of the vehicle wake. The study used 90s averages from samples analysed by a SMPS;
this could be further improved by using instruments with shorter response times and higher
sampling frequencies.

A completely different approach was used by Hak et al. (2009). They used ground-fixed sampling
to characterise nanoparticle emissions from individual vehicles by means of a CPC at a fixed location on the road surface. While capable of providing interesting information on individual particle number emission factors, the long response time of the instrument ($T_{90} = 3$ s) and sampling frequency (1 Hz) limited the detailed investigation of the exhaust plume. They found the duration of the PNC peak to be on the order of a few seconds, as was also confirmed by the experiments carried out by Kumar et al. (2009c). While integral information could be extracted with this setup, higher frequencies and shorter response times are needed to capture the particle transformation processes in the emitted plume. In order to overcome the latter problem, Kumar et al. (2009c) used for the first time a fast response particle spectrometer to characterise the evolution of number and size distributions of particles emitted by a diesel van with a sampling setup similar to the one described above. Their preliminary measurements, obtained by using a Cambustion DMS500 with a 10 Hz sampling frequency, highlighted the reliability of the measurement setup and allowed capture of the nanoparticle evolution process in the vehicle wake with the required detail. Therefore, one of the two parts of the methodology used in the present study involved the application of this technique with a more systematic approach for studying the evolution of particle number and size distributions in the wake of individual vehicles.

Considering the above, this study used an integrated measurement approach combining both ground–fixed (Section 2.1) and on–board (Section 2.2) measurements together with a portable fast response differential mobility spectrometer (Cambustion DMS50). The experimental setup allowed capturing of detailed high spatial and temporal resolution data sets, while minimising the distortion effects on the vehicle wake. Field measurements were conducted with the following objectives: (i) application and validation of an systematic experimental methodology allowing fast response measurements of PNCs while minimising vehicle wake distortion, (ii) understanding the dynamics, dispersion and transport of particle emissions in the wake of moving vehicles, (iii) investigating interaction between nanoparticle dilution and other transformation processes under various driving conditions, and (iv) providing reference cases for future work, involving the interpretation of wind
tunnel experimental data and the validation of purposely developed mathematical models.

2. Experimental setup and data collection

2.1. Ground–fixed sampling

The experimental campaign was performed at the University of Surrey car park. Fig. 1 shows the schematic representation of the experimental setup. The first set of tests was performed in a single lane of the car park about 70 m long and 6 m wide. The vehicle used for the experiments was a University owned Vauxhall Astra Van, which has a 1686 cm$^3$ diesel engine and was registered in 2004 under the Euro 4 emission standards. Exhaust emissions were sampled with a 4 m long sampling tube placed above the road surface at two fixed heights (0.10 and 0.25 m), connected to the DMS50. The DMS50 has a sampling frequency up to 10 Hz, with a response time ($T_{10-90\%}$) equal to 500 ms, and is capable of measuring number and size distributions in the 5–560 nm size range. The instrument is controlled by a laptop connected via an Ethernet interface.

Intentionally, the experimental campaign was carried out during a weekend (Saturday, 16th October 2010) so that there was negligible vehicle movement near the site in the car park. To avoid any influence of emissions from any external vehicle on our measurements, we made sure that no other cars were moving near the site and the background PNCs were steady or re-established in case there were emissions from other vehicles. Measurements were taken at both heights (i.e. 0.10 and 0.25 m above the road surface) separately after driving the car at four different speeds representing typical urban driving conditions (i.e. 20, 30, 40 and 50 km h$^{-1}$). Each set of experiment generated from the cross–combination of experimental conditions (car speed and sampling height) was repeated 6 to 10 times for reproducibility purposes (see Table 1). The car was driven above the sampling point, which was distant, in the lateral direction, approximately 0.27±0.15 m from the tailpipe exit (Fig. 1). The tailpipe had a diameter equal to 0.05 m, and its centre was approximately 0.30 m above the road surface.

Meteorological data (wind speed and direction, temperature and relative humidity) were monitored
locally by using two weather stations. The first one (Davis Weather Wizard 3) is located on top (~20 m above ground level) of a nearby University building which was about 250 m away from the experimental site. This station measured the data at 2 s intervals and logged them every 10 minutes after averaging. For monitoring the local meteorological conditions at the experimental site, the second weather station (LaCrosse WS–2350) was placed on a pole at 4 m above the road level near the sampling location (see Fig. 1). This station logged the monitored meteorological data every 3 minutes during the experiments. Weather conditions remained relatively constant during the experimental campaign, with an average temperature of 15.9 °C, an average pressure of 102.1 kPa and average relative humidity of 59%. The average wind speed measured by the campus weather station on the building roof was 4.9 m s$^{-1}$ with a prevailing wind direction approximately from north–east, while the on–site station measured an average of 1.4 m s$^{-1}$ at a much lower height.

2.2. On–board measurements

The second experimental campaign was performed again in the University of Surrey car park. The same car, as described in Section 2.1, was driven around the perimeter lane of the car park during two separate campaigns (Saturday, 13$^{th}$ November 2010, and Saturday, 29$^{th}$ January 2011). Similar to ground–fixed measurements, three car speeds (20, 30, and 40 km h$^{-1}$) were used during these experiments. The area used for these experiments (see Site 2 in Fig. 1) has an approximate extension of 300 m in the east–west direction. This arrangement was sufficient for driving the car at an approximately constant speed for about 20 to 60 s during each run in both directions. All the runs were repeated at least twice.

In this second experimental campaign, the DMS50 was placed inside the test vehicle and the sample tube (length 1.75 m) was attached to an L–shaped pole extending from the back of the car (see Fig. 1). The set up covered both the traditionally seen recirculating flow regions on each corner of a moving vehicle and centre region (Hucho, 1987), and allowed mapping of number and size distributions at 12 fixed points within the vehicle wake. These included 9 (3×3) points at $x=0.45$ m (in particular at $y=-0.45$, 0 and 0.45 m, and $z=0.10$, 0.50 and 0.90 m), and 3 further points at $x=0.80$ m.
m (at \( y = -0.45 \), 0 and 0.45 m, and \( z = 0.50 \) m). Note that, as illustrated in Fig. 1, \( x = 0 \) is placed at the tailpipe exit, \( y = 0 \) is located at the car centre line and \( z = 0 \) is at ground level, so that \( y = -0.45 \) m is in line with the tailpipe.

Meteorological conditions were monitored as described in Section 2.1. The first of the two on-board experimental campaigns was carried out in a day with very calm wind conditions. The average measured values during these tests were: temperature 11.4 °C; atmospheric pressure 99.5 kPa; relative humidity 64%; wind speed 0.4 m s\(^{-1}\); prevailing wind direction from west. During the second on-board campaign wind conditions were similar to those during the ground-fixed tests: average wind speed at roof level equal to 4.8 m s\(^{-1}\), with a prevailing wind direction from south; average temperature, atmospheric pressure and relative humidity were, respectively, 3.9 °C, 102.6 kPa, and 62%.

### 3. Results and discussion

This chapter reports and discusses the results obtained from both (ground-fixed and on-board) the experimental campaigns. After few preliminary checks for quality assurance of data (Section 3.1), experimental results are presented in terms of PNCs and particle number distributions (PNDs) in Sections 3.2 and 3.3 for both experimental setups. Discussion on the main findings and significance of the experimental study is then reported in Section 3.4.

#### 3.1. Sensitivity levels on the DMS50 and particle losses in sampling tubes

In order to ensure the quality of the measurements with the Cambustion DMS50, some preliminary checks were deemed necessary. In particular, sensitivity levels compared with noise was analysed, and an initial assessment of particle losses in sampling tubes was carried out.

Following the same methodology applied by Kumar et al. (2009c) for testing the noise level of the DMS500 in their experiments, sensitivity of the DMS50 was checked by comparing its noise level with the measured minimum (background) PNCs at the experimental site. The background PNCs at site were measured by applying the highest sampling frequency (10 Hz) when the noise level of the
DMS50 is also the greatest. As seen in Fig. 2, comparison of the measured PNDs at a maximal noise (10 Hz frequency) indicates that the background PNCs were well above the noise level of the instrument for particle diameters greater than 7 nm. The signal from particle sizes up to 7 nm, however, is comparable, or below, the noise level at 10 Hz. This fact, however, does not affect the discussion on the following sections, since most of the analysis is based on longer time averages.

Particle losses caused by the experimental set up can become relevant especially for smaller particle sizes and longer sampling tubes (Kumar et al., 2008c). In order to minimise this effect, the length of the sampling tubes has been kept to the minimum required to reach the measurement location. As described in Section 2, this length was 4 m for ground-fixed measurement, and 1.75 m for on-board measurements. The internal diameter of the tubes is 5 mm. Sampling flow rate was kept to 0.00014 m$^3$ s$^{-1}$ with a line pressure of 80 kPa. The Reynolds number ($Re$) was around 1.7 x 10$^3$, thus within the laminar flow limit.

According to previous studies (Kumar et al., 2008c), we can expect that particle losses should become relevant only for smaller sizes (< 20 nm), with the greatest effects in the 5–10 nm range. Using the semi–empirical formulation given by Hinds (1999), for example, the penetration efficiency during the tests with the 4 m tube can be estimated as around 70–75% for particle sizes ≤ 6 nm, reaching already 80% at 7 nm, and above 90% for particles bigger than 10 nm. For the 1.75 m long tube, penetration is above 80% for all size ranges detected by the DMS50, reaching 90% for particle sizes around 7 nm.

In the following sections results are discussed mainly in relative terms, comparing data from different runs, at different locations and time. In absolute terms, however, the main effects would be: (i) underestimation of total PNCs and, in particular, of PNCs in the 5–30 nm size range, that are often mentioned); (ii) overestimation of total geometric mean diameters (GMDs) and, in particular, of GMDs in the 5–30 nm size range.

3.2 Analysis of PNCs
3.2.1 PNCs during ground–fixed measurements

As reported in Section 2.1, 8 different experimental cases were studied (height $H = 0.10$ and $0.25$ m, with car speed $V=20$, 30, 40, and 50 km h$^{-1}$). Several runs were repeated within each experimental set, i.e. 10 runs for car speeds up to 40 km h$^{-1}$, and 6 runs for 50 km h$^{-1}$; the runs for each experimental case are numbered sequentially from Run 01 to Run 10 (or 06 in the case of $V=50$ km h$^{-1}$), leading to a total of 72 datasets available for analysis from the ground–fixed measurements. Seven runs were ignored in the post–processing stage due to quality issues caused by external disturbances and measurement errors. A summary of the results from these measurements is reported in Table 1.

Table 1 reports the average peak value of PNCs for each experimental case, along with its standard deviation. While the average peak value of total PNC was within one order of magnitude (i.e. in the $10^5$–$10^6$ # cm$^{-3}$ range) for all experimental cases, the actual value during each run varied within a greater range, as evidenced also by the calculated standard deviations (Table 1). In particular, the ratio between the maximum measured peak value ($H=0.25$ m, $V=50$ km h$^{-1}$, Run 02) and the minimum measured peak value ($H=0.10$ cm, $V=40$ km h$^{-1}$, Run 04) was about 50. This variability, even within the same nominal experimental conditions, was largely expected, given the unpredictability of local turbulence conditions and imperfect alignment of the car with respect to the sampling point across different runs (see further discussion on this point in Section 3.4).

Much more consistent is the time when the instrument measured the peak value for a particular run (Table 1). Confirming results from our earlier work (Kumar et al., 2009c), the PNCs reached their peak values within and just over 1 s for $H = 0.10$ and 0.25 m, respectively; $t=0$ is defined as the time when the PNC start to significantly increase from the background concentrations which can supposedly be considered as the first sign of detection of the plume. As expected, the time when the peak is detected seems to be affected more by the sampling height than the vehicle speed, as evidenced by the greater difference in peak times between 0.10 and 0.25 m than between cases at different car speeds. The duration of the event, arbitrarily defined as the time during which the PNC
is above 150% of the background value, seems to increase on average together with the vehicle speed for both $H = 0.10$ and 0.25 m. In particular, the decay time appears to increase with the car speed, as reported in the following analysis.

Fig. 3 shows the temporal evolution of normalised average PNCs for each experimental case. These normalised values are firstly obtained by dividing all the PNC values by the peak PNC value for each individual run. Then, for each experimental case, values of different runs have been averaged considering PNCs at the same time (defining $t=0$ as explained above). This average curve was then re–normalised using the average peak value for each experimental case to obtain curves with peaks equal to 1. The duration for the peak PNCs is generally larger for higher car speeds as seen in Table 1 and Fig.3. In particular, the decay time of the peak PNCs towards the site–background increases with the increasing car speed. This increase in decay time with car speeds could be due to a combination of two factors: (i) emission factors at higher car speeds are higher (Kumar et al., 2011b), and (ii) the effects of the wake at the sampling location last longer.

As evidenced by the error bars shown in Fig. 3, the average normalised PNCs obtained for the first three experimental cases ($H= 0.10$ m; $V = 20, 30$ and 40 km h$^{-1}$) have a remarkably low variability. However, a much greater variability is observed, especially during the peak decay phase, both at 0.10 and 0.25 m sampling heights for $V = 50$ km h$^{-1}$. The variability for the other experimental cases ($H = 0.25$ m, $V = 20, 30$ and 40 km h$^{-1}$) is between those two levels. In particular for $V = 20$ and 30 km h$^{-1}$, besides the variability in the decay phase, there is a smaller initial peak which is not always present in all the runs, increasing the variability at this particular stage. An explanation of this phenomenon is attempted in the following paragraphs, by analysing the single PNC evolutions and the results from the second field campaign.

Despite the variability described above, some common features can indeed be found in the evolution of the PNCs measured in these various test cases. Fig. 4 reports a selection from the total available 65 cases illustrating some of the most common patterns during the ground–fixed
measurements. For instance, the pattern visualised in Fig. 4a is one of the most common (around 28% of the runs), even though the numerical values can differ from case to case. This pattern is very similar to the one presented in a preliminary field campaign by Kumar et al. (2009c). It features a rapid building of PNC, with a peak usually before 1 s (see Table 1), then a rapid decrease followed by a slightly slower decay before returning to the background values. A slightly modified version of this pattern is presented in Fig. 4b (another 15% of the runs share this trend). This latter situation is more common for higher car velocities where, as also shown in Table 1, the decay time is longer.

Fig. 4c shows another common pattern (around 32% of the runs) where a larger peak followed by another smaller peak can be observed. This feature was frequently observed in experimental cases with higher car speeds at 0.25 m height. This pattern could probably be caused by wake effects i.e. increasing turbulence with car speeds (see, e.g., Di Sabatino et al., 2003). The pattern in Fig. 4d shows another frequently seen pattern (the remaining 25%) where a smaller peak rapidly follows a larger peak. This pattern was often observed during the measurements at $H = 0.25$ m, especially at lower vehicle speeds, and lead to the average evolution profile highlighted in Fig. 3b and 3d ($H = 0.25$ m, $V = 20$ and $30$ km h$^{-1}$). This pattern could also be due to rapid movements of the vehicle wake; we will come back on this point with more details in the next section (3.2.2), where on–board measurements are analysed. PNC evolutions for the entire dataset are available on request.

The evolution of PNCs measured at a ground–fixed sampling point is mainly driven by nucleation and dilution. As a matter of facts, the effect of the emission measured at the fixed location lasts only for a few seconds (usually about 5–15 s, see also Table 1). Within this time scale, coagulation and deposition are not likely to play a significant role in PNC evolution (see Zhang and Wexler, 2004, Ketzel and Berkowicz, 2004, and the review by Carpentieri et al., 2011). Other transformation processes such as condensation do not alter the PNCs (Kumar et al., 2010). Possible effects of various transformation processes on number and size distributions in the studied cases are further analysed in detail in Section 3.3.

3.2.2 PNCs during on–board measurements
A summary of the results for the on–board measurements is presented in Tables 2, 3 and 4 for vehicle speed equal to 20, 30 and 40 km h\(^{-1}\), respectively. Data in the tables represents averages over all the runs in same nominal conditions (i.e. car speed and measurement point) as described in Section 2.2 and Fig. 1.

Results presented in Figs. 5 and 6 highlight the spatial distribution of total PNCs in the car wake. As expected, the maximum PNCs are measured along the points in line with the tailpipe. The closest measurement points are P\(_a\) and P\(_d\) (Fig. 5a); these are respectively at \(z=0.10\) and \(0.50\) m above the ground and both at \(x=0.45\) m away from the tailpipe. However, PNCs measured at P\(_a\) are 2.5–2.7 times higher than those found at P\(_d\) in all the experimental cases. This could be explained considering the fact that P\(_a\) is within the direct emission plume from the tailpipe, while P\(_d\) is in the recirculation wake.

An interesting aspect of the on–board measurements is the large differences in PNC among the 3 measurement points at \(z=0.10\) m (Fig. 5) for all car speeds. PNCs are much more uniform at \(z=0.50\) m and \(z=0.90\) m, where the plume is within the recirculation zone (Hucho, 1987) rather than entrained in the air flow coming from below the car. This huge difference between PNCs at \(y=-0.45\) m (in line with the tailpipe) and PNCs at other positions along the \(y\)–axis can partially explain the large variability observed during the ground–fixed measurements (Section 3.2.1). Even small deviations from the planned lateral position of the passing car could have generated large differences in the measured concentrations, if the sampling point was only a few centimetres further away from the tailpipe (see Section 3.4).

The above observations also provide a possible explanation for the results presented in Section 3.2.1 about the ground–fixed measurements at \(z=0.25\) m. This height is very close to the bottom of the car, where the interface between the two behaviours observed above (the uniform PNCs observed within the wake and the PNCs measured in the direct flow below the car) is probably located (see Fig. 7). The double peaks often observed at \(z=0.25\) m during the ground–fixed measurements could
be due to the fact that the sampling point was moving in and out from the wake (or, to be more
precise, the wake moved, while the ground–fixed point was, indeed, fixed). No wonder the
variability observed during the $z=0.25$ m cases is higher than that observed at $z=0.10$ m.

At the same measurement points, the PNCs measured at higher car speeds (30 and, especially, 40
km h$^{-1}$) are generally up to a factor of 3 larger than those measured at 20 km h$^{-1}$. As for the analysis
of ground–fixed measurements (Section 3.1.1), this could be due to a combination of two factors: (i)
particle number emissions at higher speed are greater (Kumar et al., 2011b), and (ii) measurement
points at the same distance from the tailpipe are actually closer, from a temporal point of view, at
higher speeds.

3.3. Transformation of number and size distributions

3.3.1. PNDs during ground–fixed measurements

The analysis presented in this paragraph included the study of PNDs and GMDs at various
stages during the measurements. PNDs, in particular, are presented in terms of normalised number
weighted size spectrum. This normalisation has been carried out by dividing the measured number
spectral densities ($dN/d\log D_p$) for each size category (characterised by the diameter $D_p$) by the total
PNC at that particular time. This kind of normalisation was done for highlighting the relative
transformations in terms of size spectrum, removing the effect of dilution. In facts, dilution affects
all particle size ranges uniformly, and plotting the normalised spectra at different time steps on the
same graph will show a perfect superposition of those spectra when dilution is the only process
involved.

As in the case of PNCs, common features of the evolution of PNDs can be observed across the
various experimental runs, despite the expected differences among different runs even in nominally
identical conditions. Fig. 8 shows a typical behaviour of the normalised size spectrum during the
three main stages (pre–evolution, evolution and post–evolution, as defined below). The subdivision
of the transformation process in different stages is somewhat arbitrary, and it was done by observing
common trends of the PNDs during the measurements. Up to four evolution sub–stages, each
showing a distinct PND evolution pattern during various experimental runs, were also identified.

The “pre−evolution” stage represents the status of the size spectrum just before $t=0$ s (as defined in Section 3.2), i.e. site background conditions. During this stage the PNDs are, as expected, consistent across all the experimental cases, except for few observed differences due to uncontrolled external disturbances. The peak number spectral densities during this stage are usually in the 10−12 nm size range and the PNDs are dominated mainly by nucleation mode particles (Fig. 8a). “Evolution” stage is defined as the stage where most of the transformation processes occur; this is assumed to start at $t=0$ s. In the case exemplified in Fig. 8, and common to most of the runs in the first experimental case (i.e. $H=0.10$ m, $V=20$ km h$^{-1}$), the evolution stage can be further divided in two sub−stages, marking a different behaviour in the transformation process: during the first sub−stage (tagged “evolution 1” in Fig. 8), there is a rapid change in the normalised size spectrum. This shows an initial increase in spectral densities at diameters around 25 nm followed by an even greater increase for particle sizes between ~40 and ~100 nm (Fig. 8b). The second sub−stage of evolution (tagged “evolution 2”) starts at $t=0.8$ s and shows the normalised size spectrum returning back to the site background, very similar to the PNDs observed in the pre−evolution stage (Fig. 8c). From $t=1.9$ s onwards (Fig. 8d), the normalised spectrum does not deviate much from the site background and only total PNC variations are observed (dilution−only; see also Fig. 9a). This stage is defined as “post−evolution”.

Fig. 9a shows the evolution of the GMDs, and the corresponding PNCs, during all the stages highlighted in Fig. 8. GMDs increase rapidly from the background value ~15 nm to a peak of ~38 nm during the ‘evolution 1’ sub−stage due to the freshly−emitted particles in the nucleation mode from our car (Fig. 8), followed, with the same rapidity, by a decrease to the background value in ‘evolution 2’ sub−stage. Comparing the GMD trend with the corresponding PNCs (Fig. 9a), it can be noted that the former is slightly quicker in its return to the background conditions. This means that at the beginning of the post−evolution stage we still have a PNC variation, despite the fact that the GMD and the normalised spectrum do not change much (dilution only). This is, however, not
always the case, as discussed below.

The pattern outlined above, with two evolution sub-stages, is also common to the second experimental set ($H=0.10$ m, $V=30$ km h$^{-1}$), although in this case another behaviour can also be observed (see Fig. 10): besides both the evolution sub–stages seen in earlier cases (‘evolution 1’ and ‘evolution 3’ in Fig. 10, corresponding to evolution 1 and 2 in Fig. 8), another sub–stage (evolution 2’ in Fig. 10) is present. During this additional sub–stage size distributions do not change in relative terms; the remarkable superposition of the various normalised spectra suggests dilution as the only acting process. This sub–stage usually started after about 1 s, and lasted for another 2 or 3 s (see Fig. 10c), followed by a very slow return (Fig. 10d) to the original distribution (Fig. 10e). This trend is exemplified in Fig. 9b, for the same experimental case, with the help of GMD and PNC evolutions. While the PNC evolution curve is very similar to that in Fig. 9a, the GMD pattern is utterly different, with a fast initial increase up to about 24 nm and then a slow return to the initial value (~15 nm). In this second phase, dilution is usually the main transformation process. This behaviour can also be observed frequently in other two experimental cases (i.e. $H = 0.10$ m, $V = 40$ and 50 km h$^{-1}$).

Similar patterns can be identified in other four experimental cases at $H = 0.25$ m ($V = 20$, 30, 40 and 50 km/h), except an additional fourth evolution sub–stage during the initiation of evolution process is often observed (see Fig. 11). The evolution sub–stages 2, 3 and 4 in Fig. 11c, d and e, respectively, look identical to those found in evolution sub–stages 1, 2 and 3 in Fig. 10b, 10c and 10d. The additional sub–stage (Fig. 11b) at the beginning of the evolution process in the present case shows an initial rise in number spectral densities around the 17 nm diameter, followed by another increase in the 23–30 nm range and then a rapid decrease. After about 1 s from $t=0$, this trend is generally over, and the usual evolution pattern already observed in Fig. 10 is established again. This process can also be observed in the evolutions of the GMDs and PNCs (Fig. 9c), and can be explained by the fact that different parts of the emitted plume are being sampled at different times, as analysed during the on–board measurements and further discussed in Section 3.4.
3.3.2 PNDs during on–board measurements

Fig. 12 shows the particle size spectra during the on–board measurements at $P_a$ ($x=0.45$ m, $y=-0.45$ m, $z=0.10$ m) and $P_d$ ($x=0.45$ m, $y=-0.45$ m, $z=0.50$ m) at different car speeds; both these points are in line with the tailpipe as illustrated in Figs. 1, 5a and 6a.

Apart from the numerical value of PNC in different runs, which is likely to be sensitive to both the mechanical (traffic) and atmospheric (wind) produced turbulence (Kumar et al., 2008a), the shapes of the PNDs for different runs within the same experimental condition (car speed and measurement point) are reasonably similar. The magnitude of accumulation mode particles seem to be more affected by the above flow effects than the nucleation mode particles in different runs of the same experimental cases. PNDs at $P_a$ (Figs. 12a, b and c) appear to be more affected by the different car speed (or rather, as pointed out in Section 3.2.2, by the distance from the tailpipe, from a time scale point of view) than PNDs at $P_d$ (Figs. 12d, e and f), which are similar to each other. In particular, the lowest measurement point is unswervingly affected by particles (mainly in the 30–45 nm size range as evident from a distinct peak at $P_a$; Figs. 12a, b and c) coming directly from the tailpipe; this peak in the PNDs is nearly absent at $z=0.50$ m ($P_d$; Figs. 12d, e and f). Most of the measured particles at both measurement points (i.e. $P_a$ and $P_d$) are in the range 60–160 nm, as also evident in Tables 2, 3 and 4 from PNC–1, PNC–2, GMD–tot, GMD–1 and GMD–2 values. The bimodal shape of the PNDs is more evident at $P_a$ for higher car speeds. This is due to the fact that freshly emitted fine particles are sampled earlier at 40 km h$^{-1}$ than at 20 km h$^{-1}$.

PNDs at $P_g$ ($x=0.45$ m, $y=-0.45$ m, $z=0.90$ m) and $P_j$ ($x=0.80$ m, $y=-0.45$ m, $z=0.50$ m) are very similar to those observed at $P_d$ (Figs. 12d, e and f), and are not presented here for brevity reasons; however, their results are summarised in Tables 2, 3 and 4. Numerically, the differences between the average PNDs at these measurement points ($P_d$, $P_g$ and $P_j$) are very small in all experimental conditions. As shown in Tables 2, 3 and 4, GMDs at points $P_d$ and $P_g$, in particular, seem not to be greatly affected by the car speed. On the contrary, at points $P_a$ and $P_j$, car velocity seems to have a slightly greater influence, driven mostly by accumulation mode particles, while GMDs and PNCs in
the range 5–30 nm do not show much sensitivity to this parameter.

Figs. 13a, b and c show PNDs at P_b (x=0.45 m, y=0, z=0.10 m; car centre line). The strong influence of smaller particles on the total PNDs is clearly visible in these figures. Further evidence of this influence is given by the total GMD values (Tables 2, 3 and 4) which are sensibly lower than the other measurement points in all the experimental conditions. Another peculiarity of this measurement point is the size distribution of nucleation mode particles: the GMD for particles <30 nm is in the range 10–13 nm, while for most of the other measurement points this value is usually between 16 and 21 nm. These low values can only be found at one other measurement point, notably at P_c (x=0.45 m, y=0.45 m, z=0.10 m).

Spectra measured at other centre line points (specifically P_e, x=0.45 m, y=0, z=0.50 m, and P_h, x=0.45 m, y=0, z=0.90 m) are similar in shape to those at P_d and P_g. On the contrary, small differences can be observed at P_k (x=0.80 m, y=0, z=0.50 m, see Figs. 13d, e and f), with a slightly higher spectral density in the 20–40 nm size range, and a maximum spectral density value at smaller diameters (50–85 nm), tending to even decrease as the car speed increases. This is also reflected in total GMDs values (Tables 2, 3 and 4) which become smaller as the speed increases.

PNDs measured at P_c (x=0.45 m, y=0.45, z=0.10 m) are presented in Figs. 14a, b and c for different car speeds. These figures share a few similarities with P_b, and this is also evidenced by the data in Tables 2, 3 and 4, as already pointed out. These points seem to be at the interface between two different zones (the recirculation wake and the zone where the flow is coming from below the car, see Fig. 7 and Section 3.2.2) of the wake, and this is reflected in the variability observed during different runs at nominally the same experimental conditions. Other similarities can be observed between PNDs at P_l (x=0.45 m, y=0.45, z=0.90 m; Figs. 14d, e and f) and at P_k (Figs. 13d, e and f). PNDs at the other remaining measurement points (P_l, x=0.45 m, y=0.45 m, z=0.50 m, and P_l, x=0.80 m, y=0.45 m, z=0.50 m) have the common shape already seen for P_d, P_e, P_g, P_j and P_h.

3.4. Discussion
The large amount of data gathered during the two experimental campaigns offer several points for discussion. The adopted experimental strategy allowed us to look at different aspects of the nanoparticle dispersion process from a moving car, integrating the results from previous studies, performed with different measurement setups. Particularly, the present study took into account the effects of the vehicle wake on the nanoparticle transformation process, thanks to both the fast response instrument and the integrated experimental methodology used.

Some interesting observations can be made about the various transformation processes involved in the first stages from the emission of nanoparticles from the car tailpipe. Carpentieri et al. (2011) reported in their review that particles emitted by cars are subject to a number of transformation processes (i.e. nucleation, dilution, coagulation, condensation and deposition) which are discussed below in the context of our results.

Dilution is the main process acting on nanoparticles emitted by diesel cars (Zhang and Wexler, 2004; Ketzel and Berkowicz, 2004; Kumar et al., 2009b). It is mainly driven by the vehicle-produced turbulence in the near wake region while the atmospheric turbulence dominates this in far wake regions (Carpentieri et al., 2011; Kumar et al., 2011b). As soon as the exhaust emissions are released from the tailpipe, they start to dilute at a rapid rate which causes sulphuric acid–induced nucleation (Zhang and Wexler, 2004). The interaction between nucleation and dilution is very fast, and it has been rarely captured by experimental measurements under actual driving conditions. Across all our ground–fixed measurements, this effect can be clearly observed by looking at the fast growing PNCs in nucleation mode in the very first stage of evolution (see Figs. 8b, 10b, 11b and 11c). The process is usually over within 1 s, confirming the preliminary results by Kumar et al. (2009c) as well as the study conducted by Rönkkö et al. (2006) and (2007). The latter two studies conducted both on–road (with the chasing method) and in laboratory measurements of the number and size distributions of the particles. They found that fast dynamical processes (mainly nucleation) in the exhaust plume of a truck and a bus, respectively, had already taken place within 0.7 s from emission, confirming our current observations.
Irrespective of vehicle speed, results from the ground–fixed measurements show that the PNCs reached to a peak after a remarkably constant time. This aspect indicates a negligible influence of the vehicle wake in the very first phases of evolution, where dilution and nucleation are likely to be driven mainly by the immediate interaction between the plume jet and the external environment.

After reaching the PNC peak, the nanoparticles start mixing with the wake or the external flow (depending on which part of the plume we are looking at). This is evidenced by the longer decay time experienced by PNC measurements in the ground–fixed experiments with higher car speed (for example, see Table 1). PNDs measured in this phase of the evolution, show another transformation process acting on the emitted nanoparticles, besides dilution. A growth in accumulation mode particles, in particular, is driven by condensation of super-saturated vapours (Zhang and Wexler, 2004). The time scale associated with this process varies from case to case. However, it seems to last for few seconds, after which the measured plume becomes indistinguishable from the background; this finding is also in agreement with preliminary results by Kumar et al. (2009c).

Effects of dry deposition and coagulation on PNCs cannot easily be captured, even indirectly, by our experimental setups. According to previous studies (Zhang and Wexler, 2004; Ketzel and Berkowicz, 2004) the time scales associated with these transformation processes are comparable, or even higher, than the duration of our measurements. Thus, when the particles are released from the tailpipe, coagulation and deposition could start playing a significant role only after a few seconds, and certainly many metres away from the car. However, some of the emitted nanoparticles are certainly entrained within the vehicle recirculation wake and this increases the residence time making it possible for these two processes to affect PNCs and PNDs.

In fact, on–board measurements at different locations behind the moving car, as well as ground–fixed measurements at different heights above the road level, showed different behaviours for nanoparticles sampled within the vehicle wake and those sampled, supposedly, in the flow outside its recirculation vortexes. PNDs measured along the direct emission line from the tailpipe show a
typical bimodal shape when very close to the release point, while a prevalence of accumulation
mode particles can be observed further away. On the contrary, all samples taken within the vehicle
wake, even relatively near the tailpipe, displayed the common feature of PNDs dominated by
accumulation mode particles. This is further evidence that nanoparticles in the vehicle wake reside
for a longer time, showing characteristics radically different from new, freshly emitted, particles.
These results are comparable to those reported by Wehner et al. (2009) and Morawska et al. (2007).
In the former study, the sampling point was fixed on the $z$ and $y$ axes, with two locations at $x=0.45$
m and $x=0.90$ m from a diesel car; their measurements at $x=0.90$ m are very similar to our
measurements at $x=0.80$ m, while results at $x=0.45$ m show different behaviour in different
experimental conditions; the sampling point in that case is probably at the border between the
recirculation wake and external flow, and this could partially explain the fact that nucleation mode
particles were not always detected by the authors of that study. In the second work (Morawska et
al., 2007) the sampling point was both within the wake and far from the tailpipe, so that nucleation
mode particles could not be observed.

The above finding about the differences between particles sampled within the recirculation wake,
and those sampled within the external flow is also well in agreement with the numerical simulations
carried out by Chan et al. (2010) for an exhaust plume in a vehicle wake, and has at least two strong
implications. Firstly, mathematical models dealing with nanoparticle dispersion at this local scale
should take particles recirculated within, and later escaping from, the wake into account, bearing in
mind that their characteristics are different from those freshly emitted. Further information on wake
residence time, as well as an estimate on the influence of coagulation and dry deposition processes
will be needed for a proper characterisation of the particles escaping from the wake.

The second implication is about the measurement methodologies generally used for this kind of
studies. As briefly reviewed in Section 1, essentially three different methodologies have been used
for measuring nanoparticles emitted from moving vehicles at close distance from the emission
point. The chasing method, as already discussed in the introduction, cannot be reliably used to
characterise nanoparticles in the very first stages from emission, unless by using trailing vehicles
which heavily modify the natural flow behind the vehicle. On–board measurements, as
demonstrated in this work and by Wehner et al. (2009), can be very effective in this kind of studies.
Our results, however, show that careful positioning of the sampling points is needed to properly
characterise the dispersion and transformation of nanoparticles. In particular, the measurement grid
must be set up according to which type of nanoparticles the study is trying to characterise: new
freshly emitted particles, relatively aged wake–recirculated particles or both; especially in the latter
case, either a detailed knowledge of the vehicle wake or a large (and high resolution) grid is needed.
Ground–fixed measurements can give us continuous information on nanoparticle transformations
both in space and time; however, they must be carefully interpreted. Given the uncertainties on the
lateral positioning of the passing vehicle, it is not easy to control the experimental conditions. As
exemplified in Fig. 1, given the shape of the direct plume emitted from the tailpipe, even small
deviations from the plume centreline, say a few centimetres, can cause very different parts of the
plume to be sampled during different runs. With the usual experimental setup, there is no easy way
to establish the distance from the tailpipe at \( t=0 \). Furthermore, when sampling the plume at greater
distances from the tailpipe, or higher levels from the ground, the influence of the wake–recirculated
plume will not be negligible.

4. Summary and conclusions

Two sets of experimental campaigns were carried out using a fast response particle
spectrometer to measure number and size distributions of nanoparticles in the wake of a moving
diesel car. Both ground–fixed and on–board setups were used. This experimental strategy allowed
us to take into account the effect of the vehicle wake on the nanoparticle dispersion process,
providing also new keys for the interpretation of results from previous studies by other authors.
The measurements again confirmed the dilution as a main driver for controlling the transformation
of nanoparticles in the emitted plume of a diesel car. Results about the first evolution phase,
immediately after emission, agreed with previous literature and confirmed the presence of a first phase in which PNCs and PNDs change rapidly due to nucleation processes driven by quickly increasing dilution. This stage is over after a few tenths of second, when condensation processes start to become effective in increasing the size of the particles, with a fast (but slower than the first phase) increase of accumulation mode particles.

What happens next is less clear due to complex interactions between the flow in vehicle wake and exhaust emissions that start to affect the dispersion and transformation of nanoparticles. The combined analysis of ground–fixed measurements, on–board measurements and past literature clearly showed the presence of two different groups of nanoparticles in the volume immediately adjacent to the back of the moving vehicle: the new particles freshly emitted from the tailpipe, and the relatively aged particles in the flow recirculation wake of the vehicle. The two groups have experienced different transformation processes with different time scales, strongly linked with the dilution levels they are subject to. While in the immediate distance in front of the tailpipe the freshly emitted group of new nanoparticles is abundantly dominant, in most of the volume above the tailpipe level and close to the back of the car only the relatively aged group can be found. Other zones, further away from the vehicle, contain a mixture of both, and particular care should be taken in interpreting the results from measurement campaigns. This aspect related to the vehicle wake is often overlooked in past studies.

The DMS50, used in this study to measure nanoparticle number concentrations, could be employed in future works in conjunction with additional instruments to attempt an estimation of dry deposition, e.g. by using an ultrasonic anemometer to apply the eddy covariance method (Buzorius et al., 1998; Buzorius et al., 2003), or the nanoparticle emission factor using a tracer gas measurement system (Hak et al., 2009; Wehner et al., 2009). A detailed knowledge of the flow and dispersion characteristics of the vehicle wake could also further help interpreting the large amount of data gathered during this experimental campaign. Our next step is to carry out a detailed assessment of the wake behind the experimental car by means of wind tunnel tests in controlled
conditions on reduced scale models of our experimental car. This experimental study will allow us to characterise the dilution process in the vehicle wake by combining high resolution concentration measurements of a passive tracer gas and three dimensional flow velocity components, and their comparison with the nanoparticle measurements presented here. These will also help in analysing the competing influences and interactions of various transformation processes with each other.

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Figure captions

Fig. 1. Schematic of the set up for both the ground–fixed (Site 1) and on–board (Site 2) measurement campaigns (not in scale).

Fig. 2. Comparison of the noise level of the DMS50 at different sampling frequencies (0.1, 1 and 10 Hz) with the typical background PNDs, representing the minimum concentrations to be measured at the sampling site. Error bars represent standard deviation of 20 PND samples taken at 10 Hz sampling frequency.

Fig. 3. Temporal evolution of normalised PNCs for ground–fixed measurements, averaged over the valid runs for each experimental case; error bars represent the standard errors.

Fig. 4. Figures showing typically observed temporal evolution patterns of PNCs for ground–fixed measurements, experimental cases (a) $H = 0.10$ m, $V = 20$ km h$^{-1}$, Run 02, (b) $H = 0.10$ m, $V = 40$ km h$^{-1}$, Run 07, (c) $H = 0.25$ m, $V = 40$ km h$^{-1}$, Run 04, and (d) $H = 0.25$ m, $V = 20$ km h$^{-1}$, Run 08.

Fig. 5. PNCs (# cm$^{-3}$) measured at $z=0.45$ m during the on–board experiments: (a) map, (b) $V=20$ km h$^{-1}$, (c) $V=30$ km h$^{-1}$, and (d) $V=40$ km h$^{-1}$. Area of each bubble corresponds to magnitude of PNCs at that point.

Fig. 6. PNCs (# cm$^{-3}$) measured at $z=0.50$ m during the on–board experiments: (a) map, (b) $V=20$ km h$^{-1}$, (c) $V=30$ km h$^{-1}$, and (d) $V=40$ km h$^{-1}$. Area of each bubble corresponds to magnitude of PNCs at that point.

Fig. 7. Simplified representation of the interaction between the recirculation wake and the sampling points for both ground-fixed and on-board measurements. Note that wake position and extension can vary both in time and space due to turbulence and instabilities.

Fig. 8. Normalised size distributions during (a) pre–evolution, (b) evolution 1, (c) evolution 2, and (d) post–evolution for the experimental case: $H = 0.10$ m, $V = 20$ km h$^{-1}$, Run 01.

Fig. 9. Variation of GMDs and normalised PNCs (PNCs divided by the corresponding peak values) with time in various transformation stages for experimental cases: (a) $H = 0.10$ m, $V = 20$ km h$^{-1}$, Run 01, (b) $H = 0.10$ m, $V = 30$ km h$^{-1}$, Run 06, (c) $H = 0.25$ m, $V = 20$ km h$^{-1}$, Run 08.

Fig. 10. Normalised size spectra during (a) pre–evolution, (b) evolution 1, (c) evolution 2, (d) evolution 3 and (e) post–evolution for the experimental case: $H = 0.10$ m, $V = 30$ km h$^{-1}$, Run 06.

Fig. 11. Normalised size spectra during (a) pre–evolution, (b) evolution 1, (c) evolution 2, (d) evolution 3, (e) evolution 4 and (f) post–evolution for the experimental case: $H=0.25$ m, $V=20$ km$^{-1}$, Run 08.

Fig. 12. Particle size distributions for on–board measurements at $P_a$ for (a) $V=20$ km h$^{-1}$, (b) $V=30$ km h$^{-1}$, (c) $V=40$ km h$^{-1}$, and $P_d$ for (d) $V=20$ km h$^{-1}$, (e) $V=30$ km h$^{-1}$, (f) $V=40$ km h$^{-1}$.

Fig. 13. Particle size distributions for on–board measurements at $P_b$ for (a) $V=20$ km h$^{-1}$, (b) $V=30$ km h$^{-1}$, (c) $V=40$ km h$^{-1}$, and at $P_e$ for (d) $V=20$ km h$^{-1}$, (e) $V=30$ km h$^{-1}$, (f) $V=40$ km h$^{-1}$.

Fig. 14. Particle size distributions for on–board measurements at $P_c$ for (a) $V=20$ km h$^{-1}$, (b) $V=30$ km h$^{-1}$, (c) $V=40$ km h$^{-1}$, and at $P_f$ for (d) $V=20$ km h$^{-1}$, (e) $V=30$ km h$^{-1}$, (f) $V=40$ km h$^{-1}$.

Fig. 15. Simplified representation of the effects of the lateral positioning of the ground–fixed sampling on the detected plume at two different hypothetical runs (Run1 and Run2); note that the wake–recirculated plume has not been considered in this representation.
### Table 1. Summary of the results from the ground–fixed measurements; values expressed are in terms of mean ± standard deviation.

<table>
<thead>
<tr>
<th>Experimental case</th>
<th>Valid runs</th>
<th>Sampling height ($H$) and car speed ($V$)</th>
<th>Average peak PNC ($\times 10^5$ # cm$^{-3}$)</th>
<th>Average time (s) at peak PNCs</th>
<th>Average duration (s) of event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0.10 20</td>
<td>5.19 ± 3.33</td>
<td>0.8 ± 0.2</td>
<td>5.6 ± 3.6</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>0.10 30</td>
<td>9.20 ± 6.68</td>
<td>0.8 ± 0.2</td>
<td>6.3 ± 2.7</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>0.10 40</td>
<td>2.60 ± 2.41</td>
<td>0.8 ± 0.2</td>
<td>7.9 ± 3.6</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>0.10 50</td>
<td>6.58 ± 5.81</td>
<td>1.6 ± 1.2</td>
<td>9.1 ± 6.2</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>0.25 20</td>
<td>3.39 ± 3.65</td>
<td>1.8 ± 0.4</td>
<td>6.1 ± 4.6</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>0.25 30</td>
<td>6.73 ± 5.62</td>
<td>1.7 ± 0.9</td>
<td>6.7 ± 3.8</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>0.25 40</td>
<td>5.20 ± 4.20</td>
<td>1.2 ± 0.2</td>
<td>5.5 ± 1.8</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>0.25 50</td>
<td>1.95 ± 1.55</td>
<td>1.3 ± 0.4</td>
<td>10.6 ± 4.1</td>
</tr>
</tbody>
</table>

### Table 2. Summary of the results from the on–board measurements with $V=20$ km h$^{-1}$. Here and in the tables hereafter PNC–1 and GMD–1 values refer to particles with $D_p < 30$ nm (nucleation mode), while PNC–2 and GMD–2 refer to particles with $30 < D_p < 300$ (accumulation mode). GMD stands for geometric mean diameter.

<table>
<thead>
<tr>
<th>Measurement points</th>
<th>Total PNC ($\times 10^5$ # cm$^{-3}$)</th>
<th>Total GMD (nm)</th>
<th>PNC–1 ($\times 10^5$ # cm$^{-3}$)</th>
<th>GMD–1 (nm)</th>
<th>PNC–2 ($\times 10^5$ # cm$^{-3}$)</th>
<th>GMD–2 (nm)</th>
<th>Valid Runs</th>
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</thead>
<tbody>
<tr>
<td>$P_a$</td>
<td>43.04</td>
<td>61.89</td>
<td>5.69</td>
<td>19.26</td>
<td>37.35</td>
<td>74.14</td>
<td>4</td>
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<tr>
<td>$P_b$</td>
<td>2.23</td>
<td>46.77</td>
<td>0.58</td>
<td>12.76</td>
<td>1.65</td>
<td>71.09</td>
<td>3</td>
</tr>
<tr>
<td>$P_c$</td>
<td>0.69</td>
<td>88.43</td>
<td>0.64</td>
<td>13.39</td>
<td>0.63</td>
<td>111.21</td>
<td>5</td>
</tr>
<tr>
<td>$P_d$</td>
<td>16.35</td>
<td>62.20</td>
<td>1.43</td>
<td>19.81</td>
<td>14.93</td>
<td>69.72</td>
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<td>$P_e$</td>
<td>7.31</td>
<td>65.69</td>
<td>0.71</td>
<td>16.79</td>
<td>6.59</td>
<td>75.44</td>
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<td>$P_f$</td>
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<td>65.17</td>
<td>0.30</td>
<td>16.54</td>
<td>2.94</td>
<td>77.03</td>
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<td>$P_g$</td>
<td>4.15</td>
<td>69.72</td>
<td>0.32</td>
<td>20.64</td>
<td>3.83</td>
<td>77.69</td>
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<td>$P_h$</td>
<td>4.14</td>
<td>74.48</td>
<td>0.22</td>
<td>21.71</td>
<td>3.93</td>
<td>80.03</td>
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<td>$P_i$</td>
<td>2.15</td>
<td>67.23</td>
<td>0.26</td>
<td>18.22</td>
<td>1.89</td>
<td>81.66</td>
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<td>8.76</td>
<td>74.01</td>
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Table 3. Summary of the results from the on–board measurements with $V=30$ km h$^{-1}$.

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<th>Measurement points</th>
<th>$x$ (cm)</th>
<th>$y$ (cm)</th>
<th>$z$ (cm)</th>
<th>Total PNC ($\times 10^4$ cm$^{-3}$)</th>
<th>Total GMD (nm)</th>
<th>PNC-1 ($\times 10^5$ # cm$^{-3}$)</th>
<th>GMD-1 (nm)</th>
<th>PNC-2 ($\times 10^5$ # cm$^{-3}$)</th>
<th>GMD-2 (nm)</th>
<th>Valid Runs</th>
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Table 4. Summary of the results from the on–board measurements with $V=40$ km h$^{-1}$.

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<th>Measurement points</th>
<th>$x$ (cm)</th>
<th>$y$ (cm)</th>
<th>$z$ (cm)</th>
<th>Total PNC ($\times 10^4$ cm$^{-3}$)</th>
<th>Total GMD (nm)</th>
<th>PNC-1 ($\times 10^5$ # cm$^{-3}$)</th>
<th>GMD-1 (nm)</th>
<th>PNC-2 ($\times 10^5$ # cm$^{-3}$)</th>
<th>GMD-2 (nm)</th>
<th>Valid Runs</th>
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<tbody>
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</table>
Figure 1: Site Map

SITE 1
- Main Entrance
- Laptop
- Mains power
- Sample tube (4 m)
- Anemometer + Thermometer
- Weather Station
- Shed

SITE 2 (path)
- Length: ~300 m
- On-board measurements

Coordinates:
- Pa, Pb, Pc
- Pd, Pe, Pf
- Pg, Ph, Pi
- Pj,Pk,Pl

Legend:
- N
- ~70 m
- ~50 m
- ~6 m
- ~70 m
- ~50 m
- ~6 m
Figure 2. A graph showing the distribution of particle diameters (\(d_N/d\log D_p\)) in a logarithmic scale, where \(D_p\) is the particle diameter in nm. The graph includes data for different averaging times: 0.1 s average site background (10 Hz), 0.1 s average noise (10 Hz), 1 s average noise (1 Hz), and 10 s average noise (0.1 Hz). The y-axis represents the number of particles per cubic centimeter (\(\# \text{ cm}^{-3}\)).
Figure 3: Normalised PNCs for different heights (H) and velocities (V).

- (a) H=10 cm, V=20 km/h
- (b) H=25 cm, V=20 km/h
- (c) H=10 cm, V=30 km/h
- (d) H=25 cm, V=30 km/h
- (e) H=10 cm, V=40 km/h
- (f) H=25 cm, V=40 km/h
- (g) H=10 cm, V=50 km/h
- (h) H=25 cm, V=50 km/h

Time (s) vs. Normalised PNCs
Figure 4
Recirculation area

On-board sampling at $z=0.9$ m

On-board sampling at $z=0.5$ m

On-board sampling at $z=0.1$ m

Line of ground-fixed sampling at $z=0.25$ m
**Figure 8:**

(a) Plot showing the distribution of particles as a function of $D_p$ (nm) with different time intervals:
- $t = -0.9$ s
- $t = -0.8$ s
- $t = -0.7$ s to $-0.3$ s
- $t = -0.2$ s
- $t = -0.1$ s

(b) Plot showing the distribution of particles as a function of $D_p$ (nm) with different time intervals:
- $t = 0$ s
- $t = 0.1$ s
- $t = 0.2$ s to $0.5$ s
- $t = 0.6$ s
- $t = 0.7$ s

(c) Plot showing the distribution of particles as a function of $D_p$ (nm) with different time intervals:
- $t = 1$ s
- $t = 1.5$ s
- $t = 2$ s
- $t = 2.5$ s
- $t = 3$ s
- $t = 3.5$ s

(d) Plot showing the distribution of particles as a function of $D_p$ (nm) with different time intervals:
- $t = 1.9$ s
- $t = 2$ s
- $t = 2.1$ s to $3.7$ s
- $t = 3.6$ s
- $t = 3.9$ s

The plots illustrate the change in particle distribution over time.
Figure 10.ppt