AIR QUALITY ASSESSMENT IN VEHICLE IN-CABIN: FIELD AND LABORATORY APPROACHES

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ABSTRACT

Gaseous and particulate pollutants which are emitted from automotive vehicles can infiltrate the surrounding cars exposing drivers and passengers to toxic substances with serious adverse health effects. Since the infiltration process depends on the outside pollutants concentration, we undertook wind tunnel measurements to assess their dispersion and interaction with the flow dynamic in the near-wake of a vehicle model. Concurrently field measurements were conducted to assess the pollutant concentration levels inside a car cabin. On the one hand, the results dealing with the dispersion in wind tunnels have shown that the nanoparticles issued form tailpipe exhaust gas accumulate in the core of the vortices that appear in the vehicle near-wake. This behaviour plays an important role on their infiltration since the cabin air intake is located in front of most of cars. On the other hand, the pollutant on-board measurements have shown that the concentrations of NOx and ultrafine particles (UFP) inside the cabin can reach 9 and 14 times respectively the concentration outside.

Key Words: *Ultrafine Particles, Particle concentration, NOx, On-board Measurements, Turbulence, Wind tunnel.*

NOMENCLATURE

Symbols :
I/O Inside to outside ratio
h Truck model height, m
PNC Particle Number Concentration, #/cm3
U Windtunnel inflow air velocity, $m \cdot s^{-1}$
x streamwise direction, m
y spanwise direction, m
z vertical direction, m

Indices / Exponents :
∞ undisturbed flow

1. INTRODUCTION

The concentrations of toxic gaseous and particulate pollutants are very high near major roads and freeways. Indeed, in urban areas, on-road vehicles are the primary direct emission sources [1-3]. These pollutants are transported from these regions with very high concentrations to all over the surrounding local environments where they can infiltrate vehicle in-cabin to cumulate resulting in the exposure of the passengers. Several toxicological and epidemiological studies have associated the exposure to high levels of such toxic ultrafine particles (UFP) and NOx to the enhancement of respiratory inflammation, allergy and Asthma [4] and numerous long-term health problems including lung cancer and cardiovascular diseases [5]. Two major pollutant characteristics (among others) are important to assess the exposure to UFP: the concentration and the particle size. It has been shown that the ratio of inside-to-outside concentrations (I/O) during the infiltration process strongly depends on vehicle internal parameters such as vehicle mileage, age, ventilation fan speed/settings and ventilation mode (recirculation on/off) [6]. Nevertheless it is also submitted to the external parameters such as the local topology as mentioned in [7-8]. In this study, we investigate the pollutant concentrations combining the two points of view through two approaches: the first one consists of on-board measurements where we measure both in and outdoor pollutant concentrations and the second one considers a study at a small scale in a wind tunnel. In that one, the dispersion process from the emission point (at the tailpipe) and the interaction with the vehicle near-wake flow is discussed. This second approach will help to identify the region of preferential accumulation of such UFP leading to a better understanding on the infiltration process.

2. EXPERIMENTAL METHOD

In the present paper, the first approach is a characterization of the I/O ratio of NOx and UFP concentrations in a car in real-driving conditions. Outdoor NOx and UFP mass concentrations as well as UFP Number Concentration (PNC) were sampled through three 4 mm probes mounted on the left side of the vehicle. Similar probes were used for in-cabin air sampling set at the front passenger mouth level. I/O PNC were measured using two TSI P-Trak model 8525 alcohol-based condensation particle counters (CPC). The PNC for UFP ranging between 20-1000 nm were collected at a rate of 1Hz to provide high temporal resolution results. Particle mass concentrations were measured using two TSI DUST-Trak model 8533 for PM1, PM2.5 and PM10 with a time resolution of 10 seconds. Simultaneous measurements of NO and NO2 (both in and outside of the vehicle) were carried out using two Thermo Scientific 42i model with 10 seconds time resolution. The instruments were powered by a package of internal batteries and a DC to AC converter. The data were transmitted in real time via the Ecombox GSM based device. An on-board Global Positioning System (GPS) device recorded the location and speed of the vehicle at 1s intervals. Lastly, a synchronised video recordings have been used to get additional information. This means that further analyses can be performed on particular events occurring in front of the vehicle. The vehicle was the light duty Renault Kangoo (model year 2006). It is worthwhile to note that windows were closed for all the runs and the ventilation was set (mid-strength fans) and recirculation was off. Fan speed was kept constant to medium for all the tests. The on-board measurements campaign was conducted in April 2016 (sunny weather, temperatures between 5° and 20°). Many routes were tested at different moments of the day (morning, mid-day and evening). In the present paper, we only present the results corresponding to a mid-day from Versailles to Paris. Traffic was light to busy depending on road types (highways, urban, ring road). A total distance of 107 km is considered for a duration of 3 hours. The measurements were made at vehicle speed ranging from 10 $km\cdot h^{-1}$ to 130 $km\cdot h^{-1}$

For wind tunnel measurements, we were interested in assessing the dispersion of UFP downstream of a reduced-scale truck model. Two inflow air velocities are investigated (U_∞=30 $km\cdot h^{-1}$ and 50 $km\cdot h^{-1}$). We aim at simulating the dispersion of exhausted UFP in urban areas downstream of the truck. The geometric scale factor is 1/20 and the velocity of the exhausted gas/particles at the tailpipe corresponds to an engine speed of 2500 rpm. Carbon particles are generated by spark discharge and injected in the model tailpipe at a flow rate of 0.133L/s within a size range between 20 and 100nm. PNC measurements are made at 66 different locations in the streamwise (x) and spanwise (y) directions and at different heights positions (z) using an Electrical Low Pressure Impactor. The experimental setup is described in detail in [9].

3. RESULTS

Figure 1 presents typical PNC contours downstream the truck model for the yz plane at two different distances from the vehicle (x/h=0.5 and 5). The axis origins are located at the rear of vehicle (x/h=0), the centreline (y/h=0) and at ground level (z/h=0), the emission point being at (x/h=0, y/h=-0.19, z/h=0.25). h corresponds to the height of the truck.

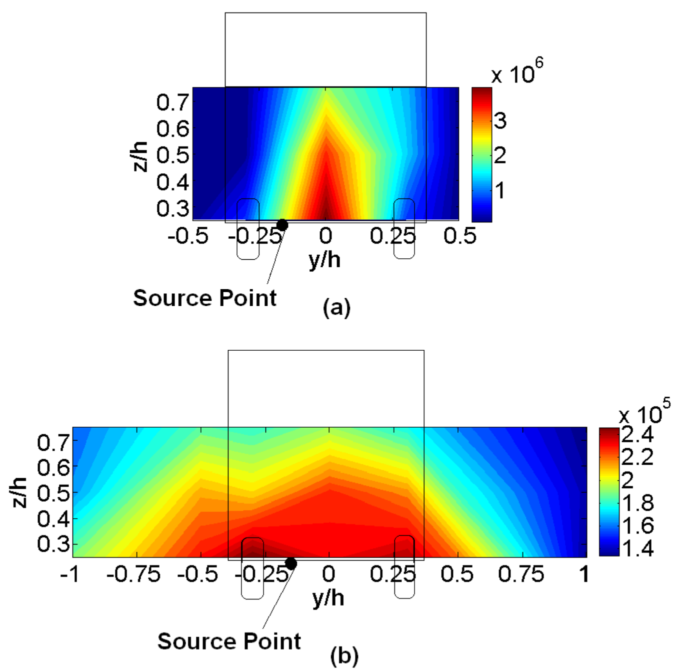


FIGURE 1. Contours of PNC (#/cm^3) downstream of the truck at U_∞=30 km·h^{-1}: (a) yz plane at x/h=0.5 and (b) yz plane at x/h=5.

The results exhibit several peaks of PNC at the rear of the truck. The first one is at x/h=0.5. This is very close to the truck (fig.1a). The area of high concentration is found in a limited and relatively small region between y/h=-0.25 and 0.25. This means that the nanoparticles are sucked and trapped by the recirculating near-wake vortices which develops in the near-wake of the vehicle. In fig.1b, two distinct peaks are found far from the emission point (x/h=5). They correspond to the pair of longitudinal vortices resulting in particle dispersion. It is then believed that particles follow the coherent turbulent structures which develop from the side edges of the car. The region of maximum PNC is wider and spreads between y/h=-0.75 and 0.75. From the full sets of the measurements, we point out that i) the ultrafine particles are very sensitive to the turbulent structure of the flow. Indeed, they tend to be strongly influenced by the turbulent coherent structures and ii) their vertical and horizontal spreading are enhanced by some turbulent structures. This is even more important when the air velocity increases [9].

These preliminary results helped us in determining some preferential regions of pollutant accumulation having an influence on their concentrations levels and thus their ability to infiltrate the following vehicle

From on-board measurements, time evolution of the concentrations inside and outside vehicle cabin as well as I/O concentrations ratios were obtained. Typical results are presented in Figure 2 for NOx and in Figure 3 for UFP.

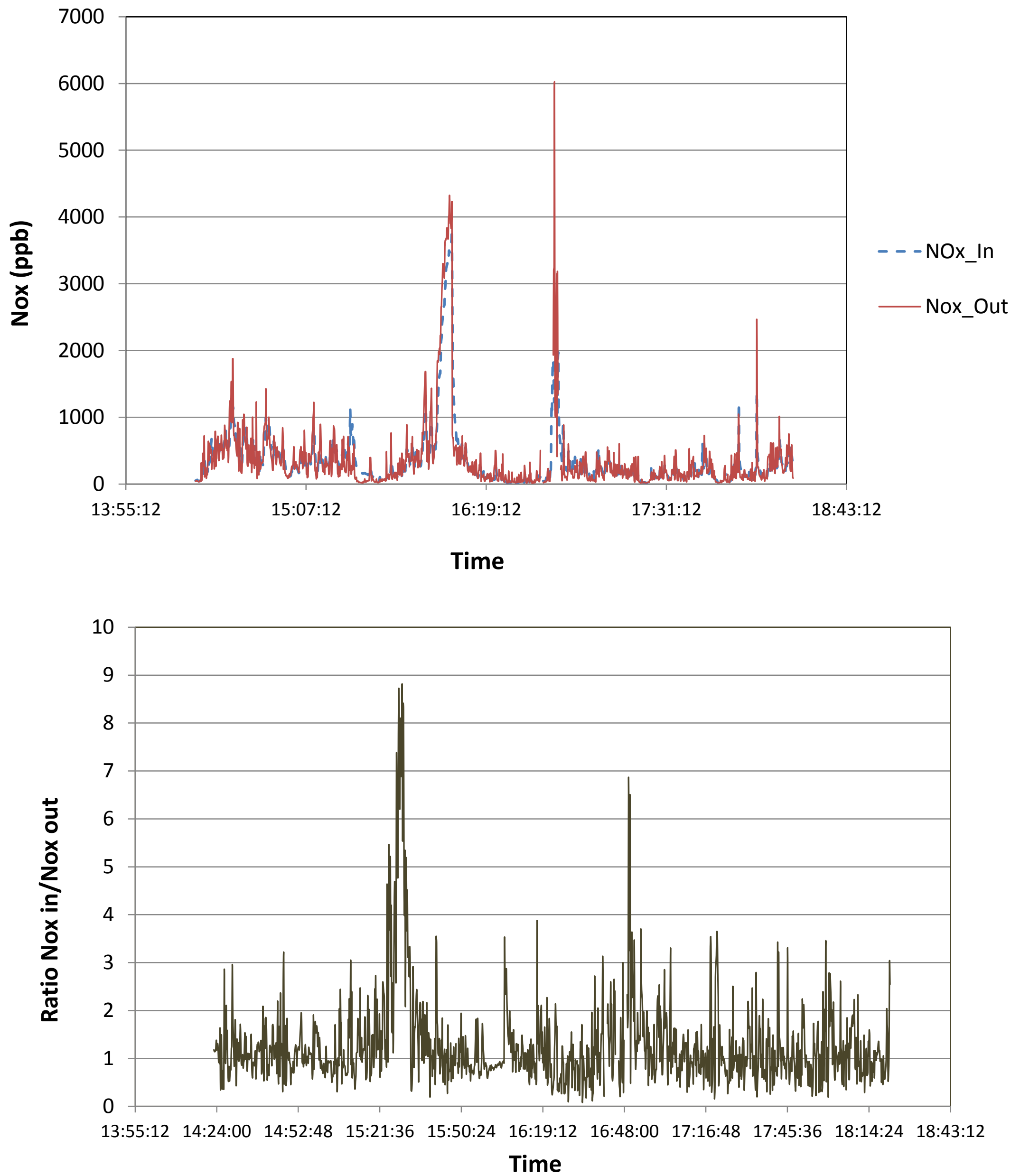
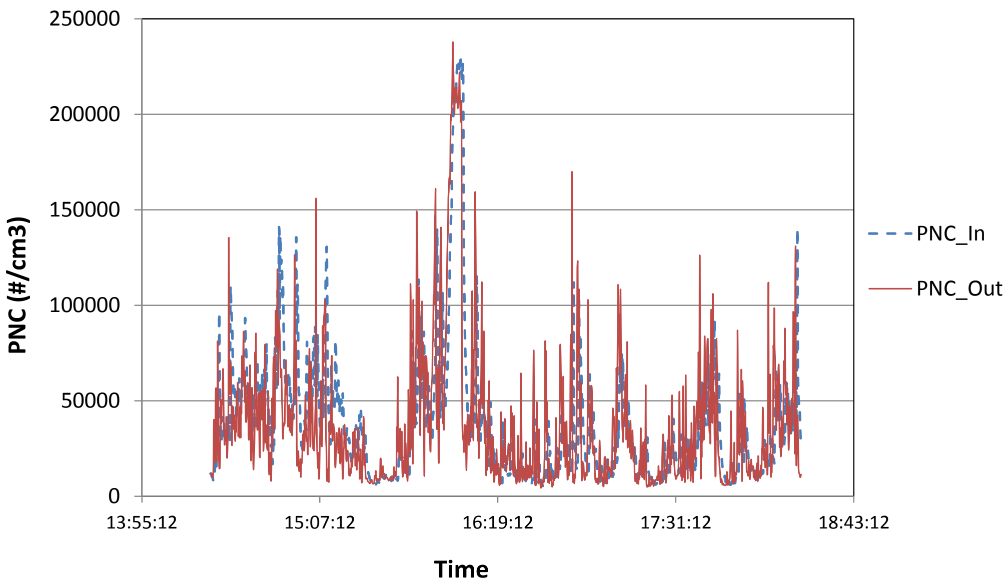


FIGURE 2. Time evolution of NOx concentrations inside and outside the vehicle cabin (top) and I/O concentrations ratio (bottom)

Even if the dynamical variation of NOx concentration outside of the vehicle is relatively more important, we still have a fluctuation inside the cabin that is almost the same. Particularly, for peaks which correspond to specific events such as tunnels. This means that when we set the fan ventilation to medium, despite the presence of the cabin filter, most of the gaseous pollutants infiltrate the vehicle in-cabin. The concentrations level inside the cabin can reach 9 times those measured outside (figure 2, bottom). It is important to underline that the average value of NOx concentration inside the cabin during the whole test is 1.27 times the one outside.



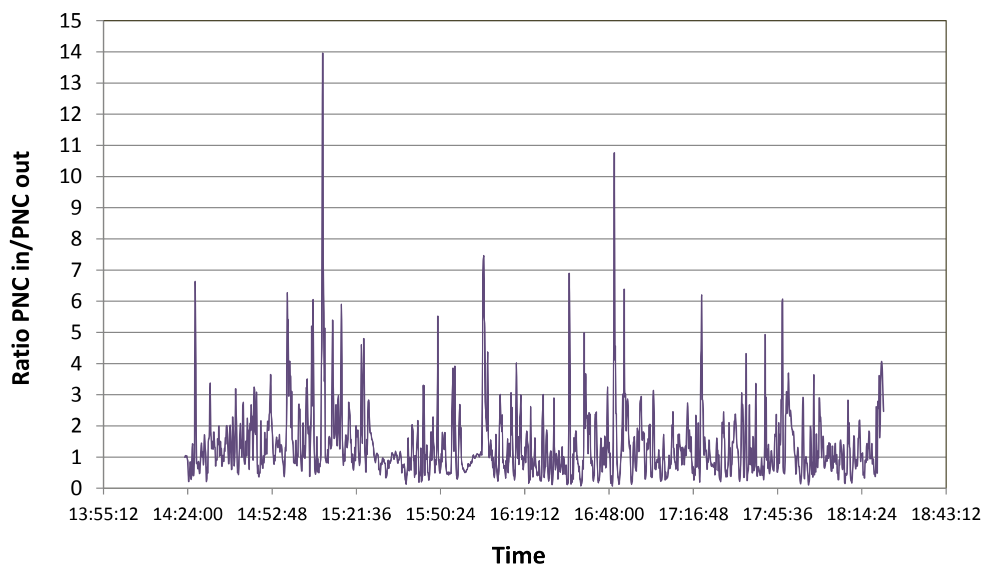


FIGURE 3. Time evolution of UFP PNC inside and outside the vehicle cabin (top) and I/O PNC ratio (bottom)

The same conclusions can be driven for UFP. Their infiltration is followed by an accumulation period that is longer since their deposition or inhalation process takes more time. This could be seen since the peaks of the blue curve are more abundant. Furthermore, in most of cases, they follow the red peaks which correspond to the outside UFP concentrations. The average PNC ratio is about 1.37 for the whole test. It is also relevant to see that the maximum inside concentration of such nanoparticles can reach 14 times the outside ones (even if it is for short time period) and correspond to weak level of UFP concentrations.

4. CONCLUSIONS

In this study two approaches were used to investigate the dispersion and infiltration of gaseous and particulate pollutants inside vehicles cabins. From wind tunnel measurements, we were able to get access to the concentrations distributions of pollutants issued from the tailpipes of a car model. These are strongly correlated with the near-wake turbulent flow which depends on the car aerodynamics. The infiltration process has been studied by conducting on-board measurements. We demonstrate that the pollutants tend to accumulate into the car, particularly for UFP., It is believed that a better understanding of these complex processes (dispersion and infiltration) are needed to improve car cabin air quality and that both approaches (on board measurements and wind tunnel investigations) are required for that.

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