WHAT DO WE BREATHE INSIDE OUR CARS?

Characterization of the infiltration of pollutants and recommendations

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As many as 300 different types of pollutants can infiltrate car cabins

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A car cabin is a small, enclosed space that is subject to pollutant infiltration or self-emissions. Depending on traffic and ventilation conditions, pollutants can accumulate, exposing passengers and drivers to serious adverse health effects. These pollutants are of different types (gaseous or ultrafine particles) and can reach very high concentrations in comparison with outdoor air.

Our research is mainly focused on the infiltration process that concerns broad types of pollutants. Since the infiltration process depends on three main factors (concentration of outside pollutants, flow topology at emission points and internal vehicle parameters such as ventilation settings), we conduct on-board and wind tunnel measurements to characterize pollutant dynamics, in interaction with the flow topology. These measurements cover their dispersion from emission sources to their infiltration through air intakes, taking into account the local pollution level.

Results dealing with dispersion in wind tunnels have shown that the ultrafine particles emitted from tailpipe exhaust gas accumulate in the core of the vortices that appear in the vehicle near-wake. This behavior has an important role on their infiltration, since the cabin air intakes are located in the front of most cars. Another finding is that distances between cars, ventilation mode combined with traffic density and route topology could worsen cabin air pollution. Understanding the impact of these different parameters can help to improve vehicle in-cabin air quality.

INTRODUCTION

Concentrations of toxic gaseous and particulate pollutants are very high in urban areas, particularly near major roads and freeways. On-road vehicles are in fact the primary source of direct emissions[1,2,3]. These pollutants are transported from areas with very high concentrations to all over surrounding local environments, including vehicles. They can infiltrate the cabins of vehicles, cumulating and increasing the exposure of passengers. Several toxicological and epidemiological studies have associated exposure to high levels of such toxic pollutants (among others ultrafine particles (UFP) and Nitrogen oxides (NOx) to the worsening of respiratory inflammation, allergy and asthma[4], as well as numerous long-term health problems including lung cancer and cardiovascular diseases[5].

Two major pollutant characteristics are important in assessing exposure to such pollutants: concentration and particle size (for UFP). It has been shown that the ratio of inside-to-outside concentrations (I/O) during the infiltration process greatly 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 subject to external parameters such as local flow topology[7,8,9]. In present ongoing research, we are investigating pollutant concentrations through two approaches. The first consists of on-board measurements where we measure both indoor and outdoor pollutant concentrations for various ventilation settings and vehicle interspacing distances.

The second focuses on an infiltration process study at a small-scale level in a wind tunnel. In this study, UFP dispersion from emission point (at the tailpipe) and interaction with flow at vehicle near-wake and air intakes is first investigated. Then, infiltration of UFP into a reduced car model is assessed. The combination of both approaches will help to improve the measurement methodology (e.g. position of the outdoor probe) but also understanding of the pollutant infiltration process. The objective is to develop solutions to improve car-cabin air quality.

POLLUTANTS FOUND IN CAR CABINS

The number of pollutants encountered in such small, enclosed spaces as car cabins can be greater than 300 types of carbon-based gases, ranging from mainly Volatile Organic Compounds (VOCs)[10] to combustive gaseous chemicals (NOx, CO, etc.) and particles[11,12] *(figure 1)*.

The VOCs[13] are emitted by a wide array of products in new car cabins due to off-gassing from materials, including natural or artificial leather, polystyrene, polyethylene, polypropylene, polyamide, adhesives, paints, polyurethane foam, etc. These materials are used in the dashboard, interior panels, seat coverings, flooring materials, and more. Unfortunately, within the confined space of an automobile's passenger compartment, concentrations of chemicals emitted from these components are consistently higher indoors (up to 10 times higher) than outdoors[14].

Additionally, external pollutants can also contribute to in-cabin contamination. The infiltration process is in fact the main mechanism contributing to the rise of UltraFine Particles (UFP) and PM (Particle Matter), NOx, CO, SO_2 and HC concentration levels inside car cabins. The infiltration process is related to the air inlet: air due to ventilation, opening windows or leakage. It has been shown that the ratio of inside-to-outside concentrations (I/O) during the infiltration process greatly depends on vehicle internal parameters such as vehicle mileage, age, ventilation fan speed/settings and ventilation mode (recirculation on/off)[5]. Nevertheless, it is also subject to the influence of external parameters such as traffic, route topology or weather[15,16]. Ultrafine nanoparticles have been the focus of numerous studies, as their high toxicity is great enough to be classified as carcinogenic by the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO), or at least having strong adverse health effects besides VOCs[4,5]. Their particular dynamics contribute to the high variability of concentration levels, since such small-sized particles are subject to strong influence from turbulence and Brownian diffusion[*][17]. It is therefore important to characterize local flow topology to enhance understanding of the pollutant infiltration process into car cabins.

[*] Brownian diffusion is the random movement of a small particle caused by the collision of the molecules of the air.

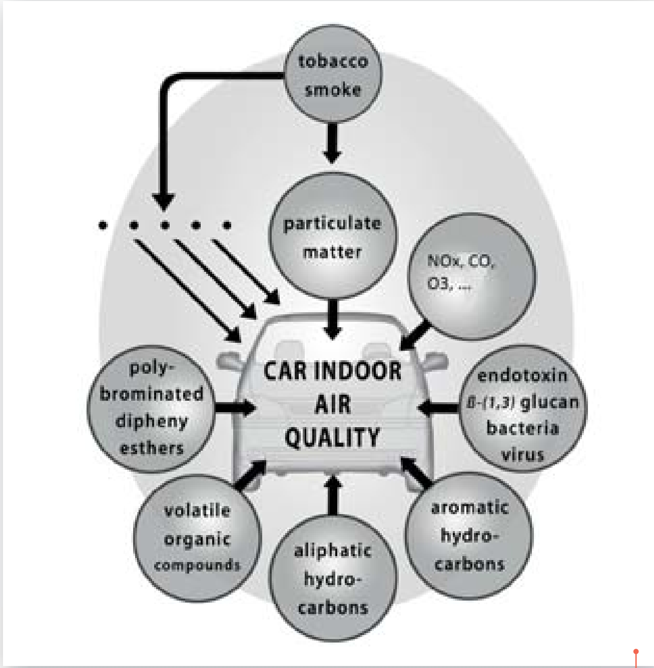

Figure 1- Common pollutant types found in car cabins (on the basis of Muller et al. (2011) [18])

DESCRIPTION OF TYPICAL EXPERIMENTAL APPROACHES FOR CAR CABIN POLLUTANT INFILTRATION CHARACTERIZATION

The originality of and need for combining both on-board and laboratory measurements to understand the transportation of pollutants from their emission point to their infiltration into the car cabin has been underlined. In this paragraph, we describe the typical experimental set-up for on-board measurements dedicated to the assessment of the I/O ratio of various pollutants. We also detail wind tunnel tests for UFP dispersion characterization in correlation with flow topology. Next is detailed the methodology used for both approaches, during a project that was entitled "CAPTIHV," which consisted in the characterization of pollutants issued from ground vehicles and infiltrating car cabins.

The first approach consisted of simultaneous on-board measurements of outdoor and indoor gaseous (NOx) and ultrafine particle concentrations in real driving conditions in the Paris area. The indoor to outdoor concentrations ratio (I/O) was measured in terms of mass concentrations for gaseous pollutants and particles, and number concentrations for UFP. The sampling was achieved through two probes mounted on the left side of the vehicle and at passenger mouth level for in-cabin air sampling (*figure 2*). Lastly, a synchronized video recording was used to obtain additional information. This means that further analyses can be performed on particular events occurring in front of the vehicle.

Figure 2 - Outdoor (a) and indoor (b) probes used for pollutant concentrations measurement © Amine Mehel

The vehicle used the most was the light-duty Renault Kangoo (2006 model, equipped with new OEM cabin filters). It is worthwhile noting that windows were closed for all runs, ventilation was on (mid-strength fans) and recirculation was off. Fan speed was kept constant to medium for all the tests. There were also measurements to characterize the influence of ventilation settings and windows on I/O ratios using two successive vehicles. The upstream car was the Kangoo while the downstream one was either a 2006 diesel-engine car fitted with old OEM cabin filters or a 2016 gasoline-engine car equipped with OEM filters of 20,000 km. The originality of these measurements using two successive cars is that we reduced the influence of the type of upstream car (engine type, model type, etc.) on the emissions in front of the test vehicle.

The on-board measurement campaigns were conducted from April 2016 (sunny weather, temperatures between 5 °C and 20 °C) to December 2017 (temperatures between 1 °C and 15 °C). Many routes were tested at different moments of the day (morning, mid-day and evening). Traffic was light to busy depending on road types (highways, urban, ring road). A total distance of 107 km was considered for a duration of three hours. The measurements were made at vehicle speeds ranging from 10 km/h^{-1} to 130 km/h^{-1}.

For wind tunnel measurements, we were interested in assessing the dispersion of UFP downstream of a reduced-scale squareback Ahmed body model[19] (*figure 3a*). The second car model (b) is a MIRA type model. This model is used as the downstream model that follows the Ahmed body model. It includes three air intakes with a hollow interior so as to allow UFP infiltration and measurements.

Figure 3 - Car models used for infiltration study: (a) Ahmed body, (b) Mira model © Amine Mehel

The flow air that was investigated was set at a velocity of $U\infty=12$ m·s[-1], which is typical of urban areas. We aimed at simulating the dispersion of UFP from vehicle exhausts in urban areas downstream of the car model and then their infiltration in the downstream Mira model. To achieve this, we injected UFP ranging from 20 to 100nm in size, and characterized their dispersion in correlation with their interactions with the flow field[20].

ACTUAL SITUATION CONCERNING I/O RATIOS AND INFLUENCING PARAMETERS

It is known that many internal parameters have an influence on I/O ratios, among them the ventilation mode, i.e. fresh air coming from outdoors, Outdoor Air (OA) or Recirculation Air (RC). This was confirmed by the CAPTIHV project results. Indeed:

- when RC mode is activated, only 22-40% of NO_2 infiltrates the car cabin. The level ranges between 25% and 90% for UFP
- when OA mode is on, all these pollutants infiltrate the car cabins.

Let me introduce here two definitions concerning the calculation of the average I/O ratio:

$$\overline{R_{I/O}} = \overline{\left(\frac{C_{int}}{C_{ext}}\right)} \quad (1)$$

$$R_{\overline{I}/\overline{O}} = \frac{\overline{C_{int}}}{\overline{C_{ext}}} \quad (2)$$

The first (Equ. 1) is the average of the instantaneous ratios (i.e. the overall average of in-cabin to outdoor concentration ratio, which is measured every 10s. The second mean ratio is the ratio of the mean in-cabin concentration to the mean outdoor concentration that is usually presented in different studies).

The difference between the two ratios is that the average instantaneous ratio $\overline{R_{I/O}}$ is indicated to characterize the infiltration process, for example when characterizing cabin filters. The $\overline{R_{I/O}}$ is the ratio of the mean in-cabin concentration to the mean outdoor concentration. Since it considers the mean concentrations measured during the entire trip, it makes it possible to assess the exposure of the passengers and hence is more indicated for this purpose.

The mean ratios of the whole single vehicle (Kangoo) measurement campaign are given in the table below:

Pollutant	Value	C_{in} (µg/m³) [(#/cm³) for PN]	C_{out} (µg/m³) [(#/cm³) for PN]	(I/O) Ratio ($\overline{R_{I/O}}$ for the average value)	Average (I/O) Ratio $R_{\overline{I}/\overline{O}}$
NO_2	Average	80	117	0.82	0.68
	Maximum	1457	4757	50.00	-
PN	Average	42,000	44,000	1.11	0.95
	Maximum	391,000	421,000	24.18	-
PM_{10}	Average	27	28	1.07	0.96
	Maximum	582	1760	16.17	-
$PM_{2.5}$	Average	26	25	1.10	1.04
	Maximum	1760	1760	8.60	

Table 1: I/O concentration ratios obtained for different pollutants for the entire single vehicle on-board measurement campaign

We notice that, depending on pollutant type, average values can be greater than one, meaning that passengers can be more exposed than if they were outside the car cabin. We can observe that the $R_{\overline{I}/\overline{O}}$ ratio for NO_2, PN and PM10, unlike the average instantaneous ratio ($\overline{R_{I/O}}$), is smaller than 1. This is particularly the case for NO_2, which is 0.68, meaning that passengers are less exposed to NO_2 in the vehicle even if the ventilation mode is set to OA.

Besides the vehicle internal parameters, the external ones, such as road type, traffic density or meteorology, can also influence the I/O concentration ratio. Fruin et al.[21] conducted an extensive campaign of outdoor pollutant levels characterization where PM (particle mass concentration), UFP (particle number concentration), NOx, CO and CO_2 were measured. They showed that the roadway segment type (freeways, tunnels, arterial road) had the biggest influence on the PM, UFP and NO concentration variabilities. This conclusion also resulted from the CAPTIHV project. Indeed, tunnels increased outdoor and in-cabin concentrations by a factor of 1.6 and 1.9 respectively for NO_2 and by a factor of 2 for PN. Moreover, the time spent in the tunnel has an influence on this factor: the more time we spend in the tunnel, the higher the increase in concentrations (*figure 4*). Hence tunnels have a strong impact on I/O ratios and this finding was noticed in Kaminsky[22]. Besides tunnels, the CAPTIHV project showed that the Parisian ring road also has a strong influence. It increased in-cabin and outdoor concentrations for the above-cited pollutants by a factor of 1.6.

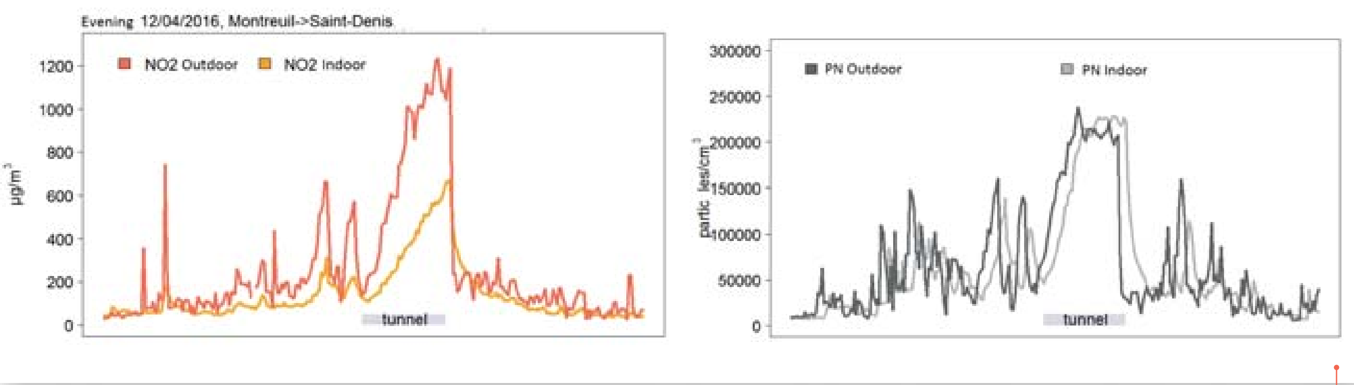

Figure 4 - Time evolution of in-cabin and outdoor concentrations for NO_2 and PN during a typical route including a tunnel

The on-board measurements using two successive vehicles also made it possible to assess the influence of inter-vehicular distance on I/O ratios. As the topology of the car wake flow is dependent on the distance from the upstream vehicle, this has an impact on particle dynamics and hence on their infiltration. This has also been investigated in a detailed manner using wind tunnel tests (next paragraph).

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

ACTUAL SITUATION CONCERNING THE IMPACT OF FLOW TOPOLOGY ON UFP INFILTRATION IN CAR CABINS

To understand the proximity of different moving vehicles and specifically vehicle inter-gap distances, measurements achieved in wind tunnels make it possible to characterize in a more detailed manner the link between flow topology and UFP dispersion/infiltration mechanisms.

First of all, Figure 5 shows the flow topology in the wake flow of the upstream Ahmed body model. Two counter rotating vortices, which constitute what is called the recirculation zone, can be seen.

The ultrafine particles emitted from the Ahmed body tailpipe interact with those vortices, which in turn influence the dynamics of the particles and hence their dispersion. The concentrations are presented in terms of non-dimensional concentration in Figure 6. In the recirculation zone, UFP vertical dispersion is enhanced due to the presence of these vortices (*figure 6*). As expected, the maximum concentration position corresponds to the tailpipe exhaust point.

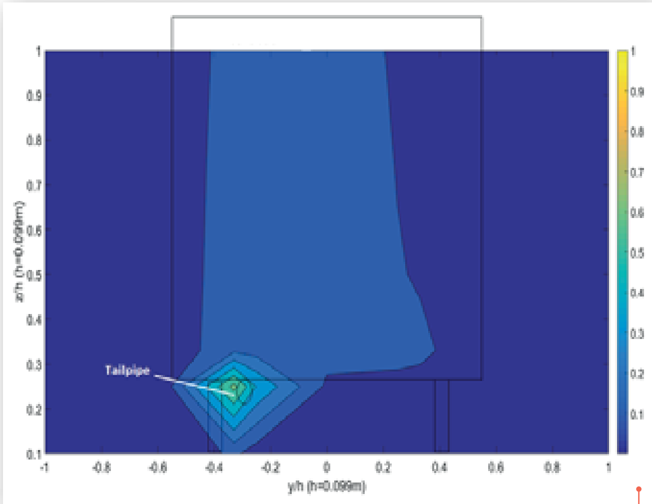

Figure 6 - Particles Number Concentrations field In the yz plane at a distance of x/H=0.5 from the rear of the Ahmed body model

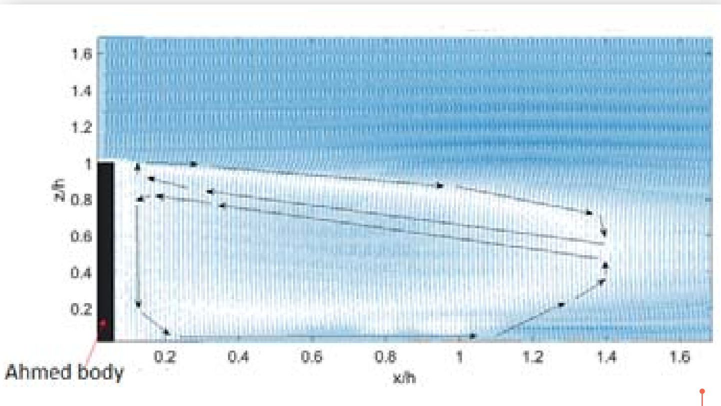

Figure 5 - Wake flow topology of the squareback Ahmed body

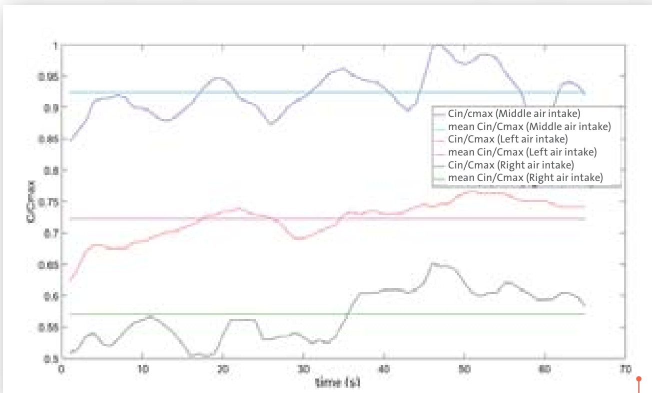

Figure 7 - Influence of the air intake position on non-dimensional indoor Particles Number Concentrations

The downstream Mira model is fitted with three air intakes. They were opened individually and the concentration measurements were achieved outside and inside the Mira model to obtain the outdoor/indoor concentrations. The results revealed that the air intake position has an influence on the infiltration process. Indeed, in Figure 7, the non-dimensional concentration is higher for the central (middle) air intake than for the left one and finally when the right one is opened. This can be explained by the PNC distribution, which showed that UFP are dispersed vertically then accumulate in the recirculation zone before diffusing in the longitudinal and transversal directions.

CONCLUSION

Car cabin pollution is due to internal pollutant emissions and external ones infiltrating vehicle car cabins, mostly NOx, CO, CO_2, UFP, PM and specific VOC (BTEX). In both cases, vehicle internal parameters such as window position and vehicle age and in particular ventilation mode and fan strength can influence in-cabin pollutant concentrations. On the other hand, the pollutant infiltration process is influenced both by the same internal parameters and by external ones such as traffic type and density, road types (tunnels, etc.), and the type and speed of vehicles ahead (upstream of the test car).

In our studies, particularly the CAPTIHV project, two approaches were used to investigate the dispersion and infiltration of gaseous and particulate pollutants inside vehicle cabins. From wind tunnel measurements, we were able to get access to the concentration distributions of pollutants issued from the tailpipes of a car model. These are strongly correlated with the near-wake turbulent flow, which depends on car-specific aerodynamics. The infiltration process was studied by conducting on-board measurements but also wind tunnel tests using a model with a hollow interior and three air intakes in different positions. It has been shown that pollutant infiltration, particularly for UFP, depends on vehicle inter-gap distances but also on the air intake position.

This shows that improving car cabin air quality could be complex and that it requires more experiments and simulations at different scales (local, upstream or cabin internal zones) to improve our knowledge and hence to implement efficient solutions for cleaner air in car cabins.

Meanwhile, some recommendations could be set out: when driving in dense traffic or on certain types of infrastructure (i.e. tunnels), it is recommended to switch on the recirculation mode for the air ventilation. However, it is better not to keep it activated for more than 15 minutes. Indeed, the CO_2 in-cabin concentration becomes high, which is not recommended when driving. Finally, it is recommended to keep a distance of at least 5 meters with the vehicle in front of us to minimize pollutant infiltration.

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