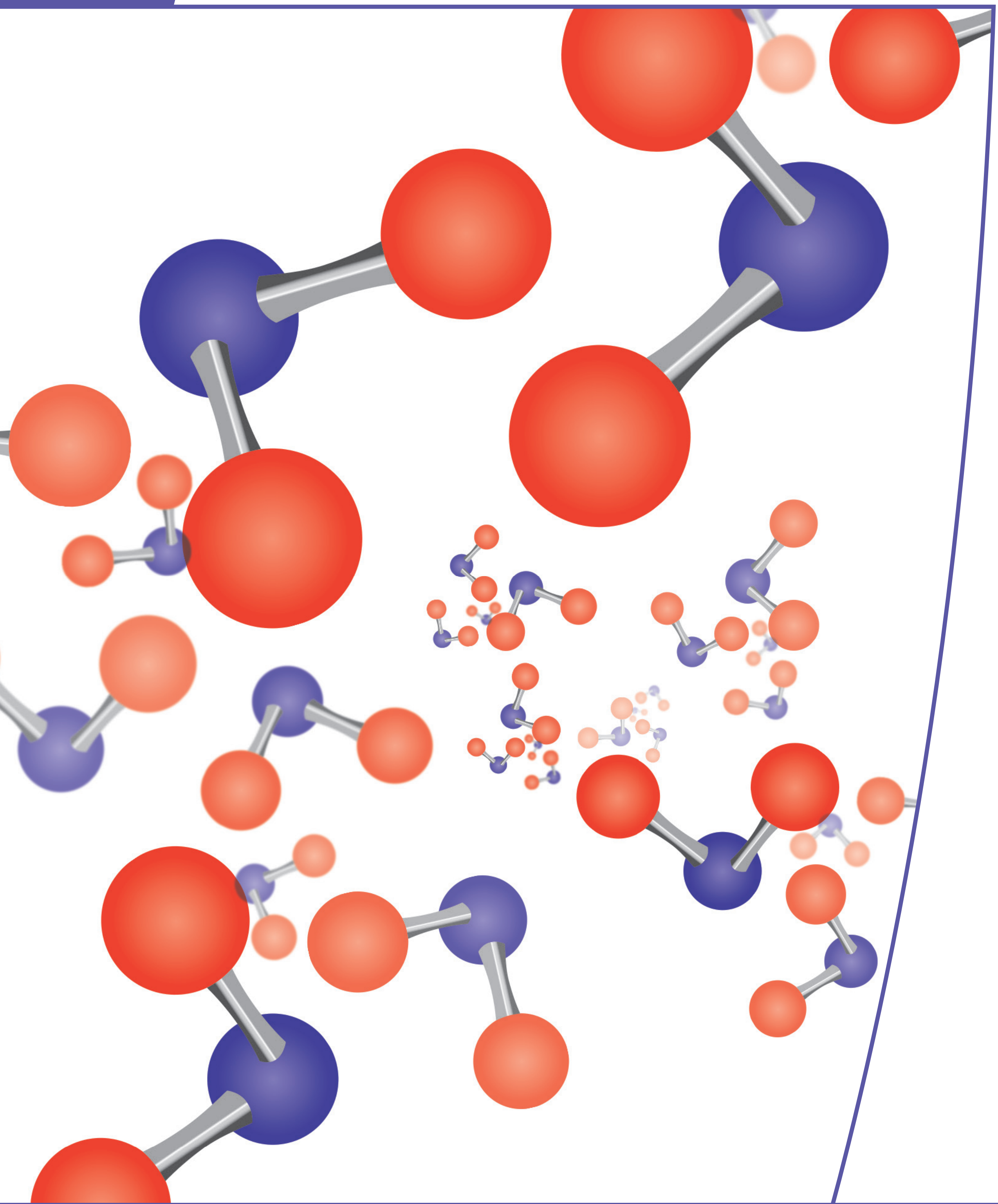
INFORMATION MEMO No. 26

Measuring nitrogen dioxide and controlling ventilation in road tunnels



November 2017

Centre d'Études des Tunnels (Centre for Tunnel Studies)

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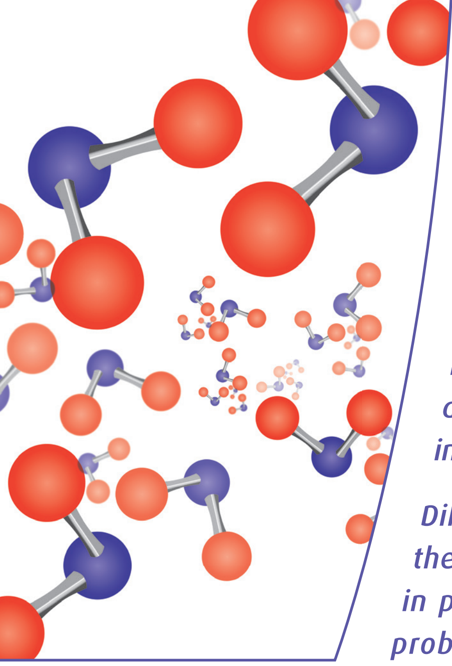

Nitrogen dioxide (NO_2) is a pollutant whose emission levels have remained at the same level despite all the technological innovations that have benefited cars on the road. Nitrogen dioxide is considered to be toxic by the WHO and public authorities. It poses a significant health challenge all the more since it is a precursor gas for equally undesirable secondary particles (ultra fine particles formed after the exhaust). Exposure to NO_2 is regulated for ambient air as well as for road tunnels where certain potentially delicate situations can arise (traffic jams, low natural air renewal levels) resulting in users being exposed to levels that cannot be neglected.

Diluting pollutants by adding fresh air ensures good air quality, on condition the fresh air ventilation control and command chain is stringently controlled and in particular the system to measure NO_2 concentrations. CETU has studied the problems involved in measuring nitrogen dioxides in road tunnels in order to propose solutions that avoid either chronically overestimating NO_2 levels or regularly ignoring incidents when regulatory levels are exceeded.

In 1999, when NO_2 levels in tunnels were regulated, it was agreed that operators could estimate concentrations of this pollutant by measuring nitrogen monoxide (NO), a much easier gas to measure. Now, direct measuring of NO_2 concentrations is to be recommended since the predefined ratio used up to now to convert NO to NO_2 is no longer valid. Indeed all the measurement campaigns performed over the last ten years have shown that the NO/NO_2 ratio was no longer equal to 10, but was instead within a range of 3 to 5 while fluctuating greatly. In addition, thanks to metrological developments, measuring NO_2 is now more reliable than in 1999.

For all these reasons, road tunnels must now be fitted out with NO_2 sensors chosen from two main families of devices: electrochemical cells or optical measuring devices. This information memo sets out the advantages and limits of both categories of sensors, comparing their respective use constraints and providing decision-support elements.

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1 Regulations applicable to nitrogen oxides in road tunnels

1.1 NO_2 threshold set by the circular No. 99-329 of 8 June 1999

The circular No. 99-329 of 8 June 1999 from the health ministry requires compliance by operators with the criteria set by CSHPF (Conseil Supérieur d'Hygiène Publique de France) for carbon dioxide (CO) and nitrogen dioxide (NO_2) in underground or covered structures as published in its opinion document of 14 December 1998.

CSHPF set the following criteria for NO_2 in road tunnels and underground road structures:

– the average NO_2 content over the entire length of the structure must not exceed 0.4 ppm[1] (800 µg/m³) for any 15 minute period.

1.2 Controlling NO_2 levels by extrapolating from NO levels – Use of the NO/NO_2 ratio

Two types of nitrogen oxides are generated by road traffic:

– nitrogen monoxide (NO),

– nitrogen dioxide (NO_2).

The sum of these two pollutants NO and NO_2 is commonly referred to as NO_x. NO_x gases are mainly emitted by diesel engines, they currently constitute a good tracer of car pollution, unlike CO whose emissions have greatly been reduced.

For toxicity reasons, only NO_2 has been regulated. No recommendation has been published for NO.

However, CSHPF had indicated in its opinion document published on 14 December 1998 that NO could be measured instead of NO_2. This flexibility had been granted because CSHPF felt that NO was much easier to measure due to it having much higher concentrations than NO_2.

Indeed, in 1998 no devices existed that were sufficiently sensitive and accurate to measure NO_2 levels in tunnels, nor sufficiently robust and easy to use to resist the aggressive tunnel atmospheres and satisfy maintenance and operating requirements.

In order to measure the NO_2 level from the measured NO level, CSHPF had recommended applying a NO/NO_2 ratio of 10 (i.e. a NO_2/NOX ratio of 1/11 ≈ 0.09). This ratio had been determined experimentally, for road tunnels, based on multiples measurements taken in the 90's. So an equivalent threshold had been introduced for NO of 4 ppm (5 mg/m³), that was not to be exceeded as an average value over the entire length of the structure for any 15-minute period.

After publication of circular 99-329, tunnels were progressively fitted out with devices to measure NO_x gases in order to manage fresh air ventilation facilities. The devices put in place were firstly almost exclusively NO electrochemical cells then as new technological developments came on the scene, NO_2 detectors gradually became the preferred choice.

1- 1 ppm means one part per million volume, i.e. 1 cm³ for 1 m³

2 Nitrogen oxide levels in road tunnels

2.1 Current situation

Over the last twenty years, CETU has carried out NO_x measuring campaigns in different types of tunnels. These measurements, carried out using chemiluminescence analysers, showed that the nature of NO_x pollution had significantly changed[1]. The lessons we can learn from these measurements are the following and are illustrated by Figures 1, 2, 3 and 4:

– the overall NO_2 pollution level remained stable in recent years whereas that of NO dropped significantly;

– as a result, the NO_2/NO_x ratio is now greater than 1/11 ≈ 0.09 and is often between 0.15 et 0.3. When trucks are taken out of the equation, this ratio is even higher and can at times exceed 0.5;

– the NO/NO_2 ratio is extremely variable; not only does it vary from one tunnel to another, but in a given tunnel it varies from one day to another or even from one hour to the next.

For its part, the World Road Association (PIARC) also found "*a significant increase in the primary production percentage of NO_2*" to the detriment of the NO share and integrated these new findings into its recommendations on sizing of fresh air ventilation facilities[2]. The problem of the nitrogen oxide pollution trend has also been carefully studied by other organizations, in Norway for example, with similar findings[3].

These developments are not specific to tunnels and were also shown up in numerous measurements performed in open air contexts, in zones with high levels of road pollution Figure 5. Thus, these measurements show a clear downward trend in terms of average NO_x and NO levels with a relative stagnation of NO_2 levels.

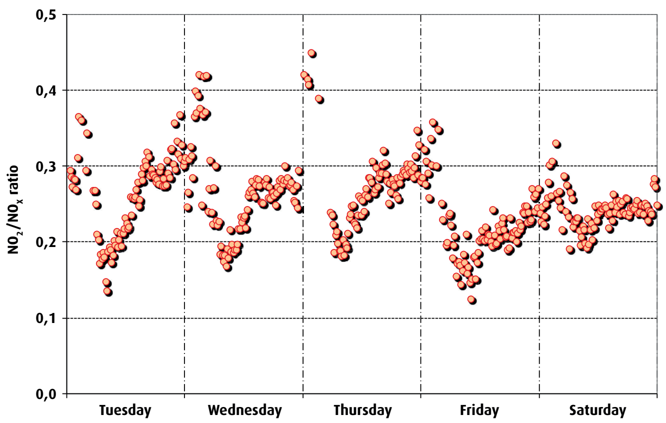

Figure 1: quarter hour trend in the NO_2/NO_x ratio in an urban tunnel [around 4000 m] - CETU measurements (2017)

1 - Observation of the ratio $[NO_2]/[NO_x]$ in road tunnels - Bernagaud & al. – Atmospheric pollution (2014)
2 - AIPCR (2012): Road tunnels - Emissions from vehicles and ventilation air needs (p12)
3 - NO_2/NO_x volume ratio in three tunnels in Norway – Norwegian Public Roads Administration (2013)

2.2 Interpretation

The levels observed in tunnels are the result of several parallel phenomena, acting in the same direction or having contrary effects, in a very variable way depending on the roads examined:

– lhe gain obtained with the fall in unit emissions imposed by EURO standards which at least partially offsets the global growth in road traffic;

– sometimes insufficient fresh air ventilation, due to the use of an inappropriate NO/NO_2 ratio resulting in NO_2 levels being underestimated;

– the strong increase in the diesel share, – that emits more NO_x than petrol – in the number of cars on the road[4];

– real traffic emissions that are much higher than the limits set by EURO standards[5].

Over the last twenty years, the reduction in the NO/NO_2 ratio can be explained by[6]:

– imperfect technological solutions when trying to simultaneously control particle emission and NO_x levels:

  – the spread of oxidation catalysts (catalytic converters) which led to a strong reduction in CO and hydrocarbon (HC) emissions, while increasing NO_2 emissions;

  – the introduction of particle filters which, depending on the technology used to regenerate them, could have led to an increase in NO_2 emissions;

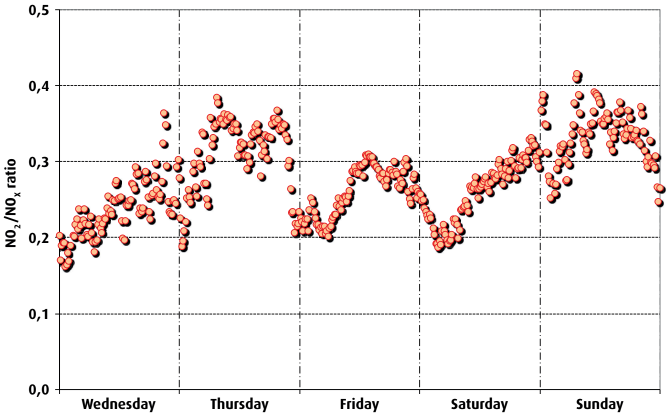

Figure 2: quarter hour trend in the NO_2/NO_x ratio in a long interurban tunnel - CETU measurements (2016)

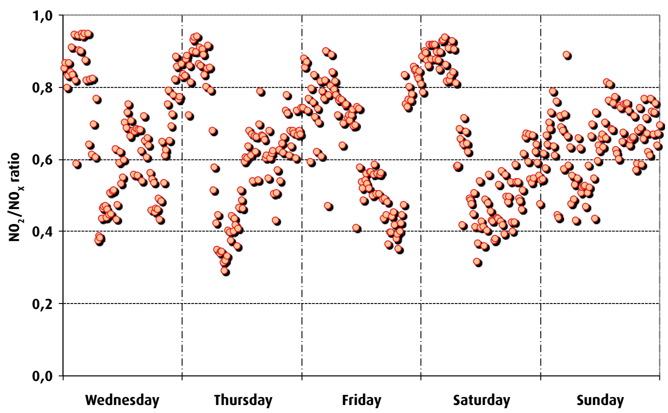

Figure 3: quarter hour trend in the NO_2/NO_x ratio in a short urban tunnel [330 m] - CETU measurements (2010)

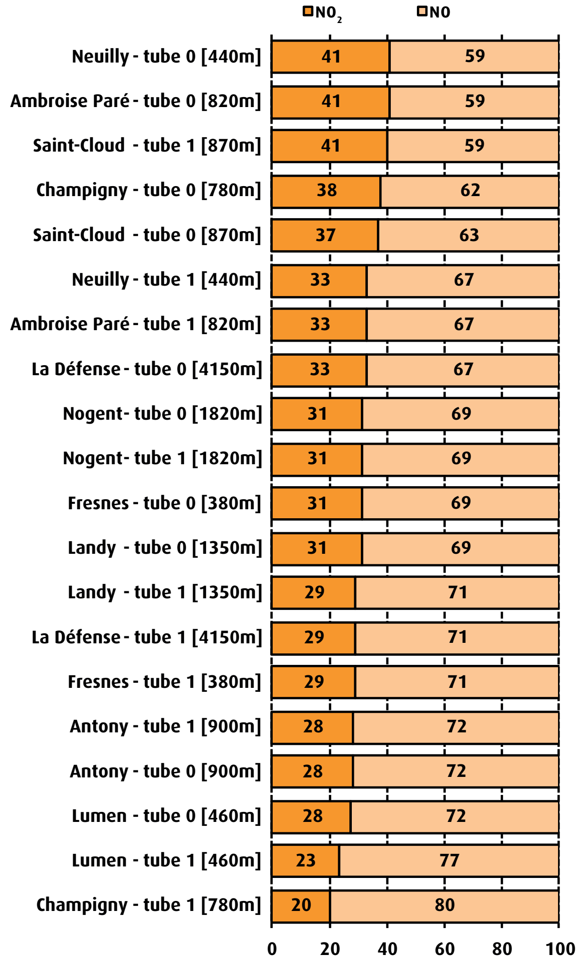

Figure 4 : distribution of the NO_2 and NO levels recorded in 2009 in a panel of 20 urban tunnels (measures taken in the passenger part of a vehicle, averaged out over several runs, with a distinction being made as to the direction of the traffic) – CERTAM-CEREMA-CETU Measurements (AIRTURIF programme)

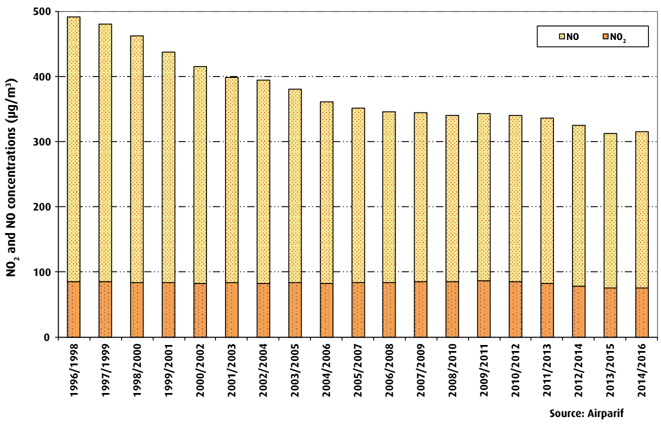

Figure 5: average trend over three years for NO and NO_2 at five measuring stations in close proximity to the traffic in the Paris region – Airparif measurements (1996-2016)

4 - "Emissions from road transport mainly (89%) come from Diesel vehicles (Diesel trucks: 41%, private diesel cars with catalytic converters 33%, light diesel utility vehicles with catalytic converters 15%)" - CITEPA / format SECTEN (2013)

5 - "The increased severity of NOx emission thresholds for diesel vehicles did not enable the real emissions of these vehicles to be reduced during usage" - ADEME (2014): Particle and NOX emissions by road vehicles

6 - AFSSET (2009): Carbon dioxide emissions from diesel vehicles, impact of post-treatment technologies on the nitrogen dioxide emissions of diesel vehicles and associated health aspects

- EURO standards that only focus on total NO_x emissions, enabling car makers to have vehicles certified with lower overall NO_x emissions but with a higher share of NO_2 emissions when compared to the previous generation of vehicles.

Current measures show that numerous parameters influence the variations in the NO_2/NO_x ratio, depending on the tunnels, the seasons or the time of the day:

- the make-up of the road traffic in particular the share of trucks, but also the proportions of diesel or petrol vehicles, the EURO class, the state of maintenance of the vehicles, etc.;
- the location of the observation point and the length of the tunnel, due to the contribution of external pollutants (ozone and NO_2) during the day. For short tunnels, a NO_2/NO_x ratio close to 0.5 was observed;
- traffic conditions (average speed, free-flowing traffic or a succession of accelerations and decelerations, engines cold or hot, etc.) and the ambient temperature.

2.3 Consequences of the trends observed

The measurements taken in recent years in tunnels show that control of NO_2 pollution by detecting NO and using the NO/NO_2 = 10 ratio (i.e. a NO_2/NO_x ratio of 1/11 ≈ 0.09) are no longer appropriate.

The excessively high 10 ratio results in NO_2 levels being underestimated. In addition, the very significant fall in NO levels makes them difficult to measure, current levels are close to the detection limits of commonly used devices, which can lead to either an underestimation or an overestimation of the NO level and ultimately that of NO_2.

Direct determination of NO_2 concentrations is now the most relevant solution and must become the norm. This is now possible due to the strong technological progress made on NO_2 sensors.

3 Nitrogen dioxide sensors for air quality management in road tunnels

Two types of materials are currently used in road tunnels to measure NO_2:

- electrochemical cells, based on the principle of adsorption of the pollutant being measured, causing the formation of an electric current in an electrolyte;
- optical type devices, using NO_2 absorption properties for specific wavelengths in the near ultraviolet.

3.1 Electrochemical cells

3.1.1 Background

Electrochemical cells have been widely installed in tunnels for the last thirty years to control CO levels, due to the low cost of installation and maintenance, as well as their robustness. Furthermore, the regulatory threshold for this pollutant is compatible with the measuring ranges of market devices which are therefore perfectly suitable for CO detection in road tunnels.

When circular 99-329 had required that NO_2 levels be measured in underground structures, the detection devices installed were of the electrochemical type. Only NO cells had been used, due to the preponderance of NO in road tunnels – the NO levels were then 10 times greater than NO_2 levels – and the fact that NO_2 electrochemical cells were not suited to the low concentrations of this pollutant.

Since 1999, the intrinsic performance of NO_2 electrochemical cells has progressed significantly (better immunity to gas interferents, greater sensitivity) and the best of these devices can obtain a "measuring quality" equivalent to that of NO electrochemical cells. At the same time, the fall in NO levels has made measuring this pollutant less relevant. Finally, determining NO_2 levels can no longer be extrapolated from NO levels using the NO/NO_2 ratio the value of which now fluctuates greatly.

Now in light of:

- **the recent technological progress on NO_2 electrochemical cells,**
- **the significant falls in NO levels (but not in NO_2) observed in recent years in tunnels,**
- **fluctuating NO/NO_2 ratios,**

it is recommended to cease using NO electrochemical cells and instead opt for NO_2 electrochemical cells when the electrochemical cell detection technology can be used (see 4.3), whether this be a new installation or a renewal.

3.1.2 Advantages and disadvantages

Originally designed for industrial applications, the measuring ranges of electrochemical cells are usually greater than the pollutant concentration ranges present in the tunnel. In addition, there is a detection limit under which it is no longer possible to measure and this restricts the choice of models that can be used in road tunnels.

If we compare them with the analysers widely used by air quality monitoring networks, electrochemical cells are relatively simple instruments, suitable for the severe environmental conditions and operating constraints of road tunnels. However they have inferior measuring efficiency and being robust does not dispense them from requiring stringent maintenance (drifts and limited life times).

The technical specifications of these devices must therefore be very carefully analysed keeping in mind that they were drawn up in a laboratory environment and that their performances are likely to degrade significantly in the severe use conditions specific to road tunnels.

Sensors to be used with caution:

« These sensors are influenced by temperature and hygrometry. Low temperatures (from 0°C) can inhibit the efficiency of some sensors, whereas high temperatures (above 30°C) can generate faults (even when temperature compensation is applied). Low hygrometry dries out the cell, making it inefficient. This phenomenon is reversible. A pressure level lower than the pressure present at the time of calibration influences the response, with an underestimate of the concentration present by between a few percent to some tens of percents, depending on the pressure difference. The life time of the sensors is from a few months to 24 months, depending on the use context, in the case of optimal maintenance. » [1]

« Fume gases most often contain solid particles. They must be pre-filtered. Otherwise, the measurements risk being wrong very rapidly, due to the membranes and capillary elements becoming clogged up, to the extent even of damaging the sensors. »[2]

3.1.3 NO_2 electrochemical cells

NO_2 measurement in tunnels comes up against the metrological limits of NO_2 electrochemical detectors. So, in the best cases, with stated values of 0.2 to 0.3 ppm, the detection limit remains very close to the regulatory threshold of 0.4 ppm, whereas it would be best that this detection limit remain less than 0.05 ppm.

The levels of pollutants we wish to observe are at once very low when compared with the lowest measuring ranges of the best models on the market (some percents of the measuring range), and very often close to the minimum detection threshold. Finally, numerous zero drifts (long term, damp, temperature, etc.) can rapidly lead to very strong uncertainties as to the concentrations being measured. NO_2 electrochemical cells can only be used in tunnels by taking stringent precautions and without losing sight of their metrological limits.

Several manufacturers on the French market (Drager, Pillard, Sick...) offer NO_2 electrochemical cells. For all manufacturers, the measuring principle is the same, each developing their own technical solutions to best meet the different needs of road tunnel operators.

Figure 6: NO_2 electrochemical cells
(1) DRAGER Polytron 7000
(2) FIVES PILLARD Nocostop

In line with all the technological progress already achieved in these products, some manufacturers are currently developing new models with improved efficiency and sensitivity. However how appropriate they would be to detection in a tunnel context remains to be seen.

3.2 Optical type sensors

Optical type NO_2 sensors have recently (2006-2007) arrived on the tunnel equipment market. Three manufacturers currently offer this type of device in France: CODEL, SICK and TUNNEL SENSORS.

In general, the low requirement levels in terms of specifications for NO_2 measurement in road tunnels in France have not enabled optical type NO_2 sensors to gain a hold on the French market. To date, only some twenty devices have been installed, all of the CODEL brand. There is less feedback therefore for this type of material than for electrochemical cells.

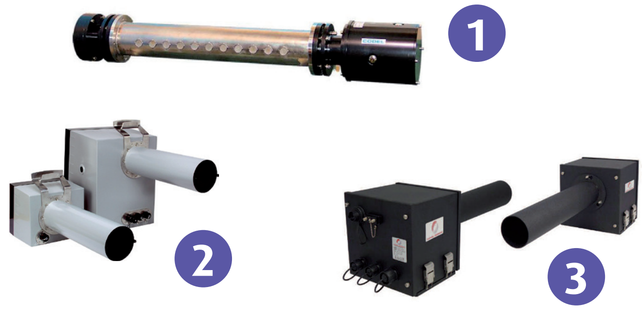

Figure 7: Optical type NO_2 sensors
(1) CODEL TunnelTech 205
(2) SICK Vicotec 320
(3) Tunnel Sensors Viconox

Two different technologies are used:

- measurement of the absorption by NO_2 of a monochromatic light beam emitted by a blue LED, with two variants:
  - for CODEL, the gases are measured in a 1-metre long diffusion cell;
  - for TUNNEL SENSORS the measurement is recorded directly in the tunnel atmosphere using a sender unit and a separate reflector placed ten metres apart;
- measurement by Differential Optical Absorption Spectroscopy (DOAS) in the near ultraviolet spectrum for SICK.

When compared with electrochemical cells, these materials offer much better metrological specifications (detection limit, uncertainties, drifts...). In addition, they have an auto-calibration function which ensures much better stability and makes them immune to drifts. Less maintenance is also required (1 year is recommended).

Thus optical sensors are from the outset better suited than electrochemical cells for NO_2 measurement in road tunnels.

3.3 Main technical specifications for NO_2 measurement in road tunnels

In order to have a tool that can reliably indicate changes in NO_2 concentrations in road tunnels in operation, devices must be selected that satisfy the following criteria:

- measuring range, detection limit, sensitivity, response time, insensitivity to interferents, suitability for the concentrations and change speeds of the phenomena to be observed;
- control of drifts over time, either by means of an auto-calibration system, or by drifts that are much less than the values to be measured;

1 - INERIS Study Report (2009) "Principles and techniques for gas detection"

2 - www.euro-index.be : "Measuring emissions by means of electrochemical gas sensors" by Dr. Karl-Heinz Pettinger (Compur Monitors Sensor Technology GmbH): "Emissionsmessung mit elektrochemischen Gassensoren"

– conditions, frequency and cost of maintenance and calibration compatible with operating constraints;

– sufficiently long lifetime for the main elements.

These criteria must appear in the form of precise technical specifications. The table below provides standard recommendations that satisfy NO_2 measurement requirements for road tunnels.

Optical type sensors satisfy these requirements and this is not yet entirely the case for electrochemical cells.

Minimum characteristics required for a NO_2 sensor in road tunnels:

Measuring range	0 to 2 ppm (to be possibly adapted for very specific tunnel situations)
Detection limit	≤ 0.05 ppm (50 ppb)
Sensitivity	≤ 0.05 ppm (50 ppb)
Response time	300 seconds maximum
Zero reproducibility	≤ ± 0.05 ppm (50 ppb)
Long-term drift	≤ ± 0.05 ppm (50 ppb) / month
Influence of humidity on the zero	≤ ± 0.005 ppm (5 ppb) / %RH
Influence of the temperature on the zero	≤ ± 0.005 ppm (5 ppb) / °C
Intervals between two calibrations or between two maintenance sessions	Desirable: 12 months Minimum: 3 months

4 Choice of NO_2 measurement device for road tunnels

4.1 Technical criteria

The metrological properties of optical type sensors are superior to those of electrochemical cells, but they are above all better suited to the stated need (detection limits, measuring scales, drifts...) Furthermore, these devices are better suited to the environmental and operating constraints (maintenance) observed in road tunnels.

From a purely technical point of view, installing optical type devices should therefore be systematically recommended.

4.2 Cost criteria

Despite having inferior technical properties, electrochemical cells have been installed in most French road tunnels to the detriment of optical type sensors due to the very favourable purchase cost. This financial choice does not take into consideration maintenance costs and eludes the negative impact of downgraded metrological performance and its consequences on operating costs (risks of over-use of fresh air ventilation).

4.2.1 Investment cost

On the basis of recent calls for tenders, it is seen that the purchase cost of optical type sensors remains relatively high and depends on the model. The NO_2 optical sensor can sometimes be coupled with an visibility monitor or CO sensor which also has an impact on the price.

For information, the supply and installation cost observed in recent calls for tenders is around €15 K to €20 K excluding tax, compared to €1 K to €2 K for NO_2 electrochemical cells

Only the highest quality electrochemical cells – but which are not the least expensive – have technical specifications that come close to those given in paragraph 3.3. Some manufacturers offer such products in their range, better suited to road tunnels.

4.2.2 Maintenance costs

These are the costs of replacing worn parts and the cost of testing and calibrating the devices, to which must be added all the costs linked to tunnel intervention constraints.

The feedback from CO electrochemical cells shows that these devices are very reliable in tunnels, with a low cost both for consumables (cells or filter) and for the intervention.

This observation can be partially transposed to NO_2 electrochemical cells, the unit cost of consumables being similar to that of CO sensors. However:

– intervention frequencies must be quarterly rather than annual to manage drift risks;

– the cells must be changed more often due to the usage at the limits of this type of device's capabilities;

– calibration interventions must be very carefully performed by perfectly trained technicians, because the zero setting on these sensors is extremely delicate and sensitive, and does not tolerate the least discrepancy[1].

Annual maintenance[2] is recommended by manufacturers of optical type devices, but the content of this maintenance is very variable from one manufacturer to another depending on the technical level required.

In the current state of feedback which mainly concerns CODEL devices, this device requires an annual inspection consisting of:

– examining the condition of the light source (blue LED), to be changed every 5 to 10 years;

1 - The settings on NO_2 electrochemical cells consists in calibrating the zero and the sensitivity by using two different bottles of titrated gas. In the specific road tunnel environment, an inspection at least once a quarter is recommended.

2 - To be adapted depending on the clogging speed of the structure.

– careful cleaning the inlets (sintered metal) to the measuring chamber;

– possible calibration of the device with a titrated gas.

In general, the technical level required for maintenance of NO_2 sensors, whether they be of the optical or electrochemical type, require an intervention from a qualified technician, typically a specialist provider whose intervention budget must be examined before investing. The cost of maintenance must be taken into account when deciding which sensor to buy.

4.2.3 Operating cost

Fresh air ventilation can represent a large share of the operating budget in some tunnels. How much ventilation is required is likely to be very directly impacted by the quality of NO_2 measurement.

For this pollutant, since the detection limit of electrochemical cells is very close to the regulatory value to be complied with, drifts by these devices – in particular zero drift – mean there is a serious risk of overestimating NO_2 levels resulting in chronic over-ventilation of the tunnel, i.e. excess power consumption and the ensuing extra operating costs.

Optical NO_2 measurement devices which have a better detection limit and have potentially fewer measuring drifts, enable the risks of over-ventilation of the tunnel to be significantly mitigated

4.2.4 Conclusion on costs

It must be remembered that even if the investment cost of optical sensors is significantly higher, maintenance costs are lower with however significant differences between manufacturers.

The final choice of NO_2 measurement material must not neglect the possible impacts on tunnel operating costs nor on the function expected, i.e. compliance with regulations on air quality in road tunnels.

4.3 Choice of sensor

Despite clearly inferior performances, the use of electrochemical cells cannot be ruled out. They will be reserved for situations in which the risk of NO_2 exposure being in excess of regulatory levels is very small.

When high levels of NO_2 are present, the choice must be for optical type sensors. The main reasons that may lead to this high level of sensitivity are:

– a significant emission density (intense traffic, traffic congestion, significant declivity, strong proportion of trucks),

– low air renewal levels (two-way tunnel, traffic congestion),

– long period of exposure by users (very long tunnel, traffic congestion).

e.g.

– In an urban tunnel of average length (from around 1 km), with dense traffic (several tens of thousands of vehicles per day), the installation of optical sensors is essential. This is justified by the high level of exposure as a result of the potentially high NO_2 levels which may be further aggravated during operating incidents (abnormal congestion level due to a vehicle broken down or a lane being closed) even if the tunnel crossing duration remains in general moderate;

– in a long tunnel (several kilometres), the installation of optical sensors is essential, even if the traffic is moderate (less than 10,000 vehicles per day) and the tunnel is not an urban tunnel. In such a case, the high exposure risk is proven.

– conversely, in a short tunnel, even when it is urban with substantial traffic, or in a tunnel of average length that is not an urban tunnel with moderate traffic levels, and on condition these are one-way tunnels, simple electrochemical cells are sufficient.

Furthermore, the choice must also take account of the possibilities of intervention in the tunnel for maintenance operations. If there is a desire to reduce the number of interventions, then optical type devices must be preferred.

5 Installation and use principles

Given that regulations concern average spatial values and that pollution levels vary at different points in the tunnel, it is essential to install several measuring points in a given tunnel tube. It is also a means of providing a certain redundancy if a device fails.

The principles given below must be adapted based on the specific geometric configurations of each tunnel (presence of ramps for example) and the architecture of the ventilation system (longitudinal or transversal, number of blocks if any, etc.).

Experience shows that it is difficult to manage two types of different sensors in the same tunnel, both from the point of view of interpreting readings and maintenance. So mixing electrochemical cells and optical sensors in the same tunnel should be avoided.

5.1 Case of electrochemical type sensors

Since the information produced by this type of device is subject to relatively significant uncertainties, it is important to have a sufficiently large number of devices to fully cover each tube and to not be excessively dependent on a sensor if one were to fail. A commonly agreed maximum distance between two successive measuring points is around 400 metres (usually at the level of the visibility monitors to rationalise cabling).

The spatial average used to steer ventilation will be calculated by working out the arithmetic average, over a sliding 15-minute period, of the values given by each sensor and eliminating any abnormal values.

5.2 Case of optical type sensors

Given the specific nature of the tunnels for which optical sensors are required (risk of high exposure for users in case of recurring congestion, long or two-way tunnels), it is best to have at least two devices per tube. Ideally, a distance between measuring points of around 400 metres should be aimed for, as is the case for electrochemical sensors, so as to have a representative longitudinal profile of NO_2 concentrations. However, given the price of optical type sensors, a slightly higher distance between devices could be accepted in order to optimise the number of sensors.

When two sensors are installed in a tube they will be placed one third of the distance in at each end. More generally, all sensors will be at equal distances along the tube.

In general, the value used to steer ventilation will be the arithmetic average of all the values given by each sensor with any abnormal values being eliminated. However, some special tunnel configurations may require changes to this calculation principle (e.g., weighing of readings according to the longitudinal speed profile of the air flow recorded by anemometers). As for electrochemical sensors, the arithmetic average will be calculated over a sliding 15-minute period.

Remote measuring in technical rooms:

Great caution must be exercised if the operator wishes to install the electrochemical cells in a technical room (remote measuring). This solution requires an air flow system that risks causing pressure fluctuations on the membranes of the electrochemical cells that could thus be the cause of other sources of error on the measurements. It is important to ensure that the volume of air is applied to the cells without interfering with other devices (visibility monitors for example).

CETU considers that it is best to avoid this type of installation and to prefer on-site operation, with sensors being installed in the part of the tunnel having the traffic.

For optical type sensors, CODEL proposes a remote measuring solution with the TunnelTech402 model (and its variants) integrating an optical sensor, a visibility monitor and a CO electrochemical cell all in one measurement cabinet.

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