# Nitrogen Oxides and Particles Matter Levels in the Tunnels of the Ile-de-France Motorways Network

*B. Vidal[1],C. Bernagaud[1], J.F. Burkhart[1], J.P. Grand[1], D. Preterre[2] , F. Gouriou[2], J.F. Petit[3], T. Le Priol[3], A. Guilloteau[3], P. Barbe[3] and M. Bouquet[3].*

[1] Centre d'Etude des Tunnels (CETU), Bron, 69500, France
[2] Centre d'Etude et de Recherche Technologiques en Aérothermique et Moteurs (CERTAM), Saint Etienne du Rouvray, 76800, France
[3] Centre d'Etudes et d'Expertise sur les Risques l'Aménagement, la Mobilité et l'Environnement (CEREMA) DTer Ile de France, 78190, Trappes, France

## Context and aims of the study

As in all very large conurbations, there is a high level of background atmospheric pollution in the Île-de-France region (Airparif, 2014). There is heavy traffic on road routes with recurrent congestion, thus exposing populations to high levels of pollution (Airparif, 14-05-2014). Furthermore, due to the confinement effect, the concentrations of pollutants in road tunnels may rise to relatively high values during rush-hour traffic jams. Users' health may be affected, depending on their exposure time (Morin et al., 2006), and this may also apply to local residents exposed to emissions at tunnel portals (Brousse et al., 2005). With 22 tunnels and cut-and-cover structures of over 300 m amounting to a total length of 45 km, on *routes nationales* (French main roads) alone (not including the Paris ring road and structures within inner Paris), the Île-de-France region's road network exposes its users to potential health risks that need to be assessed (Airparif, 2007).

In 2009, this observation (Afsset, 2008; Airparif, 2009), prompted the Prefect and Regional Director of Public Works for Île-de-France to commission a major exploratory study to review the current status of the air quality within and around road tunnels, followed by an assessment of current air treatment processes and of methods that could be applied to tunnels.

This project – entitled AIRTURIF (Guilloteau et al., 2010) – involves several departments of the French Ministry of Ecology, Sustainable Development and Energy (Ministère de l'Écologie, du Développement Durable et de l'Énergie): CETU (Centre d'Étude des Tunnels – [French Tunnel Research Centre]), CEREMA Dter IDF (Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement [Centre for Research and Expertise on Risks, the Environment, Mobility and Planning] – Direction territoriale d'Ile de France [Ile-de-France Regional Directorate]) and departments of the DIRIF (Direction des routes d'Île-de-France [Île-de-France Highway Department]), which are responsible for managing tunnels in Paris.

This article sets out to review the main results of the measurement campaigns conducted during the course of this study, based primarily on the findings of a global study concerning all tunnels, and consolidated by *in situ* measurements recorded within several structures. This global approach, carried out with technical support from CERTAM (Centre d'études et de recherche technologique en aérothermique et moteurs [Aerothermic and Internal Combustion Engine Technological Research Centre]), involved the continuous recording of pollution levels by a "laboratory vehicle" travelling throughout the whole of the road network in question (2009, 2010 and 2014). After describing the conditions under which the measurements were recorded and the methodology specific to on-board measurements, this article covers the following aspects in turn:

- The recorded concentrations of $PM_{10}$, NO and CO, presented in the form of a statistical approach or as longitudinal profiles
- The typical daily changes in the levels of pollutants ($PM_{10}$, $PM_{2.5}$ and $NO_2$) in a tunnel subject to very high levels of traffic and recurrent congestion
- A comparison of the mean concentrations recorded at each passage of the laboratory vehicle and the regulatory levels to be complied with in road tunnels
- The $[NO_2]/[NO_X]$ ratio values observed in tunnels and their fluctuations
- An assessment of the impact of sanitary ventilation on the concentrations of pollutants in the Bobigny (2010) and Guy Môquet (2013) tunnels.

In addition, in support of the measurements recorded with an aerosol LIDAR, and with the assistance of the Léosphère company (2012), this article presents an estimate of the extent of the particulate pollution plume observed at the eastern entrance to the Bobigny tunnel.

## French regulations concerning air quality in road tunnels

The air quality regulations that apply to users of road tunnels are set out in the following documents:

- Circular of the Direction Générale de la Santé (General Health Directorate) 99-329 of 08 June 1999 (Ministère de la Santé,1999) based on the recommendation of 14 December 1998 issued by the Conseil Supérieur d'Hygiène Publique de France (French Higher Public Health Council) [Conseil supérieur d’hygiène publique de France,1998]
- Appendix no.2 of inter-ministry circular no. 2000-63 of 25 August 2000 relating to safety in tunnels in the national road network (Ministère de l'intérieur [Ministry of the Interior] and Ministère de l'équipement des transports et du Logement [Ministry of Public Works, Transport and Housing], 2000)

The CETU pilot ventilation project also puts forward a recommendation for opacity levels (CETU, 2003).

**Table 1:** French regulation overview

| Pollutants | Situations | Regulatory or recommended levels | | | Reference texts |
|---|---|---|---|---|---|
| | | Exposures | | Limit values | |
| | | Durations | Situations | | |
| *Regulations or recommendations applying to road tunnel users* | | | | | |
| Carbon monoxide (CO) | Exceptional situation, accident | Instantaneous values | In any area of the tunnel | 150 ppm | Technical instruction of 25 August 2000 |
| | Normal operating conditions | 15 minutes | On average over the entire length of the structure | 90 ppm | DGS circular of 8 June 1999 |
| | | 30 minutes | | 50 ppm | |
| Opacity | Exceptional situation, accident | Instantaneous values | In any area of the tunnel | 9 $km^{-1}$ | Technical instruction of 25 August 2000 |
| | Normal operating conditions | | | 5 $km^{-1}$ | CETU recommendation |
| Nitrogen dioxide ($NO_2$) | Normal operating conditions | 15 minutes | On average over the entire length of the structure | 0.4 ppm | DGS circular of 8 June 1999 |

## Study area and tunnels driven through

The global investigation of all of the tunnels was conducted by the CERTAM laboratory vehicle, which was driven through all of these structures on numerous occasions. The routes taken were chosen in such a way as to maximise the number of tunnels driven through on each day of the vehicle's rotation. The different circular routes thus created allowed 20 structures to be driven through on a regular basis in both directions, amounting to a total of approximately 700 through journeys.

There are significant variations in the characteristics of the twenty tunnels driven through (see table 2). They vary in length from 300 metres to 4 kilometres, and their traffic levels range from 90,000 to 210,000 vehicles per day (in both directions).

**Table 2:** Characteristics of the main tunnels studied.

| Name of the tunnel | Lenght | AADT[(1)] | Characteristics |
|---|---|---|---|
| La Défense | 4,150 m | 100,000 | Twin-tube, 2 lanes in each direction |
| Landy | 1,350 m | 210,000 | Twin-tube, 4 lanes in each direction |
| Nogent | 1,810 m | 136,000 | Twin-tube, 3 lanes in each direction |
| Bobigny | 2,220 m | 90,000 | Twin-tube, 3 lanes in each direction |
| Saint Cloud | 870 m | 165,000 | Twin-tube, 3 to 4 lanes per direction, according to direction |
| Champigny | 780 m | 178,000 | Twin-tube, 3 lanes in each direction |
| Ambroise Paré | 820 m | 130,000 | Twin-tube, 3 lanes in each direction |
| FFF | 740 m | 133,000 | Twin-tube, 3 lanes in each direction |
| Nanterre | 1,020 m | 90,000 | Twin-tube, 2 lanes in each direction |
| Guy Môquet | 590 m | 133,000 | Twin-tube, 3 lanes in each direction |
| Antony | 900 m | 80,000 | Single-tube, 4 lanes |
| Neuilly | 440 m | 145,000 | Twin-tube, 3 to 4 lanes per direction, according to direction |
| Lumen | 460 m | 90,000 | Twin-tube, 2 lanes in each direction |
| Fresnes | 380 m | 108,000 | Single-tube, 5 lanes |
| Rueil | 1,100 m | 36,600 | Twin-tube, 3 lanes in each direction |
| La Courneuve | 360 m | 110,000 | Twin-tube, 2 lanes in each direction |
| Norton | 180 m | 90,000 | Twin-tube, 2 lanes in each direction |

[(1)] *AADT : Average annual daily traffic*

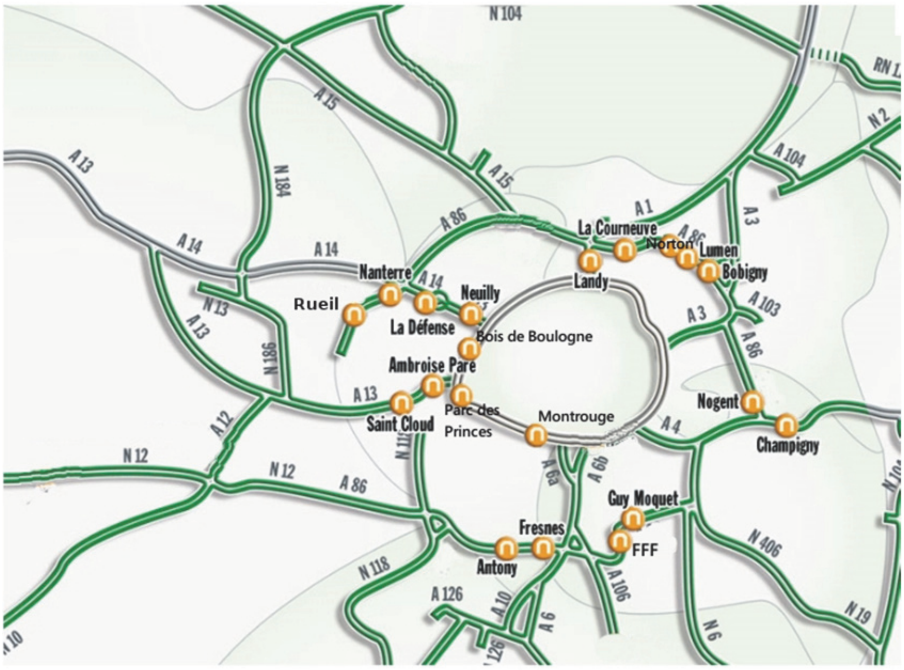


**Figure 1:** *Île de France national road network*

The choice of tunnels for measurements recorded by a fixed station was dictated by the scientific interest of the site (potentially significant levels of pollution), the instrumentation options and the operating conditions for the structure (no road works):

- Landy tunnel: 1,357 m, semi-transverse, one-way ventilation, 103,000 vehicles per day in the direction in which the measurements were recorded, little declivity, measurement point situated 1,207 m from the tunnel entrance
- Saint-Cloud tunnel: 832 m, semi-transverse, one-way ventilation, 78,000 vehicles per day in the direction in which the measurements were recorded, average declivity of 1.2%, measurement point situated 400 m from the tunnel entrance
- Bobigny tunnel: 2,220 m, semi-transverse, one-way ventilation, 50,000 vehicles per day in the direction in which the measurements were recorded, little declivity, measurement point situated 1,827 m from the tunnel entrance

The measurements in the Landy and Saint-Cloud tunnels were recorded in 2009 with the Paris LCPP (Laboratoire Central de la Préfecture de Police de Paris)

## Conditions for the recording of measurements

**Except for the performance of specific ventilation tests, the sanitary ventilation never operated in these structures during the measurement campaigns.** The pollution observed was thus the "crude" pollution caused by vehicle emissions and the re-suspension of particles deposited on the carriageway. However, motor vehicle traffic generates a draught by exerting a piston effect on the air. By bringing in fresh air, the traffic helps to dilute the pollutants at a proportional rate to its speed. When the traffic is congested, the draught through the tunnel becomes very weak and brings in hardly any fresh air. In such situations, the emissions are maximal (high density of vehicles and inadequate engine speed) and the users' exposure reaches a peak (extended stay inside the tunnel). In two-way tunnels, piston effects on the air are observed in both directions. As these pressures cancel each other out, the resulting air draft is generally weak. This type of structure is more sensitive to pollution than one-way tunnels.

The pollution in 20 tunnels was assessed using the CERTAM laboratory vehicle, which recorded continuous measurements for CO, $NO_X$ (NO and $NO_2$) and $PM_{10}$. The measurements recorded at fixed stations allowed for the continuous assessment of the changes in these parameters over several weeks. The specific methodology used will be described in greater detail in each paragraph.

## On-board measurement methodology

The laboratory vehicle is a two-seater commercial vehicle, specially fitted out to accommodate gas analysers and recording equipment. It is equipped with:

- A Topaze 32M (Environnement SA) double-chamber chemiluminescence analyser for the simultaneous and dynamic measurement of nitrogen oxides [frequency: 1 Hz; measurement scale: 0-10 ppm]
- An Environnement SA CO12M model infrared correlation carbon monoxide analyser, set to a rate of 3 seconds
- An ELPI (Electrical Low-Pressure Impactor) (Dekati) for particle measurements [1Hz with 12 aerodynamic filtration stages (7nm-10µm Da)]
- A GPS location device used for locating the vehicle
- And, for the measurements carried out in 2014, a system used to locate the curvilinear abscissa at all times, which is not dependent on the GPS and is thus operational in tunnels. Spatial location is based on the continuous recording of the vehicle's speeds, on the use of a "switch" which allows the operator to locate the tunnel entrances/exits (and may also be used when travelling past fixed measurement stations), and on a continuous telemetric measurement of the distance between the right-hand side of the vehicle and possibly the sidewall of the tunnel.

Sampling is carried out at the air intake, situated upstream of the cabin filter, in order to collect the ambient air around the vehicle's windscreen. The different measuring appliances are connected in such a way as to take account of their specific flow rates and response times, in order to synchronise the arrival of the air samples at the sensors. The use of several sampling points in the cabin was analysed in advance and the equivalent measured dose was identical for both measurement points used, i.e. firstly around the air vents and secondly around the driver's head (Gouriou et al., 2004).

The vehicle equipped with instrumentation travelled as part of the normal road traffic and the driver received no special instructions. He seemed to show a preference for driving in the right-hand lane and was given no instructions concerning the distance to be maintained from the vehicle in front.

The tunnels were driven through 10 to 15 times in each direction of traffic, apart from two structures that underwent additional investigations requiring around thirty tunnel journeys in each direction in one case (Landy tunnel) and over a hundred tunnel journeys for the other (Bobigny tunnel). Only the Antony and Fresnes tunnels are two-way structures. For the twenty tunnels in question, the journeys were carried out during rush-hour periods, as a preference. Finally, congestion would appear to have had little effect on the campaigns with only 6% of the tunnel journeys being carried out at speeds below 20 km/h.

## Limitations of on-board measurements specific to tunnels

The exploitation of the laboratory vehicle's recordings must take account of certain metrological limitations. In light of their excellent performance, the ELPI (particles) and Topaze 32M ($NO_X$) analysers proved to be very suitable for the dynamic monitoring of pollutants. On the other hand, the response time of the CO12M analyser is too slow to record measurements at 1Hz. It can thus only provide measurements every 60 to 80 m travelled [0.33 Hz]. The longitudinal profile of CO concentrations along the structure is thus approximate, but the results will still be presented.

For measurements recorded in 2009 and 2010, the GPS was the only system used for locating the laboratory car. As this device could not operate in the tunnel, the location of measurements could only be determined by interpolation based on an assumption of constant speed inside the structure. A measurement campaign was carried out inside the Bobigny tunnel in February 2014 in order to assess the performance of $NO_X$ measurements by comparing the on-board measurements to a fixed measurement station. For this assessment, the spatial location system was improved (see on-board measurement methodology) to ensure that the compared values are indeed derived from the measurements recorded on the same abscissa.

Comparing the fixed and on-board measurements recorded in 2014 shows that the difference between these two types of measurements is much greater for nitrogen dioxide than for nitrogen monoxide, which concurs with previous measurements recorded in 2009 and 2010. For example, the differences between fixed and on-board measurements of $NO_2$ vary between - 30 and +150% for the measurement day of 18 February 2014 (figure 2). The biggest uncertainties concerning $NO_2$ may be justified by:

- Uncertainties relating to the low levels of concentrations measured, in view of the sensitivity of the appliance (scale of 0-10 ppm, working over 10% of the range), with the knowledge that the need for a high temporal resolution in on-board mode rules out the use of more sensitive analysers which are slower.
- The additional uncertainty over the measurement of NO2 as it is an indirect measurement: the results are obtained by calculating the difference between the total NOX measurements and the NO measurements
- And, to a lesser extent, the different temporal resolutions between the two measurement methods.

As the correlation between the fixed / on-board measurements was satisfactory for NO, but much less reliable for $NO_2$, the exploitation of the on-board measurements will not concern $NO_2$.

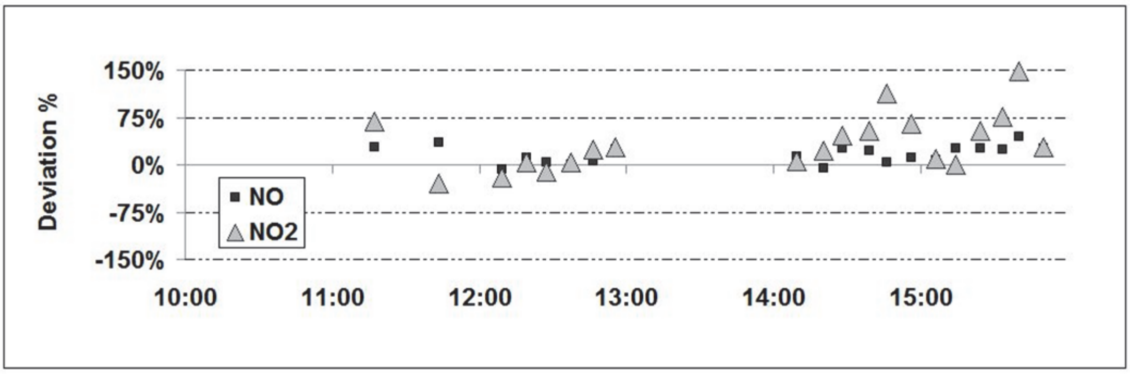


**Figure 2:** Differences between fixed and on-board measurements for NO and $NO_2$ for the measurements recorded on 18 February 2014

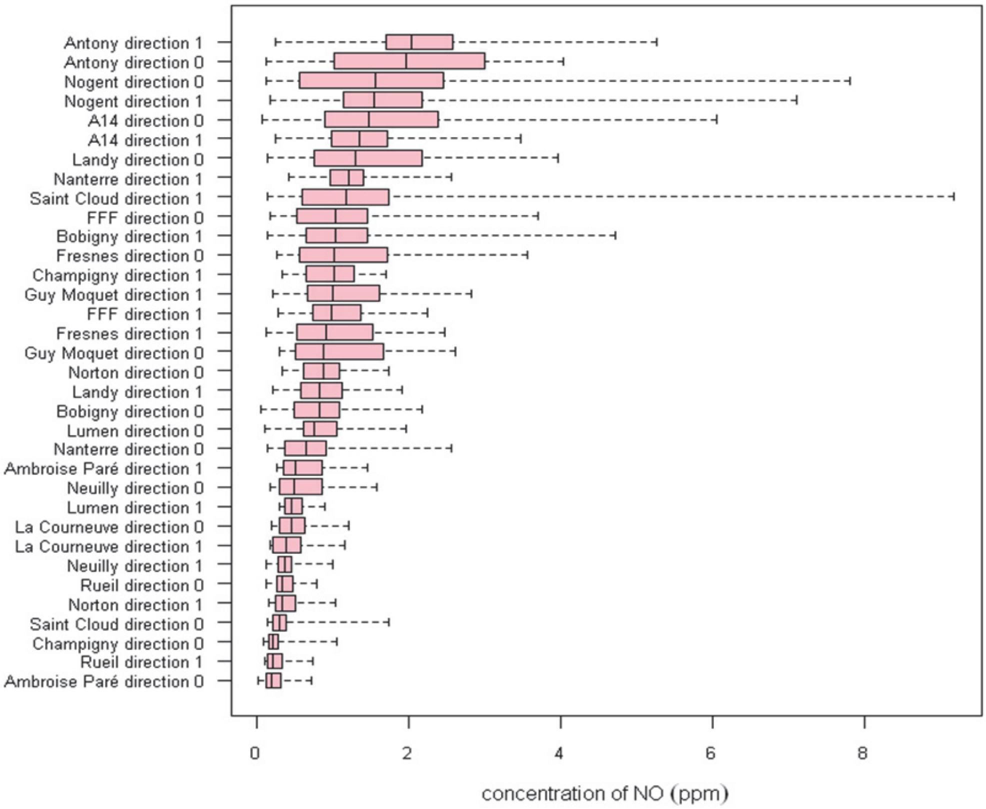


**Figure 3:** Box plot representation of statistics for NO concentrations measured by the laboratory vehicle for each tunnel

## Observed concentrations

For each tunnel, the statistical results concerning all of the one-off measurements carried out by the laboratory vehicle are represented in the form of a box plot with the minimum value, first quartile, median value, third quartile and maximum value. Direction 0 corresponds to the Province→Paris direction for the radial tunnels around Paris, i.e. to the clockwise direction for the "ring road" tunnels surrounding Paris and direction 1 corresponds to the Paris→Province direction or to the anti-clockwise direction.

By covering a large number of tunnels, the on-board measurements allowed for the ranking of the structures and the highlighting of factors responsible for high levels of pollution:

- Two-way traffic in the structure – resulting in a smaller draught to dilute the pollutants – this applies to the Antony tunnel and, to a lesser extent, the Fresnes tunnel,
- Significant tunnel lengths and / or high levels of traffic: Tunnels of La Défense, Nogent, Landy [direction 0], Nanterre [direction 0] and Bobigny [direction 0],
- Non-negligible declivity – despite a shorter length: tunnels of Fresnes, Champigny [direction 1], Guy Môquet [direction 0] and Saint-Cloud [direction 1].

Conversely, in short tunnels (La Courneuve, Norton, Lumen and Neuilly), tunnels with moderate traffic (Rueil) and tunnels with negative declivity (Champigny [direction 0] and Saint-Cloud [direction 1]), there are no incidences of remarkable concentrations of any types of pollutants.

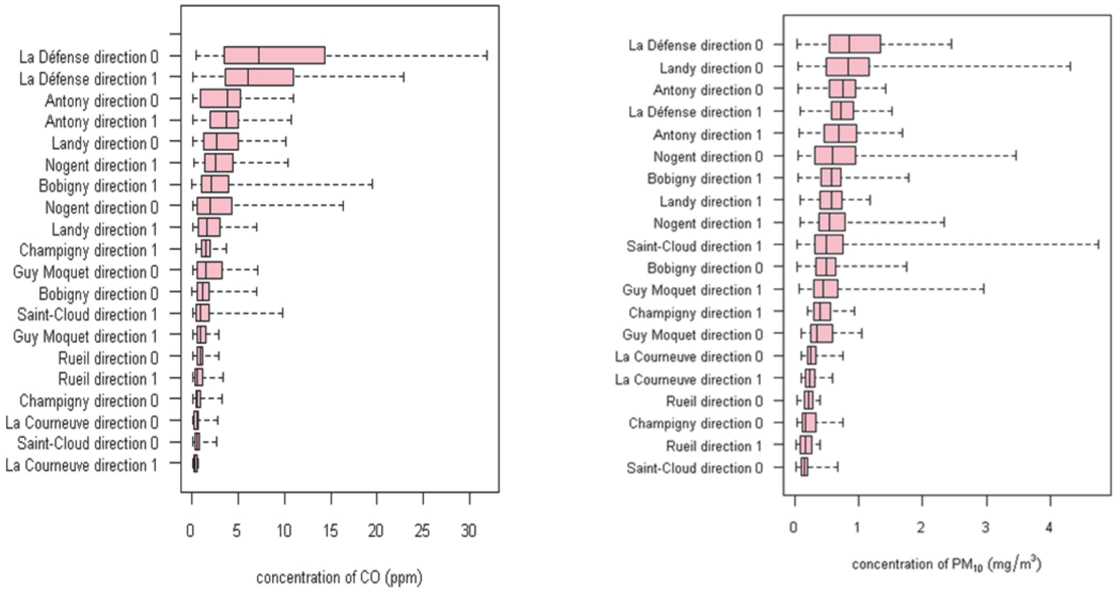


**Figure 4:** Box plot representation of statistics for CO and PM10 concentrations measured by the laboratory vehicle for several tunnels

The highest 75th percentile values are:

- 1.34 mg/m$^3$ for $PM_{10}$ in the La Défense tunnel (Province→Paris direction)
- 2.994 ppm for NO in the Antony tunnel
- 14.4 mg/m3 for CO in the La Défense tunnel (Province→Paris direction)

The box plot diagrams differentiate between the directions of traffic flow for the two-way Fresnes and Antony tunnels, whilst the traffic in both of these tunnels always passes through a single tube. In both of these structures, 13 through journeys were undertaken in one direction and 14 in the other. For the Fresnes tunnel, very few differences in the statistics for both directions of traffic flow can be observed. For the Antony tunnel, the dispersion of the statistics for the NO measurements shows that the traffic conditions (and therefore the pollution conditions) were markedly different according to the direction of flow. This is not detectable in the CO measurements – which is certainly due to their very low levels – nor in the $PM_{10}$ recordings, whose fluctuations show greater inertia (see ventilation tests).

The findings concerning the detectable differences in the NO statistics for the Antony tunnel illustrate the need for caution in formulating conclusions. For example, the presence of a lorry producing a great deal of pollution just in front of the laboratory vehicle could result in significantly higher readings for a particular journey. The statistics, which are only based on a small number of tunnel journeys made by the laboratory vehicle, are highly sensitive to such types of events.

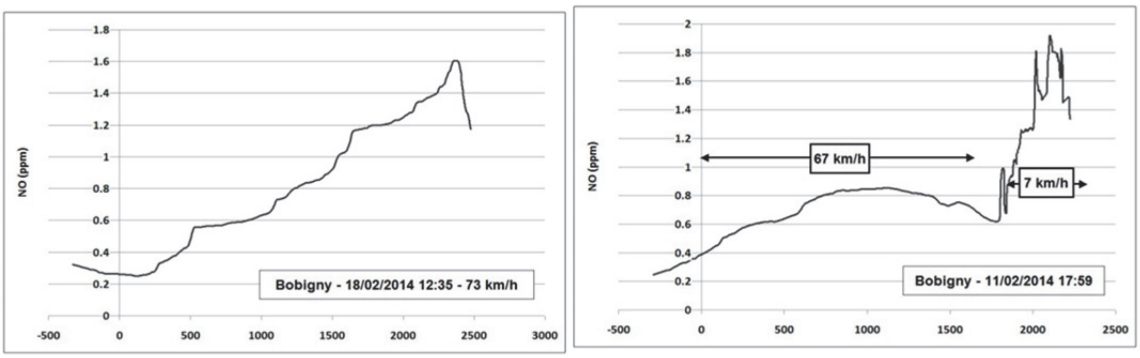


**Figure 5:** Longitudinal profile of NO concentrations in the Bobigny tunnel in February 2014. On the left: free-flowing traffic. On the right: traffic congestion at the end of the tunnel

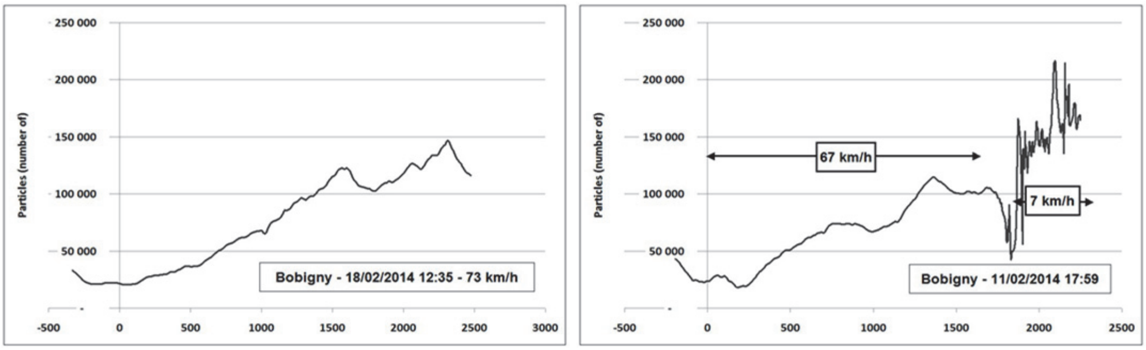


**Figure 6:** Longitudinal profile of particle counts in the Bobigny tunnel in February 2014. On the left: free-flowing traffic. On the right: traffic congestion at the end of the tunnel

The Bobigny tunnel consists of two one-way tubes and includes slip roads (entry and exit) at each third of its length. When the traffic is flowing freely, a draught is created in the direction of traffic and the concentrations of pollutants increase from the entrance to the exit of the tube (left-hand side of figures 5 and 6). In the event of partial congestion at the end of the tube (right-hand side of figures 5 and 6), the concentrations increase markedly in the stationary sector and the vehicles in front of the laboratory vehicle have a visible influence (conflicting peaks). However, in the non-congested zone, the profile is virtually linear, with the exit slip road situated at abscissa 1600 exerting an influence. The fresh air brought in by this slip road has a noticeable influence on the particulate profile for free-flowing traffic.

The Antony tunnel is a single-tube structure with two-way traffic. The measurements presented in Figure 7 were recorded in 2009 and at that time, the laboratory vehicle had no way of locating the curvilinear abscissa. The longitudinal profiles were established by linear interpolation, with the assumption of a constant vehicle speed. Depending on the traffic densities in each direction, and according to the impact of the wind that may blow through a portal, an air draught may or may not be created in the structure. The left-hand graph shows a situation without a significant draught and with a bell-shaped longitudinal profile for the NO concentration. The NO concentrations remain significant in a large part of the structure. The measurements recorded on 25/03/2009 show a profile of increasing concentrations throughout the length of the tunnel, associated with a draught moving in the same direction as the laboratory vehicle. By applying a $[NO_2]/[NO_X]$ ratio value of 0.20, the mean $NO_2$ concentration for the tunnel journey can be estimated at 0.78 ppm (on the left-hand side) and 0.61 ppm (on the right-hand side). These significant values confirm that two-way tunnels are particularly sensitive to pollution.

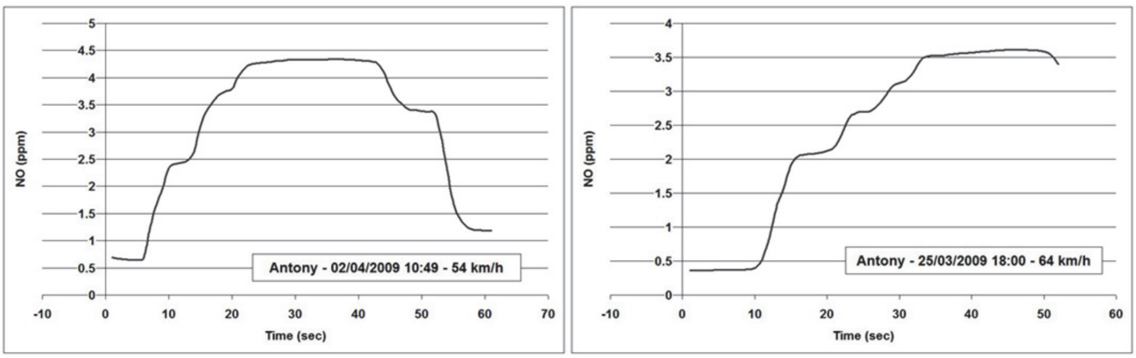


**Figure 7:** Longitudinal profiles of NO concentrations in the Antony tunnel in 2009

## Daily profiles of pollutant concentrations

Measurement campaigns at fixed stations have allowed for the continuous recording of changes in pollutant concentrations over time. For example, the recordings of $PM_{10}$, $PM_{2.5}$ and $NO_2$ at 150 metres from the Landy tunnel exit on 25 March 2009 show an excellent correlation between these three parameters (figure 16). The main pollution peak occurs at between 7 a.m. and 8:30 a.m., with $NO_2$ concentrations of over 800 ppb, $PM_{10}$ rising to 600 µg/m$^3$ and $PM_{2.5}$ reaching 400 µg/m$^3$ for a period of around 50 minutes.

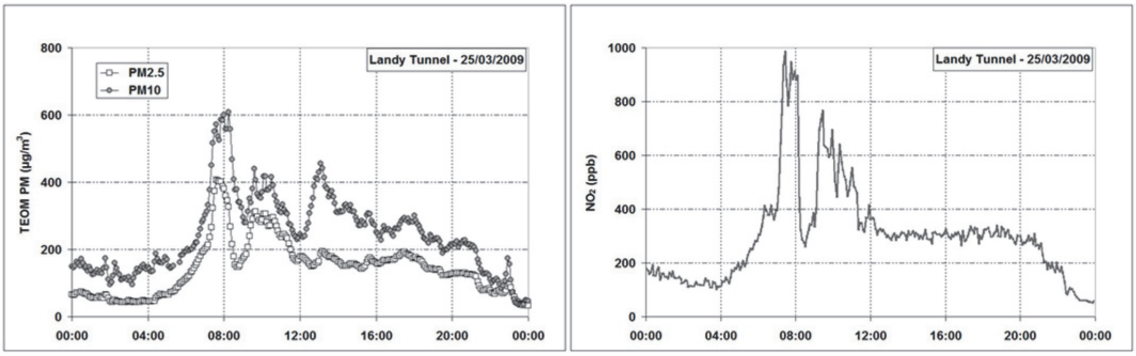


**Figure 8:** Daily profiles for $PM_{10}$, $PM_{2.5}$ and $NO_2$ in the Landy tunnel

## On-board measurements: compliance with regulatory levels

Measurements recorded using the laboratory vehicle were carried out in peak traffic periods, without necessarily encountering many instances of congestion. These measurements are representative of the most polluted periods in the road tunnels included in this study, even though more serious cases of pollution may occasionally occur (e.g. in the event of prolonged congestion).

The regulatory levels for CO and $NO_2$ correspond to averages which are both spatial - throughout the length of the tunnel - and temporal - over a 15 minute period. The duration of the laboratory vehicle's journey through the tunnel is generally from one to several minutes, with one second intervals between recordings.

As for CO, the individually observed concentrations of this pollutant are generally between 0 and 15 ppm, and are always well below the regulatory levels. Therefore, the regulatory levels for CO are not exceeded.

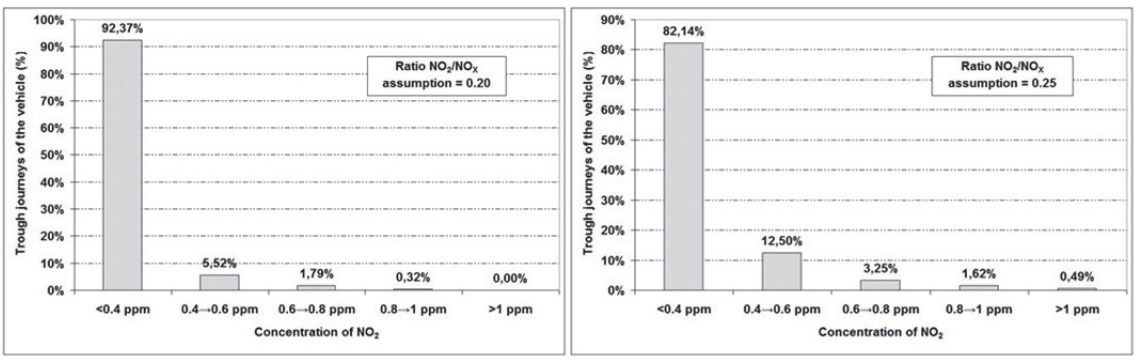


**Figure 9:** Distributions of $NO_2$ concentrations extrapolated on the basis of NO measurements by the laboratory vehicle according to two assumptions for the $[NO_2]/[NO_X]$ ratio value.

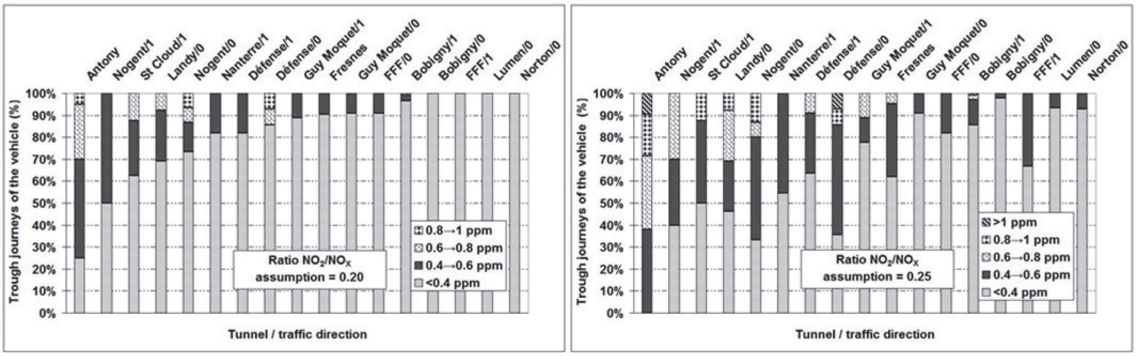


**Figure 10:** Distributions of $NO_2$ concentrations extrapolated on the basis of NO measurements per tunnel according to two assumptions for the $[NO_2]/[NO_X]$ ratio value.

With regard to $NO_2$, for which the on-board measurements cannot be considered to be reliable, a specific method was applied for spotting situations in which the regulatory levels were exceeded (0.4 ppm):

- As the $NO_2$ measurements recorded by the laboratory vehicle were not used, the $NO_2$ values in a structure were estimated on the basis of the on-board measurements of NO recorded in this structure and an $[NO_2]/[NO_X]$ ratio. Two ratio assumptions are examined in this paragraph;
- For each journey through the tunnel, a mean concentration C over the length of the structure is estimated in the following manner:
  - Between the (i-1) and (i) measurements, the concentration is considered to be constant and equal to that measured in (i), noted $C_i$;
  - The speed of the vehicle in the tunnel is assumed to be constant (equal to the length of the tunnel L divided by the time of the journey in question)
  - The distance $d_i$ travelled between the (i-1) and (i) measurements is equal to the time elapsed between two measurements (1 second) multiplied by the speed;
- Finally $C = \Sigma\ di\ Ci / L$.

This method was used to produce the graphs in figures 9 and 10 according to two $[NO_2]/[NO_X]$ ratio assumptions:

i) $[NO_2]/[NO_X]$ equal to 0.20, which is the most commonly observed mean value during the day in tunnels with high levels of traffic (see paragraph concerning the $[NO_2]/[NO_X]$ ratio)

ii) $[NO_2]/[NO_X]$ equal to 0.25, which may be adopted as the higher level assumption.

Without the use of sanitary ventilation, compliance with the regulatory threshold for $NO_2$ is observed on 92.4% of the journeys through the tunnels, with the assumption of an $[NO_2]/[NO_X]$ ratio equal to 0.20. On 82.1% of tunnel journeys, there is compliance with this threshold if a ratio of 0.25 is chosen.

The distribution of situations in which the regulatory thresholds are exceeded per tunnel provides further confirmation that one-way (Antony), and long tunnels (La Défense, Nogent, Bobigny), in addition to those subject to congestion (Landy, la Défense, Guy Môquet, FFF) and characterised by a declivity (Saint Cloud, Guy Môquet) are more sensitive to pollution peaks.

## Ratio $[NO_2]/[NO_X]$

Measurements recorded in tunnels in recent years show that the $[NO_2]/[NO_X]$ ratio has increased in road tunnels. The requirements of the CSHPF (Conseil supérieur d'hygiène publique de France – French Higher Public Health Council), which estimated the $[NO]/[NO_2]$ ratio at approximately 10, i.e. at 1/11th of the $[NO_2]/[NO_X]$ ratio, are no longer realistic. Furthermore, these observations are similar to those also carried out in the open air in proximity to highway infrastructures. They are a consequence of changes in techniques for treating vehicle exhaust gases (Afsset, 2009).

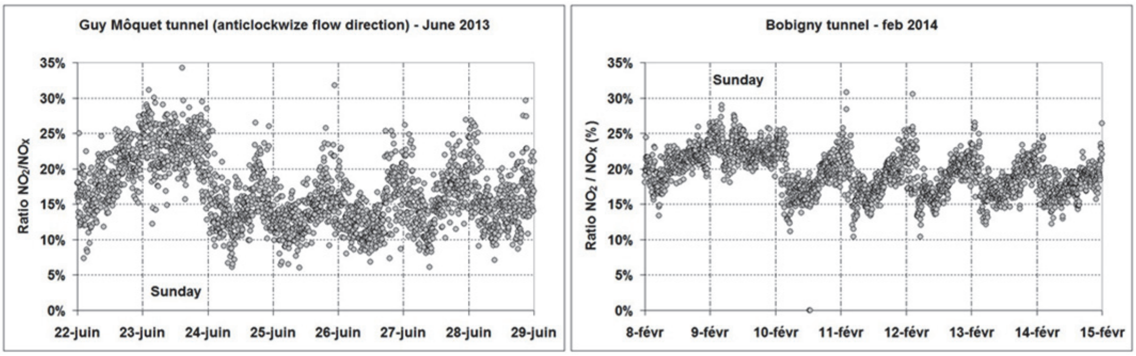


**Figure 11:** Changes in the $[NO_2]/[NO_X]$ ratio over one week for the Bobigny (on the left) and Guy Môquet (on the right) tunnels

Measurements recorded by fixed stations in the framework of the AIRTURIF programme have revealed a median $[NO_2]/[NO_X]$ ratio of approximately 0.20. This ratio tends to be higher at the weekend especially on Sundays due to the lack of heavy goods vehicle (HGV) traffic. Indeed, the $[NO_2]/[NO_X]$ ratio for the vast majority of HGVs conforming to the Euro 5 standard is approximately 10%, whereas for light diesel vehicles conforming to Euro 5, it varies considerably according to the manufacturer and may exceed 50% (European Environment Agency, 2013). Figure 11 shows the changes in the $[NO_2]/[NO_X]$ ratio over one week, based on the automatic recordings at two sites:

- At 200 metres from the exit of the interior Bobigny tube (length of 2,220 m) during the winter of 2014.
- At 125 metres from the exit of the interior tube of the Guy Môquet tunnel (length of 560 m) during the summer of 2013. This relatively short tunnel sees high levels of traffic – 65,000 vehicles per day in the direction in question, 20% of which are HGVs – with periods of congestion and a significant declivity.

In road tunnels, on weekdays and during rush hour periods, the $[NO_2]/[NO_X]$ ratio is mainly between 0.15 (in the morning) and 0.25 (in the evening). On Saturdays and especially on Sundays, this ratio is higher (from 0.20 to 0.40) but with lower $NO_X$ concentrations due to the lack of HGVs (Bernagaud et al., 2014). The $[NO_2]/[NO_X]$ ratios in tunnels also reveal both daily and seasonal cycles (Bruxelles Environnement, 2012). The $[NO_2]/[NO_X]$ ratio is not a constant and varies with traffic levels, emission, tunnel length, draught strength and ventilation type (if working). It also depends on variations in external level of ozone and chemical reaction and processes, such as reactions with radicals, leading to changes of the $[NO_2]/[NO_X]$ ratio along the tunnel length (Australia government, 2008).

## Performance of ventilation systems

This field was investigated for a structure with longitudinal ventilation (Guy Môquet tunnel – December 2013) and for a structure with semi-transverse ventilation (Bobigny tunnel – November 2010).

The Guy Môquet tunnel is 560 meters long and longitudinally ventilated by 12 accelerators with a respective unitary thrust of 1,100 N, arranged in two banks of 6. The ventilation can be operated at full speed (ventilation at 100%) or at moderate speed (ventilation at 50%). The tunnel was equipped with instruments 125 metres from the exit portal of the Northern tube with:

- An APNA (Horiba) chemiluminescence analyser for nitrogen oxide concentrations
- A TEOM (Thermo Scientific) for particulate concentrations with a diameter of less than 10 µm ($PM_{10}$)
- A Tunnel rotating vane anemometer (Thies) installed on the sidewall to monitor variations in the air draught speed.

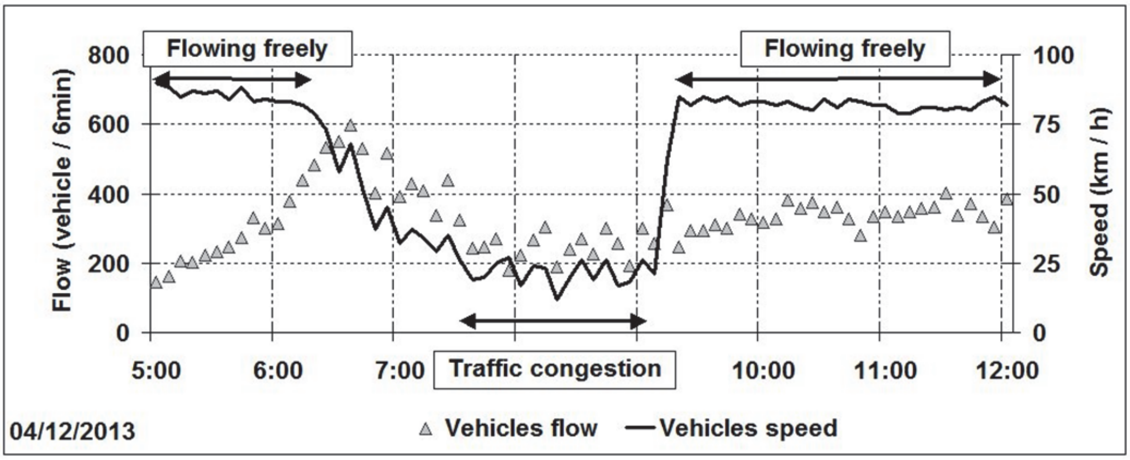


**Figure 12:** Traffic and air draught speed in the Guy Môquet tunnel in the morning

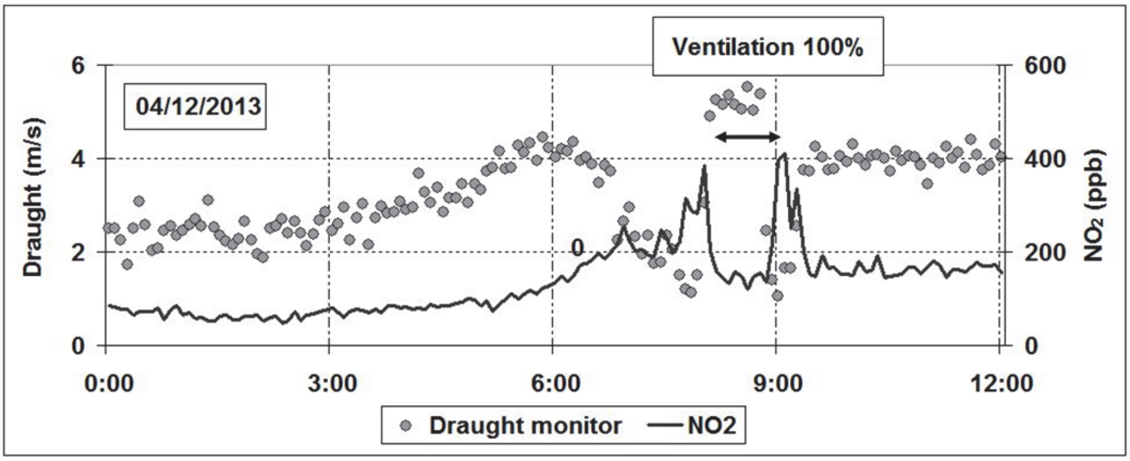


**Figure 13:** $NO_2$ concentrations and air draught speed in the Guy Môquet tunnel

The relatively high repeatability of the build-up of congestion was observed in this tunnel during the testing. Congestion almost always appears at around 7:00 a.m. with a drop in speeds that level out at between 10 and 30 km/h (figure 13). The congestion ends at around 9:00 a.m. The ventilation tests took place in the middle of the peak traffic period between 8:00 a.m. and 8:45 a.m., over a nine-day period.

Figures 13 and 14 show the variations in levels of $NO_2$ and $PM_{10}$, during a test with the ventilation operating at 100% of its power. In a congestion situation, the air flow in the tunnel is low and pollutant concentrations are high. As soon as the ventilation is activated, the air flow increases, thus bringing in fresh air. There is a rapid drop in $NO_2$ concentrations. There is a slower response time for $PM_{10}$.

Figure 15 shows that by activating the sanitary ventilation at 50% of its maximum power, we obtain a fast and significant decrease in pollutants.

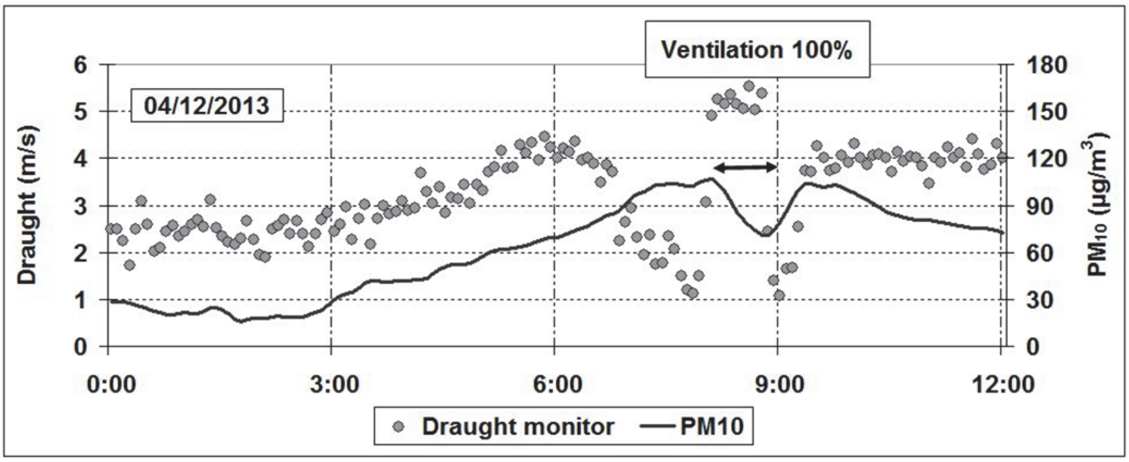


**Figure 14:** $PM_{10}$ levels and air draught speed in the Guy Môquet tunnel

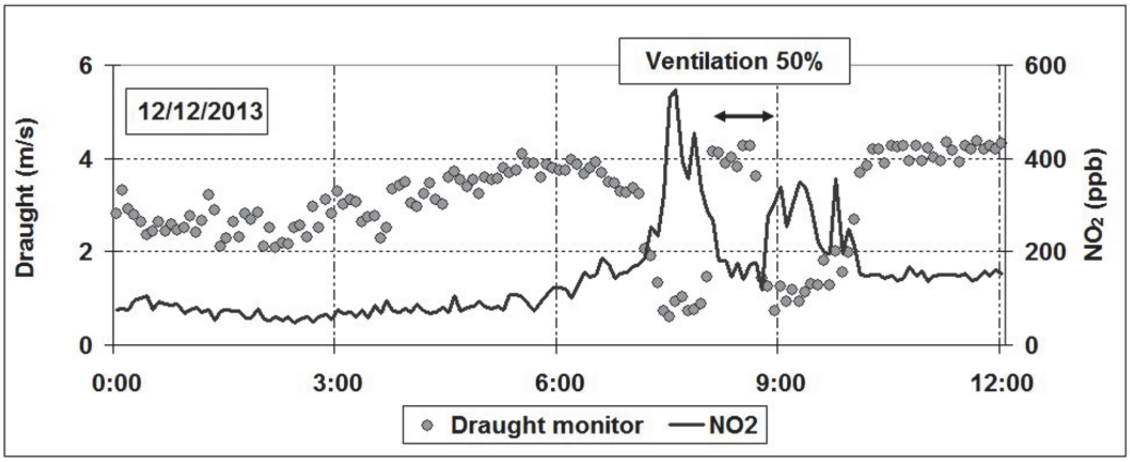


**Figure 15:** Ventilation test at 50% of maximum power in the Guy Môquet tunnel

The CERTAM laboratory vehicle recorded measurements in the interior tube of the Bobigny tunnel with the transverse ventilation operating. This tube is equipped with 132 fans throughout the length of the structure capable of introducing fresh air with a maximum blowing capacity of 396 $m^3/s$. Figure 16 shows the highly smoothed mean concentrations of NO for the tunnel journeys without any ventilation and with the sanitary ventilation operating at 100%. This long tube, with two access slip roads, possess a high degree of inertia to ventilation. However, a marked dilution of NO can be observed when the ventilation is operating at 100%.

Ventilation tests in tunnels with transverse ventilation but without an access slip road had been carried out in the Landy tunnel and in the Siaix tunnel in the Alps (Brousse et al., 2003). In the Western tube of the Landy tunnel (Province→Paris direction) the measurements, recorded during rush hour periods by a chemiluminescence analyser positioned at the exit portal, showed a reduction in $NO_X$ concentrations (figure 17) – which at that time, were generally higher. In the Siaix tunnel – a two-way structure – the measurements had been recorded by an opacimeter situated 2/3 of the way along the structure, during periods of congestion that occur during the departures from winter sports resorts on Saturdays. These tests had shown a quick and significant reduction in the levels of opacity.

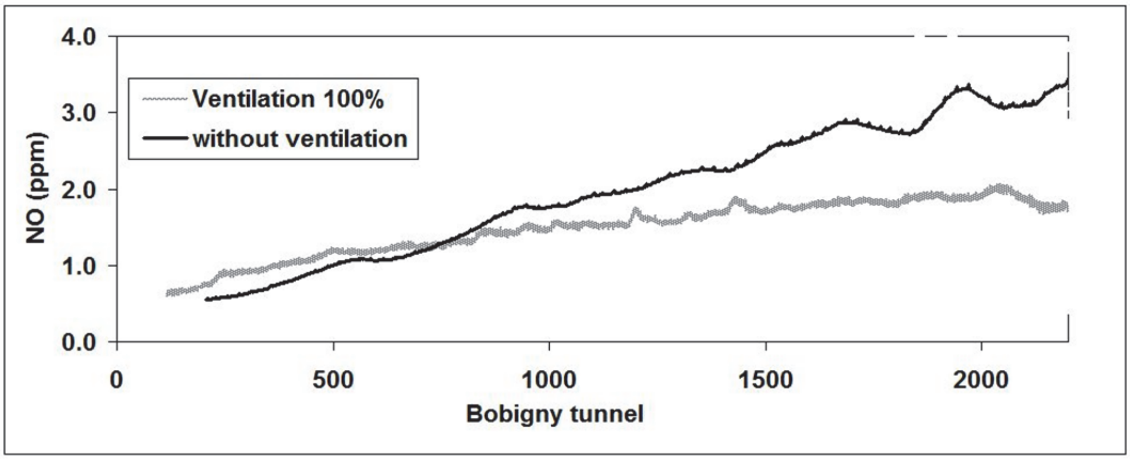


**Figure 16:** Ventilation test in the Bobigny tunnel – longitudinal profiles of NO concentrations with and without sanitary ventilation

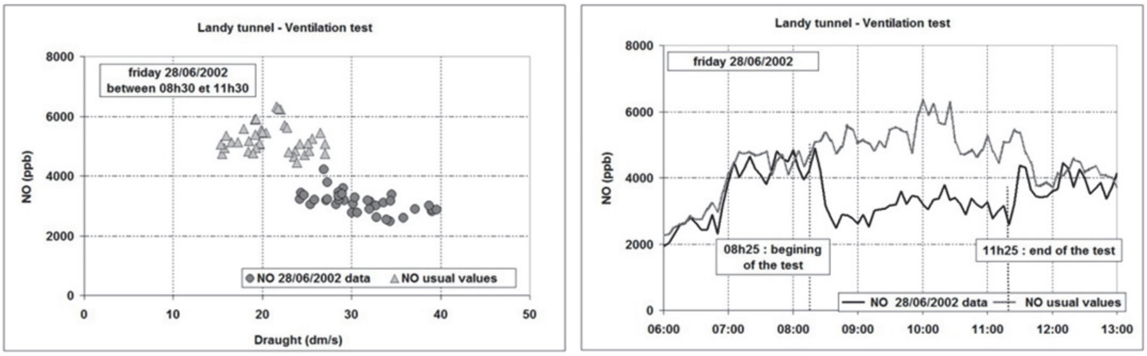


**Figure 17:** Ventilation test in the Landy tunnel on 28 June 2002

In conclusion, longitudinal ventilation proved to have a visible impact during periods of congestion by reducing the concentrations of pollutants to the levels observed when there is no congestion. These tests – limited to two tunnels – show that longitudinal ventilation seems to be more effective at rapidly diluting pollutants than transverse ventilation.

## Pollution outside structures

The one-off measurements recorded outside tunnels do not provide sufficient geographical coverage to allow for a global assessment of the environment of tunnel portals. In order to develop a better understanding of the dispersion of particulate ($PM_{10}$) plumes at the ends of tunnels, a Lidar measurement campaign involving the Léosphere company was conducted in May 2012 at the Eastern portal of the Bobigny tunnel, on the A86 motorway. Lidar technology works on a similar principle to radar, except for the fact that it emits pulses of light from lasers rather than radio waves. The particles suspended in the air reflect the beam which is analysed and then used for mapping particulate pollution plumes.

This campaign was carried out using an ALS LIDAR (or aerosol LIDAR) device, which emits short laser pulses in the ultra-violet band at 355 nm. This wavelength does not correspond to any rays that absorb atmospheric components, which means that the signal processing need only take account of the laser beam diffusion phenomenon. Furthermore, there is negligible gas diffusion (Rayleigh diffusion) in relation to the particulate diffusion (Mie diffusion) due to the size of the particles, which facilitates the processing of the signal into a particulate concentration.

The LIDAR device was installed on a hotel roof 240 metres from the tunnel portal and at an altitude of 20 metres in relation to the tunnel carriageway. In approximately 15 minutes, it performed:

- 3 horizontal sweeps with 80° of amplitude (one laser beam emitted every 2°)
- 2 vertical profiles of 10° starting from the top of the tunnel portal (one beam emitted every 2°).

Two fixed measurement stations, equipped with TEOMs, allowed for the validation of the $PM_{10}$ concentrations provided by the LIDAR. They were positioned:

- On the roof of a building at the same altitude as the LIDAR, but in the immediate environment of the tunnel portal
- Above the tunnel portal, on a roundabout.

Although three-dimensional measurements would have been preferable for evaluating the impact of the tunnel, only the measurements recorded in the fixed horizontal plane could be exploited. It was not possible to convert the vertical planes into mass concentrations; this information – provided in the form of extinction data – must be interpreted with caution. In addition, the vagaries of the weather and periods of reduced congestion also contributed to making the campaign less representative.

There is a satisfactory correlation between the $PM_{10}$ measurements recorded by the LIDAR and those recorded by the fixed measurement stations.

The LIDAR device allowed for the coverage of an area of several $km^2$ and thus for the observation of the behaviour of concentrations in the environment of the Bobigny tunnel for several configurations defined in the following manner: "night", "day without any traffic event", "congestion or heavy traffic in direction 1", and "congestion or heavy traffic in direction 0".

- For the "night" and "day without traffic event" periods, no plumes emerge from the tunnel in relation to the $PM_{10}$ background level.
- For the "congestion or heavy traffic in direction 1" episodes, the signature of the A86 motorway in terms of $PM_{10}$ concentrations can be primarily observed in the canyon formed by the motorway. Plumes may occasionally escape from the canyon but they remain limited.
- For the "congestion or heavy traffic in direction 0" episodes, situations with variable levels of concentrations were observed:
    - Occasional plumes of pollution that are not obviously linked to congestion in the tunnel
    - Occasional plumes of pollution occurring outside of congestion phenomena
    - A low pollution footprint at the tunnel portal, even during congestion
    - Pronounced plumes in very windy conditions.

It should be borne in mind that when the most pronounced plumes emerged from tunnels, they extended horizontally for a maximum radius of 100 m and to a height of approximately 20 m. Other sources of pollution have also been revealed, such as the RN 186 main road and residential areas.

## CONCLUSIONS

The first part of the AIRTURIF programme to further the knowledge of air quality within and around road tunnels led to a wide-ranging investigation concerning 45 km of underground structures which underwent a global assessment involving the CERTAM laboratory vehicle, supplemented by several specific measurement campaigns (continuous measurements in the tunnels, analysis of emissions from tunnels, analysis of the $[NO_2]/[NO_X]$ ratio and ventilation testing).

The measurements showed that during rush hour periods and in the absence of sanitary ventilation:

- There is always compliance with the regulatory levels of CO
- The regulatory levels of $NO_2$ are exceeded for approximately 10% of the laboratory vehicle's journeys
- The tunnels with the greatest sensitivity to pollution peaks are tunnels with one or more of the following characteristics: congested, two-way, long or featuring a declivity.

The efficiency and importance of the sanitary ventilation systems in road tunnels have thus been confirmed. Their activation during periods of traffic congestion when there is less air flow through the structure allows for a significant dilution of the pollutants due to the introduction of fresh air. Longitudinal ventilation systems, which directly accelerate the movements of air masses in tunnels, have proven to be more responsive than transverse ventilation systems.

The LIDAR measurement campaign, dedicated to studying the emission of fine $PM_{10}$ particles at tunnel portals, supplemented by one-off measurements around tunnel exits, has shown that a tunnel may have a detectable, but limited, impact. The emissions may be detectable during certain traffic congestion situations, depending on the weather conditions, but it is hard to dissociate them from other pollution sources. The emission plume observed extended for a maximum radius of 100 metres and a height of 20 metres.

In conclusion, road tunnels – due to their confined nature – concentrate the emissions from vehicles travelling through them. They thus have higher levels of pollution than those encountered outside the tunnels. A draught moving at 3 to 5 m/s is generally sufficient to dilute this pollution adequately and conform to the regulatory criteria for air quality within road tunnels. This draught is most often generated by the traffic itself, due to the sustained piston effect exerted on air masses. In the event of traffic congestion, the addition of sanitary ventilation can mechanically generate an air flow and thus reduce the concentrations of pollutants.

The exposure of tunnel users to pollution is generally limited in road tunnels as they only remain within these structures for short periods (from several tens of seconds to several minutes, depending on the length of the structure and the fluidity of the traffic). It is thus important to be particularly vigilant during periods of traffic congestion by ensuring the optimal ventilation of structures at these times. Tunnel operators should also pay particular attention to two-way tunnels.

In summary, this study shows that when sanitary ventilation was not activated, levels of $NO_2$ – the most critical pollutant – conformed to the regulatory requirements on approximately 90% of the laboratory vehicle's journeys during rush hour periods. The measurements recorded during the sanitary ventilation tests in congested traffic situations confirm its positive impact on pollutant concentrations. Finally, and although it remains necessary to study the potential impacts of emissions at tunnel portals, this study has confirmed – with reference to the findings for the Bobigny tunnel – that emissions at tunnel portals are quickly diluted in general and are difficult to dissociate from other sources of pollution.

## References

Afsset (2008), *Caractérisation de l'exposition personnelle d'un échantillon de Franciliens* [Characterisation of the personal exposure of a sample of Île-de-France residents].

Afsset (2009), *avis et rapport d'expertise collective Émissions de dioxyde d'azote de véhicules diesel, impact des technologies de post-traitement sur les émissions de dioxyde d'azote de véhicules diesel et aspects sanitaires associés* [Recommendation and collective assessment report: Carbon dioxide emissions from diesel vehicles, impact of post-treatment technologies on the nitrogen dioxide emissions of diesel vehicles and associated health aspects]

Airparif (2007), *Mesure dans le flux de circulation, Étude exploratoire* [Measurement of traffic flows, Exploratory study.]

Airparif (2009), *Exposition des automobilistes franciliens à la pollution atmosphérique liée au trafic routier* [Exposure of Île-de-France-based motor vehicle drivers to road traffic-related atmospheric pollution].

Airparif (2014), *La qualité de l'air en Île-de-France en 201*3 [Air quality in the Île-de-France region in 2013].

Airparif (14-05-2014), *Bilan de l'épisode de pollution et de la circulation alterné [Review of the pollution episode and "circulation alternée" (road space rationing scheme based on odd and even registration plates)]*

Australia government – National Health and Medical Research Council (2008), A*ir quality in and around tunnels – Final report 2008.*

Bernagaud C, J.F. Burkhart, B. Vidal, T. Lepriol, J.F. Petit, T. Brunel, F. Gouriou and D. Préterre (2014), *Observations of the [$NO_2$]/[$NO_X$] ratio in road tunnels,* Pollution Atmosphérique n° 221.

Brousse B., P. Carlotti and B. Vidal (2003), *Measurement of pollution levels in three alpine road tunnels,* 11th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Luzern, Switzerland: 7-9 July 2003

Brousse B, B. Vidal, X. Ponticq, G. Goupil, R. Alary (2005), *Pollution dispersion at an urban motorwaytunnel portal: Comparison of the small-scale predictive studywith the actual conditions measured on the site,* Atmospheric Environment, Volume 39, Pages 2459-2471

*Bruxelles Environnement - Institut Bruxellois pour la Gestion de l'Environnement (2012), Mesures de la qualité de l'air dans le tunnel Leopold II.* [Air quality measurements in the Leopold II tunnel] CETU (2003), *les dossiers pilotes du CETU – Ventilation*.

Conseil supérieur d'hygiène publique de France (1998), *Qualité de l'air dans les ouvrages souterrains ou couverts* [Air quality in underground and covered structures].

European Environment Agency (2013), *Air pollutant emission inventory, Technical guidance to prepare national emission inventories, Exhaust emissions from road transport,* Guidebook.

Gouriou F., J.P. Morin and M.E. Weill (2004), *On-road measurements of particle number concentrations and size distributions in urban and tunnel environments,* Atmospheric Environment, Volume 38, Issue 18, Pages 2831-2840.

Guilloteau A., B. Vidal, L.Paillat, G.Thiaut, D. Preterre and V. Dunez, (2010), *Air Quality in the Ile de France road tunnels (AIRTURIF project): presentation, methodology and preliminary results,* Transport and Air Pollution 2010

Ministère de l'intérieur, Ministère de l'équipement des transports et du Logement (2000), *Annexe n°2 de la circulaire interministérielle n° 2000-63 du 25 août 2000 relative à la sécurité dans les tunnels du réseau routier national – Instruction technique relative aux dispositions de sécurité dans les nouveaux tunnels routiers.* [Technical instruction relating to safety provisions in new road tunnels] Ministère de la Santé (1999), *Circulaire n°99.329*.

Morin J.P., F. Dionnet and V. Delmas (2006), *Caractérisation des Expositions Professionnelles et des Usagers des Transports Routiers: Mesures Dynamiques en Habitacle de Véhicule Inséré dans le Trafic,* [Dynamic measurements in the cabin of a vehicle travelling in traffic] INSERM U644 Rouen CERTAM Air Normand Convention EST 2006-1-37