POLLUTION
PAR LE DIOXYDE D'AZOTE
DANS LES TUNNELS ROUTIERS

POLLUTION
BY NITROGEN DIOXIDE
IN ROAD TUNNELS

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Key Words

Pollution, Tunnel, Ventilation
Nitrogen oxides, Health
Traffic, control

Nomenclature

CO	Carbon monoxide
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NOX	Total nitrogen oxides
WHO	World Health Organisation
EP	Early phase for reaction of people exhibiting an allergic asthma and exposed to stimuli
LP	Late phase for reaction of people exhibiting an allergic asthma and exposed to stimuli
PM_{10}	Particulate matter which passes through a size selective inlet with a 50% efficiency cut off at 10 µm aerodynamic diameter
$PM_{2.5}$	Particulate matter which passes trough a size selective inlet with a 50% efficiency cut off at 2.5 µm aerodynamic diameter
ppm	Parts per million (1 $cm^3/1m^3$)
ppb	Parts per billion (1 $mm^3/1m^3$)

Guide value	Aim of quality level to be reached for human health
Threshold limit value	Level fixed on the basis of scientific knowledge with the aim of avoiding, preventing or reducing harmful effects on human health and/or the environment as a whole, to be attained within a given period and not to be exceeded once attained
Percentile 98	Hourly mean respected 98% of time
Percentile 50	Hourly mean respected 50% of time

Characteristics

Element	**Specific mass**	**Equivalent for 1ppm**
Carbon monoxide	1,150 g/m^3	1,150 µg/m^3
Nitrogen monoxide	1,230 g/m^3	1,230 µg/m^3
Nitrogen dioxide	1,880 g/m^3	1,880 µg/m^3

I. INTRODUCTION

Yves DARPAS (France)

Road traffic is undoubtedly an important source of environmental nuisance in our cities and densely populated areas. Despite all efforts and recommendations to try to control and even reduce traffic, it may be expected to increase for the next few decades. A solution to this problem is to put the traffic underground, meaning that more road tunnels need to be built. Some of these tunnels could ultimately be interconnected, creating underground networks, the complexity of which, from the ventilation point of view, should not be underestimated.

If tunnels are the solution to traffic management, their ventilation should be operated in such a way as to provide conditions of comfort and safety for the vehicle users. But, ventilation consumes energy, the cost of which for long and complex tunnels may be substantial.

The tunnel designer then has two problems :

- To design and size the ventilation system
- To establish the principles of ventilation control.

Ventilation systems to date are sized to dilute the CO to acceptable levels and to reduce opacity due to soot emission by Diesel engines of cars or trucks. Air flows needed for CO dilution were also supposed to guarantee the dilution of other pollutants, and in particular nitrogen oxides, without the need for further consideration. It can be underlined that no criteria existed concerning the sizing of ventilation systems nor the threshold levels not to be exceeded for nitrogen oxides during operation.

Regulations issued by numerous countries on pollutant emissions by vehicles have resulted in a significant decrease of CO emission, especially for light vehicles with petrol engines (rates of 1400 l/h in 1975 have become 180 l/h today).

Awareness of the problem raised by nitrogen oxides in urban environment which came up following pollution phenomena (e.g. in London in 1952) has led to studies being carried out on the noxiousness of NO_2, (NO by itself is not considered a harmful pollutant at commonly encountered levels) which is a matter of deep concern, and to the measurement of existing levels in tunnels.

The complexity of the problem arises from the oxidization of NO into NO_2, which depends on external climatic conditions (temperature, sunlight, ozone level, humidity), as well as from the lack of industrial equipment capable of measuring NO_2 levels within the required range.

For the urban environment recommendations have been issued by the World Health Organisation:

- WHO 1987 — 400 µg/m^3 (0.2 ppm) during one hour
  150 µg/m^3 (0.08 ppm) on a average during 24 hours
- WHO 1996 — 200 µg/m^3 (0.1 ppm) during one hour
  40 µg/m^3 (0.02 ppm) on a average during one year,

and by the European Community: (Counsel Directive n° 1999/30/CE of 22/04/99)

- Hourly threshold value for human health protection : 200 µg/m^3 (not to be exceeded more than 18 times in a year)
- yearly threshold value for human health protection : 40 µg/m^3.

The Directive foresees possible excess margins until January 2010 ; it fixes an alert threshold value of 400 µg/m^3 for 3 hours in succession.

In France the ordinance 98-360 of 6 May 1998 fixed the following targets:

- quality value target:
  - Percentile 50: 50 µg/m^3
  - Percentile 98: 135 µg/m^3
- Alert threshold value: 400 µg/m^3 in an hourly mean
- Limit value: percentile 98: 200 µg/m^3

These values correspond to long exposure times and are very far from being acceptable in tunnels due to the consequences in sizing ventilation systems.

The definition therefore remains outstanding, of design values for ventilation systems to remain within technical and financial feasibility limits, and of threshold levels to be respected during operation that are acceptable for human health and compatible with reasonable operating costs.

Also, it should be underlined that studies on NO_2 noxiousness show totally different sensitivities between healthy people and people having asthmatic predisposition. The design criteria appear all the more difficult to be established.

Classically most ventilation control systems are based on CO measurements in tunnel.

Due to the decrease of CO emissions, these measurements are no longer sufficient to control the ventilation.

NO_2 cannot currently be measured reliably by industrial devices and it is therefore unsatisfactory to use these measurements as a base for ventilation air flows. There are many laboratory devices enabling to measure NO_2 precisely. However, the complexity, the cost and environment needed for this type of device do not allow to envisage their systematic use in the ventilation control system.

In addition, the issue of the information to be delivered to sensitive people can also be raised.

Taking this context into account, the aim of this report is to:

- review studies about NO_2 noxiousness,
- collate NO_X and NO_2 levels measured in tunnel, as well as the NO_2/NO_X ratios,
- indicate how to evaluate NO_2 flows emitted by vehicles in tunnel,
- give alternative means for ventilation control avoiding the control based on pollution measurements.
- make recommendations on ventilation flows design taking account of NO_2 levels, and on ventilation regulation and pollution control in tunnel.

II. EFFECTS OF NO_2 ON HEALTH

Mickael BJORNBACK (Sweden)

Background

Nitrogen oxide (NO) and nitrogen dioxide (NO_2) are pollutants resulting from the combustion of fossil fuels. Emissions from vehicle engines and power plants are the main external sources in urban areas.

Most of the nitrogen oxides consist of NO but this is oxidised into NO_2 in the presence of ozone (O_3).

The NO_2 levels in towns vary according to season, temperature and time of day. In areas with intense traffic, one-hour peak levels can reach from 250 - 300 µg/m^3 (Göteborg and Stockholm, Sweden) up to 400 - 700 µg/m^3 in cities like London, Los Angeles and Mexico City. In heavily trafficked road tunnels in France and Sweden, NO_2 levels up to 1,500 µg/m^3 have been monitored.

Results of studies where people have been exposed to NO_2 have demonstrated that this gas can affect healthy people as well as sensitive people. But sensitivity levels are very different. For healthy people effects have been noted for levels higher than 4,000 µg/m^3 ; no effects have been observed for levels under 2000 µg/m^3. For sensitive people, effects have been observed for concentrations exceeding 190 µg/m^3. Noting this difference, it is important to appreciate the effects of NO_2 on sensitive people.

Health Effects of Short-term Exposure to NO_2 on Sensitive People

Generalities

The people most sensitive to NO_2 exposure are those suffering from asthma. Asthma is a global health problem and its prevalence is increasing world-wide among children and adults.

In Sweden the extent of asthma is now about 5 - 9 % among school children and 4 - 9 % in the adult population. Studies have shown a considerable increase compared with the prevalence reported in studies some decades ago.

Effects of NO_2 on sensitive people raise many questions: effects of exposure following time and level, cumulative effects.

An interesting contribution has been provided by Sweden where recent studies have been implemented.

At Karolinska Institute in Stockholm, Sweden, five controlled studies on humans have been carried out to investigate the effects of NO_2 exposure and non-specific (histamine) or specific (allergen) stimuli on respiratory tract response in persons with mild allergic asthma. Stimulation by allergen challenge is known to induce early, late or both asthmatic reactions in sensitive subjects.

In four of the studies the exposure took place in the environmental chamber at Huddinge Hospital in Stockholm. In one of the studies the subjects were exposed to polluted air in a heavily trafficked road tunnel in the centre of Stockholm.

In all these studies, the effect on lung function has been measured by the variation of the forced expiratory volume in one second.

Tests in an Environmental Chamber

The findings on exposure to NO_2 (about 500 µg/m^3 during 30 minutes) from the four studies in the environmental chamber show that:

- there is a significant effect of a single exposure to NO_2 and histamine (non-specific stimulus) on the respiratory response.
- exposure to NO_2 increases the respiratory response to allergens (specific stimulus).

- exposure to NO_2 followed by a low dose of allergen causes an increase in the early asthmatic reaction. The allergen dose was so low that it could not by itself cause any change in the lung function measured.
- exposure to NO_2 causes an increase in the respiratory response during the late phase after an allergic stimulation with a high dose of allergen, but not after a low dose.
- there is a small but significant intensification of both the early and late phase asthmatic responses to daily exposure to NO_2 and low doses of allergen.
- there is an influence on lung function after exposure to NO_2 and a second stimulus, either histamine or allergen.
- there are small changes on blood cells and mediators reflecting inflammatory reactions of the respiratory tract. Interpretation of these small changes is difficult.

The studies have shown that a short exposure to an ambient concentration of NO_2 enhances respiratory tract responses to histamine and allergens. In these studies histamine reflects exposure to non-specific stimuli like cold air, exercise, etc.

Tests Carried out

Twenty volunteers with allergic asthma were exposed for 30 minutes in a Stockholm city road tunnel. The subjects were exposed on two separate occasions at least four weeks apart during December 1996 to February 1997.

The tunnel has a length of about 1,500 m and is used by about 35,000 vehicles per day. The car was placed 1,000 m from the entrance, in the northbound tunnel tube.

The median NO_2 level during exposure was 313 µg/m^3 (range 203-462). Median PM_{10} and $PM_{2.5}$ were 170 (103-613) and 95 (61-218) µg/m^3.

Four hours after the exposure, the persons inhaled a low dose of allergen. These tests highlighted the following points:

- during the stay in the tunnel the effects related to the airways, such as irritation with increased tendency to cough, breathing discomfort and chest tightness, were small or moderate. The lung function measured as forced expiratory volume in one second was not influenced during the stay in the tunnel, and there was no clear association between levels of NO_2 or $PM_{2,5}$ and lung function during the following morning hours. However, it must be taken into account that all subjects had a bronchial asthma of a mild type with normal lung function.

- the asthmatic reaction induced by allergen inhalation four hours after the stay in the tunnel was significantly enhanced, measured both as fall in lung function immediately after stimulation (early phase reaction), and an increase in symptoms of asthma during the following evening and night during the late phase. The enhancement of the asthmatic reaction during the early phase was related both to high NO_2 (> 300 µg/m^3) and $PM_{2.5}$ (> 100 µg/m^3) levels.

  It is thus reasonable to assume that exposure to air pollutants during half an hour in a road tunnel can increase the bronchial response to allergens several hours after the exposure in people with allergic asthma.

Discussion

In conclusion, short-term exposure to air polluted at a median level of 0.17ppm in a road tunnel during rush hours enhanced the asthmatic response to an allergen inhaled several hours later, although lung function during the exposure was not affected. The adverse effect was related to exposure levels of NO_2 and to some extent to particles, without being able to separate their effects.

Exposure time in tunnels varies normally from a couple of minutes up to 20 - 30 minutes in longer tunnels, over 3-4 km, during rush hour with congested traffic.

It is, however, possible that the exposure during the trips to and from the test site of the subjects in the tunnel exposure study above, could have influenced the results.

At present, studies on cumulative effects of NO_2 are not available and should be carried out to clear this important point. It would also be advisable to conduct “blind” tests in an environmental chamber to avoid subjective bias.

References

[4] Arbetslivsintitutet (The National Institute for Working Life), Luftföroreningar i fordon – Halter och atgärder (Air Pollutions i vehicles – Levels and measures). In Swedish. 1196:18.

[5] Vanderstaeten PF et al. Tunnel air quality – The carbon balance as an alternative to evaluate traffic emissions. Staub-Reinhaltung der Luft, 1991.

III. NO_X MEASUREMENTS IN TUNNELS

Jean-Pierre MARSAULT (France)

NO_X measuring methods

The first difficulty encountered in taking into account nitrogen oxides is explained by the fact that vehicle emissions are expressed in NO_X ($NO + NO_2$) while the recommendations on acceptable levels (WHO or European Directives) only consider NO_2.

Nitrogen oxides are unstable pollutants. The most reliable real time measurement technique that enables a distinction to be made between NO and NO_2 involves a highly elaborated technology based on chemicaluminescence. The technique has been used for a long time in laboratory conditions, and the principle has led to the development of high performance detectors which can be used on site, albeit requiring specific monitoring and maintenance operations.

NO_2, which accounts for a very low percentage (< 10%) of NO_X in tunnel, is obtained by a differential measuring technique (NO_x - NO). This necessitates highly reliable measuring equipment, as well as frequent and delicate checks which tunnel operators find difficult to perform.

The use of other, less expensive and easily maintained detectors, such as those based on special electrochemical cells, has been envisaged. However, if these detectors can be considered acceptable for measuring NO concentration in tunnel, for NO_2 measurements they lack selectivity. The continuous recording of NO levels can be envisaged, so as to deduce NO_2 concentration levels by applying a coefficient determined from NO_2/NO_X ratios measured in tunnel.

NO_X Measurement Performance in Tunnels

A great number of studies give NO_X measurements recorded in tunnels. But to be valid, these measurements should be recent, well targeted and comprehensive.

The available reports or data from the following studies were analysed, but only the first three categories led to valuable results in accord with the selected approach:

1) "NO_X measurements in three Swedish road tunnels, 1993-1996" - Swedish National Road Administration Report.
   Measurement results from SÖDERLEDSTUNNEL
   TINGSTADTSTUNNEL
   GNISTÄNGSTUNNEL
2) Two studies conducted by the *Laboratoire Central de la Préfecture de Police* on tunnels in Paris, in 1997: SAINT-CLOUD TUNNEL
   AMBROISE PARE TUNNEL
3) Two studies conducted by the CETU: MONT-BLANC TUNNEL in 1996
   LA CROIX-ROUSSE TUNNEL in 1997

4) A study conducted in Brussels tunnels in 1988: REYERS TUNNEL
LÉOPOLD II TUNNEL

These results are somewhat old and some basic data are missing.

5) A study conducted in a ZURICH tunnel in 1994: GUBRIST-ZURICH TUNNEL

The results are given in NO_X with no distinction between NO and NO_2.

6) A study conducted in a MADRID tunnel in 1997:
PASO SUBTERRANEO PLAZA DE CASTILLA
The results are given in NO_2 and NO_X but over a limited period of time, and there are not enough data available with regard to the site and measurement conditions.

Summary of the NO_X Measurement in Tunnels

Comparison between the results of the various measurements performed in tunnels is difficult since the experimental conditions and presentation of the results often differ significantly from one study to another. Nevertheless a selection of the most recent and explicit results enabled a table to be drawn up, giving the NO_2 levels recorded in tunnels depending upon the type of tunnel.

Presentation:

In the table below the concentration levels are given in ppb (10^{-3} ppm). The maximum levels are given in mean values over 10-15 minutes, during a number of hours (shown in parenthesis).

Average concentrations correspond to mean daily values recorded during working days or during the whole measurement period.

NO_2 concentration levels measured in a number of tunnels

Experimental Sites	Maximum ppb	Average Concentration ppb
SÖDERLEDSTUNNEL (S)		
1st test 1993	273	103
2nd test 1996	256	80
TINGSTADSTUNNEL (S)	413	52
GNISTANGSTUNNEL (S)	708	47
AMBROISE PARÉ TUNNEL (F)	181 (153)	63
SAINT-CLOUD TUNNEL (F)	452 (365)	81
CROIX-ROUSSE TUNNEL (F)	590 (562)	290
MONT-BLANC TUNNEL (F/I)	1280 (1070)	500

Comments

This table shows significant differences between the concentration levels – both maximum and average – recorded in the various test tunnels. This can be explained by their specific features: location, length, number of tubes, vehicle type and traffic conditions, ventilation, etc.

The highest levels for an urban tunnel were recorded in the La Croix-Rousse Tunnel which is a two-way tunnel, 1,750 m long and where traffic is heavy between 6 am and 10 pm. Ventilation is servo-controlled by the CO concentration recordings, the level being maintained below about 40 ppm.

The Mont-Blanc Tunnel shows much higher levels since the NO_2 daily average concentration level is about 500 ppb (estimated value). This two-way tunnel is 11.6 km long, with dense international traffic including a high percentage of very heavy goods vehicles, distributed practically over the whole day. The ventilation system is often switched on since its control is based on opacity recordings.

Illustration

A number of charts showing the evolution of daily traffic and pollution in several of the above-mentioned tunnels are appended.

NO_2/NO_X Ratios Measured in Tunnels

We have already discussed the advantage of determining the NO_2/NO_X ratio (expressed in terms of volume), with a view to designing tunnel ventilation systems on the basis of vehicle emissions (in NO_X) and allowable levels (in NO_2).

The notion of average values for this ratio should be clearly defined since it can vary significantly with the reference period.

Whilst no laws have yet been determined, it has been observed that this ratio may vary with the tunnel length, type of ventilation system and average NO_X concentration level.

An analysis of the results recorded over a long period in the La Croix-Rousse Tunnel in 1997 allow the following values to be retained for the middle of the tunnel:

- **daily average values** recorded between 6 am and 10 pm (for weekdays from Monday to Friday) are between **7.3 and 9.2%** (in volume).
- **daily maximum values** recorded over the same time periods range between **8.7 and 9.6%**, but they can reach 19% when incorporating night time with low traffic and low pollutant emission levels (i.e. from 0 am to 12 pm).

In conclusion

A 10 % NO_2/NO_X ratio can be considered an upper value, and consequently a safe value for the design of ventilation systems according to NO_X emission levels. However this ratio is no longer meaningful when exiting the tunnel, where it becomes much higher due to the background pollution. It is also more important when NO_2 emission levels are low (see measures in the Ambroise Paré Tunnel).

References

[8] Mesures de NO_x, NO, NO_2 et CO au tunnel de la Croix-Rousse à Lyon - Rapport CETU (1997).

[9] Étude de la pollution du tunnel sous le Mont-Blanc - Rapport CETU (1997).

IV. VENTILATION CONTROL

Eddy JACQUES (Belgium)

Problem Statement

There are two principal aims of a well designed ventilation control system :

- in routine operations, to provide fresh air at a rate that is consistent both with the comfort of the tunnel users, and with economical operations i.e. at the minimum rate for an acceptable level of air quality;
- in exceptional circumstances or emergency cases (equipment breakdowns, accidents or fire in the tunnel), the ventilation system must be capable of responding quickly and reliably to each specific ventilation demand.

Where routine ventilation is concerned, an optimal air flow rate is one that satisfies two conflicting requirements; the rate of ventilation must be sufficient to dilute the pollutants generated by the vehicles, while at the same time the air flow quantities should be as small as possible in order to reduce the energy consumption at the fans and therefore reduce running costs.

The constant adjustment of air flow to cope with the needs is a difficult problem especially in the case of long and complex tunnels where the control of the ventilating airflows can be difficult to maintain.

Emergency ventilation, on the other hand, needs fast and well targeted interventions, short response times, and a well defined sequence of all the operations. The objectives of incident ventilation are therefore quite different from those of normal ventilation, and economic considerations are no longer the principal concern.

The aim of the following text is to review possible solutions for ventilation control.

Control based on Pollutant Concentration

So far, almost all ventilation control systems are driven by the measurement of pollutant concentrations, of which the CO-concentration, and for long tunnels with heavy traffic the opacity, are the only ones to be used as control variables.

This system encounters the following difficulties:

(i) *Measurement reliability*
For some pollutants such as for example NO_2 there is a real difficulty in measuring their concentration due to the lack of reliable industrial equipment.

(ii) *Measurement device location*

Measurements are made in several points in tunnel, and the use of these measurements raises two major problems; some measurements are not always representative of the mean level of pollutants and in the case of complex tunnels control must be global and cannot be set out by section without running the risk of transferring pollutants from one section of the tunnel to another, and of control instability.

(iii) *Response time*

In the case of variable traffic flow rates, the tunnel volume introduces an inertia that causes a delay in measuring the new pollution levels. This phenomenon leads to delayed responses that do not allow economical operation.

(iv) *Ventilation stability*

Pollution varies constantly with time and space. The control system should produce stable responses to avoid mechanical fatigue of the ventilation equipment and to avoid the frequent starting of fans and their associated large starting currents.

Alternative Control System

An alternative solution to the control based on pollution measurements is to use directly measured traffic characteristics as control variables for setting the ventilation system, pollutant flows being directly linked to the traffic.

The principle is as follows:

- measurement of the traffic before entering the tunnel, or if this is not possible, in different sections of the tunnel
- calculation of the required ventilating air flow
- evaluation of natural ventilation
- determination of the air-handling capacities of the tunnel ventilation fans.

Traffic measurements (flows, speed, type of vehicle) are easily made using inductive loops, video imaging, etc.

Emission rates can be evaluated as a function of these data and of the geometry of the tunnel using data given by PIARC [10].

The evaluation of the appropriate ventilation rates can be made by air speed measurements, comparing real conditions to theorical conditions resulting from the ventilation generated by traffic flows, and by the action of the tunnel ventilation fans.

Conclusion

Control principles based on a description of the traffic that uses the tunnel avoid the difficult task of pollutant measurement and allow immediate control of the ventilation system as soon as traffic variations are confirmed.

It is not linked to a given pollutant but could take into account all pollutants emitted by the traffic.

It is easy to predict, to set, and to modify, the ventilation levels. The control algorithms can also be updated from time to time in line with developments in vehicle emission and regulations or recommendations.

Of course it is necessary to maintain some atmosphere control device to oversee the threshold levels at safety point of view or in case of specific incident.

Reference

[10] Road tunnels, emission, ventilation, environment. Committees on Road Tunnels PIARC 1996 (Montréal), 05.02.B.

V. CONCLUSION AND RECOMMENDATIONS

Yves DARPAS (France)

Existing Situation

Until now, ventilation systems were designed so as to dilute CO and reduce opacity due to soot emissions by Diesel engines. The air flows required for the dilution of CO also ensured dilution of the other gaseous pollutants, in particular nitrogen oxides.

New Data and Trends

CO emissions from vehicles have been significantly reduced owing to engine improvements and the significant increase in the proportion of Diesel engines in the vehicle fleet. The role of CO as a tracer of vehicle-induced pollution for the design and control of tunnel ventilation systems is continuously decreasing, and taking into account a number of other noxious gaseous pollutants such as nitrogen oxides, in particular NO_2, becomes necessary.

NO_2 exposure studies carried out on humans show that NO_2 can affect healthy people for levels in the range of 4,000 µg/m^3 but that under 2,000 µg/m^3 no effect on lung function has been noted.

These values apply to healthy people. The studies described in Chapter 2 of this paper show that for persons with allergies or asthmatic predisposition, values in the range of 500 µg/m^3 (0.27 ppm), without having direct effects, increase the sensitivity to allergic stimuli.

It is not now possible to define harmless threshold levels for this sensitive population; moreover, the effect of exposure time has not yet been quantified.

It should also be emphasised that allergic reactions are not only limited to sensitive people and to their exposure to NO_2 in tunnels, but also to dust, pollen, and other allergenic elements to which they could be exposed elsewhere.

The results of measurements carried out in tunnels show that the mean levels of NO_2 are much lower than the maximum levels acceptable for healthy people, but the decrease of emissions from vehicles is leading to a decrease in the ventilation capacity in new tunnels where the design criteria are referenced to CO and opacity levels.

Consequences

The consequences of the points outlined above are :

- “tracers” pollutants have to be reviewed taking into account new trends;
- NO_2 must be taken into account in the calculation of ventilation flows;
- acceptable threshold levels for “tracer” pollutants and especially NO_2 must be fixed on the basis of specific medical studies;

- existing studies concerning NO_2 are to be completed for sensitive people, investigating the influence of levels, exposure time and the consequences of the cumulative levels. Blind tests should be carried out to remove subjectivity from these considerations;
- precise, reliable, easily maintained and inexpensive devices should be sought to measure tracer pollutants in tunnels;
- when these systems do not exist (NO_2 being a case in point) alternative approaches should be taken.

Recommendations

- It is necessary to take into account NO_2 in sizing and operating tunnel ventilation systems.

- The threshold limit recommended for healthy people is 2,000 µg/m^3 (1 ppm) for NO_2; this threshold value leads to ventilation systems reasonably sized and coherent when compared with the needs of opacity criteria.

- In order to avoid oversizing ventilation systems, and by reference to environment regulations expressed in centiles, it is acknowledged that the recommended threshold levels should not be exceeded more than 2% of the time. Finally, for clarification, it should be noted that the design values given correspond to the average concentration levels throughout the length of a tunnel.

- In the absence of precise conclusions concerning sensitive people, it is up to each country to define its own policy, taking into account that the adoption of an excessively onerous design standard could increase tunnel construction costs to an unacceptable level in the face of public health concerns.

- The results of measurements carried out in tunnels and described in this report show that, for values in the range of acceptable threshold levels, the ratio $NO_2/NO_X = 0.1$ (volume) may be retained in order to evaluate NO_2 flows in tunnel.

- The calculation of air flows to dilutes NO2 can be done using the emission factors of NO_x by vehicles issued in 1995 in the PIARC (05.06.B, 1996) report “Road tunnels, emissions, ventilation, environment” on the occasion of the Montreal Congress and the ratio NO2 / NOx= 0.1 (in volume).

- Taking into account the lack of industrial equipment capable of measuring NO_2 levels within the required range, the permanent control of NO_2 is not necessary to appreciate the NO_2 levels and it is possible to assess NO_x using the ratio

$$NO_2 / NO_x = 0.1 \text{ (in volume)}$$

- Ventilation control based on traffic figures can be considered a valid alternative to control based on pollution measurement.

APPENDIX: EXAMPLES OF TRAFFIC CONDITIONS AND POLLUTION LEVEL VARIATIONS IN FIVE ROAD TUNNELS

The enclosed charts give a comparison of the daily changes in traffic conditions and pollution levels recorded in five tunnels whose main features are listed below:

1) SÖDERLEDSTUNNEL (Stockholm)

length: 1,500 m
two tubes
longitudinal ventilation
traffic: 39,000 vehicles per day (working days)
pollution recordings taken 1 km from the tunnel portal.

2) SAINT-CLOUD TUNNEL (Paris)

length: 851 m
two tubes (2 x 4 lanes)
longitudinal ventilation
daily traffic: 36,500 vehicles in each direction, and
hourly peak: 6,150 vehicles in each direction
pollution recordings taken in the middle of the tunnel in the Paris/Province direction.

3) TUNNEL AMBROISE PARÉ (Paris)

longueur : 781 m
deux tubes (2 x 3 voies)
ventilation semi-transversale
trafic journalier : 26 000 véhicules par sens
pointe horaire : 3 800 véhicules par sens
mesures de pollution au milieu du tunnel.

3) AMBROISE PARÉ TUNNEL (Paris)

length: 781 m
two tubes (2 x 3 lanes)
semi-transverse ventilation
daily traffic: 26,000 vehicles in each direction, and
hourly peak: 3,800 vehicles in each direction
pollution recordings taken in the middle of the tunnel.

4) LA CROIX-ROUSSE TUNNEL in Lyon (France)

length: 1,750 m
one two-way tube (2 x 2 lanes)
semi-transverse ventilation
daily traffic: 40,000 vehicles in each direction, and
hourly peak: 4,000 vehicles in each direction
pollution recordings taken in the middle of the tunnel.

5) TUNNEL du MONT-BLANC (France / Italie)

longueur : 11 600 m
un tunnel bidirectionnel à deux voies
ventilation semi-transversale
trafic journalier : 5 600 véhicules comprenant 2 200 poids lourds (36 t)
mesures de pollution dans le puits de rejet au portail français.

5) MONT-BLANC TUNNEL (France/ Italy)

length: 11,600 m
one two-way, two-lane tunnel
semi-transverse ventilation
daily traffic: 5,600 vehicles including 2,200 heavy goods vehicles (36 t)

pollution recordings taken in the air shaft at the French portal.