

## **Road tunnels and the environment<sup>(§)</sup>**

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### **INTRODUCTION**

« Environment » is one of these in-words, that is a subject for many discussions and publications, but the content of which is not always very well defined and therefore does not always cover the same concept. Obviously, environment is everything that surrounds.

Webster's dictionary defines it more precisely as :

“ The surrounding conditions, influences, or forces that influence or modify : as :

“ a) the whole complex of climatic, edaphic and biotic factors that act upon an organism or an ecological system and ultimately determine its form and survival;

“ b) the aggregate of social and cultural conditions as customs, laws, language, religion and economic and political organisation that influence the life of an individual or community.

An engineer in his professional activities would often use the word « environment » as a sort of opponent to pollution which again, is a word difficult to define. Environment to him then would mean a set of standards and recommendations that he must comply with and threshold values that must not be exceeded. His technical solutions would be developed keeping in mind that the inevitable outputs as noise nuisance, waste or effluents do not debase the living and working conditions inside and outside the process that he is designing or operating.

But, environment would also mean that he should pay attention to safeguarding the natural resources by using as much as possible of the e.g. renewable energy sources and recycled materials, and strive to achieve long-lasting developments.

### **OBJECTIVE OF THE PAPER :**

The objective of this paper is to look at one particular achievement, i.e. urban road tunnels, the ventilation of which directly concerns the environmental problems. Indeed, ventilation is precisely designed and operated to secure an ambient atmosphere inside the tunnel that is clean, healthy and possibly pleasant for the user.

But the immediate surroundings of the tunnel should also not be overlooked. Indeed, the environmental conditions near the tunnel portals must be preserved. This is specially true in urban sites. Moreover, controlling the discharge of pollutants through chimneys or exhaust openings in the ceiling is also an important issue.

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## ROAD TUNNELS

Building road tunnels is today a manner of responding to the unavoidable problem of the ever increasing traffic volumes in densely populated areas.

Besides the psychological and stress aspects, driving through tunnels adds new problems to the ones already created by traffic on open roads. The new problems concerned include :

- air pollution with subsequent possible health hazards,
- absence of escape lanes which constitutes a severe risk for people who have to stop their cars,
- reduced visibility that causes higher accident rates,
- fire hazards and subsequent smoke development which could be a real threat in tunnels,
- etc ...

In the context of creating a healthy and safe environment in tunnels, one has to maintain a high standard air quality, good visibility, an acceptable noise level, and reduce as much as possible all potential hazards by carefully designing the tunnel management system. This goal is achieved mainly by :

- \* identifying correctly the different characteristic parameters of the traffic flow, such as speed, concentration, congestion and/or presence of stopped cars, and so on, ...,
- \* predicting, based on this traffic information, the forthcoming pollution,
- \* acting subsequently on the mechanical ventilation equipment (injecting and extracting fans, jet-fans, and so on, ...) in order to maintain the required air quality level, yet at minimum energy costs,
- \* detecting, instantaneously, all kind of hazards, and,
- \* taking adequate decisions by e.g. dispatching the alarms according to some priority rules, sending effective and efficient messages to the user, if and when needed, and so on, ....

Since the complexity of tunnels is increasing and users are ever more demanding, especially when their health and safety are concerned, there is an undeniable need to install sophisticated and expensive equipment such as high-sensitive pollution meters, fire detection systems, traffic sensing devices and video cameras. Unfortunately, most of this equipment, sometimes installed at different life stages of the tunnel, operates in a stand-alone mode, the first concern being only the display of the measured data.

Nevertheless, one could gain more from these valuable measurements and information by integrating them into a single processing system, making not only the expenses more profitable, but there could also be other benefits too, such as :

- information of different nature and origin, processed together may increase the reliability of the system, and hence reduce false alarms,
- part of the operator's decision making may be supported by proposals issued by an artificial intelligence processing unit, the so-called "expert system",
- operational ventilation costs due to pollution could be reduced, either by controlling the traffic through changeable road signs and variable message panels, or by anticipating certain actions on the ventilation. In the latter case, traffic data would be processed together with pollution measurements. The calculated pollution trend could then help predict the forthcoming concentrations, thus enabling to smooth out critical pollution peaks by anticipating the necessary actions on the fans.

With the help of a representative example of a long, complex and well equipped tunnel, for example, the Belliard tunnel in Brussels, Belgium, most aspects of the environmental problems will be tackled.

## SOURCES OF POLLUTION

Traffic is undoubtedly one of the important sources of environmental and air pollution. It does not only have a harmful impact on health but also indirectly debases quality of life by disturbing the eco-system, destroying our urbanistic and cultural inheritance, and so on. Despite all efforts and all kinds of recommendations to reduce, specially in large cities, both traffic flow and one of its first nuisances, i.e. the pollutant emissions, it may be expected for the next few decades that traffic will remain an important source of pollution. Therefore a lot of money has been invested in installing monitoring equipment, developing data transmission networks and building supervision centres.

The combustion of fuels (gasoline, LPG, diesel oil, and so on, ...) in vehicle engines produces a lot of substances. Depending on their concentration, their chemical stability and their adverse effects on environment and human being, the most relevant compounds in the exhaust gas are :

**SO<sub>2</sub>** The production of SO<sub>2</sub> due to the traffic is related to the sulphur content of the fuel. Today, diesel contains a mass concentration lower than 0.2%. For gasoline it is even lower and for LPG it is virtually zero. Since the traffic contributes only 5% of the total SO<sub>2</sub> emission, the possible presence of this pollutant is usually not taken into account as far as tunnel ventilation is concerned.

**CO<sub>2</sub>** This compound is the main product of the combustion of a fossil fuel. The substance is not directly responsible for health damage, but could contribute to what is called the « greenhouse » effect. Although a non negligible amount of the produced CO<sub>2</sub> has to be taken on account of the traffic, the problem, if real, has a world-wide extent and as such is not specific to tunnel ventilation.

**CO** This pollutant is produced in a reducing atmosphere, either by an overall shortness of the combustive, or by a local deficiency due to the non-homogeneous character of the mixture of fuel with air. As a rule, spark ignited engines produce more CO at lower speeds. The introduction of a catalyst, however, drastically reduces the emission of CO by a factor of 10.

**NO<sub>x</sub>** The mixture of NO and NO<sub>2</sub>, of which the latter is a very toxic substance, is often referred to as NO<sub>x</sub>. Measurements show that traffic contributes for about 60% to the entire NO<sub>x</sub> pollution. This compound is not related to the kind of fuel used but to the fact that air is used for combustion. At high temperatures, its two main compounds combine in order to form NO (together with small amounts of N<sub>2</sub>O) and this reaction is sufficiently fast enough to produce a measurable quantity. On the other hand, the cooling down after the combustion process is too fast to allow a reversible dissociation of NO into its two compounds. A small amount of this NO is then transformed by oxidation into NO<sub>2</sub> at the exhaust pipe of the vehicle. The mutual interactions of the triangle NO, NO<sub>2</sub> and O<sub>3</sub> in a pure atmosphere under the influence of solar light irradiation are already very complex. But, if we additionally take into account that other polluting free radicals such as (CHO)<sup>·</sup>, (OH)<sup>·</sup> and (HO<sub>2</sub>)<sup>·</sup> are present or produced in exhaust gases, then the production of NO<sub>2</sub>, together with some other pollutants and fog, becomes extremely complex and may involve hundreds of equations. More details could be found in Chovin, [1].

It is worth noting that the rate of oxidation is very dependant on the NO concentration, and that the formation of NO<sub>2</sub> is favoured by a higher pressure and a lower temperature (<160°C).

**VOC** Subjective and unpleasant impressions often reported in some tunnels makes one assume that other pollutants than CO and NO<sub>2</sub> must be present in the air. Among them we can identify substances such as aromatic and aliphatic hydrocarbons that are produced by the vaporisation of the incombusted liquids and their partially burnt compounds C<sub>x</sub>H<sub>y</sub>O<sub>z</sub> as a residue of incomplete combustion. Usually, these HC's are measured as a whole, mostly by a technique of flame ionisation (FID).

Congested traffic situations with a lot of accelerations will inevitably increase this kind of pollutant production. Typical concentrations can be found in (Haerter, [2]), see table 1.

**Particles** They constitute a different kind of pollution. Although some of them, such as polycyclic aromatic hydrocarbons are known for their cancer producing effects and asbestos for causing malignant pneumoconiosis, their presence, after a certain concentration, has mainly the inconvenience to reducing visibility.

Threshold limit values and biological exposure indices can be found in ACGIH, [3]. Fortunately, the quantities involved are only of the order of a few µg /km/vehicle. Typical concentrations can be found in table 1 (Haerter, [2]).

		fluid traffic average 60 km/h		congested traffic average 20 km/h		congested traffic average 5 km/h	
		pass. cars	city trucks	pass. cars	city trucks	pass. cars	city trucks
Carbon monoxide	CO	6	4	16	12	42	38
Hydrocarbons	HC	1	3	2,5	8	5,5	28
Nitric oxides	NO <sub>x</sub>	2	14	1,5	15	1,5	21
Sulphur dioxide	SO <sub>2</sub>	0,02	1,5	0,04	2	0,1	3
Lead	Pb	0,01	-	0,02	-	0,03	-
Soot	C	-	0,2	-	0,4	-	1

Table 1. Emissions in g/km of German passenger cars, reference year 1985

Of course, all these chemical substances don't show the same damaging hazards : some can, even in very low concentrations, be harmful to one's health (toxic) while others may cause only inconveniences that, nevertheless, could lead to a poor safety level.

Toxicity is defined by Lauwerys, [4], as the capacity inherent in a substance to producing a deleterious effect on the living organism. One could define it as a limit above which the organism is no longer capable of neutralising the permanent influence of the considered

substance without leaving visible irreversible damage, the so-called after-effects. These substances cover, of course, a lot of different meanings and almost each of them acts in a different manner on the human body. Tolerated quantities are given by Lauwerys, [4].

## LEGISLATION

As a rule, standards limit the emission of noxious substances produced by vehicles. A fortunate interaction between the legislator and the vehicle building industry has enabled there to be a significant reduction in the tolerable limits over the past decades, mainly where CO is concerned.

It is only recently that NO<sub>x</sub> has also been taken into account. Lately, equipment has been installed to also measure this substance inside the tunnel. Today, there is at least one official decree known that enforces an upper limit value of the NO<sub>2</sub> concentration in tunnel air.

It is also important to be aware that in the vicinity of the ventilation stations and the portals, the NO<sub>2</sub> limits imposed are most likely to be exceeded. Thus the NO<sub>x</sub> emission, which almost exclusively occur in the form of NO, and the conversion from NO into NO<sub>2</sub>, must be known in order to assess the situation.

Even though the HC's are most unpleasant pollutants, there is no hygienic limit value for total HC, making it difficult to use concentration levels for the assessment of environmental impact.

The effectiveness of emission standards depends, of course, on the level of average emission that can be achieved and that can be monitored. Practically, there are three categories accepted in their authority in setting standards :

- US standards;
- EU standards;
- Japanese standards.

These standards were put together in table 2 by Pischinger, [5].

From the point of view of air quality in tunnels, a general basic idea seems to prevail : short time exposure would allow a higher pollutant concentration than a prolonged exposure. This would be in the case, for example, of traffic being congested.

Tunnel ventilation is usually designed and monitored with regard to CO and smoke. But in order to have some information about the possible concentrations of other pollutants, Patigny, [6], made a comparative study. It was aimed at defining the minimum air flow volume that would be sufficient enough to dilute all the other known substances below their TLV. Based on values in literature (ACGIH, [3]), (Lauwerys, [4]), (A.P.P.A., [7]), which unfortunately for some compounds show a lot of dispersion, this study concluded roughly that, except for the aldehydes, which act in a similar manner as the NO<sub>2</sub>, and therefore their effects should be added, all the pollutant substances stayed well below their threshold value if the TLV of NO<sub>2</sub> was not exceeded. Nevertheless this result should be taken with precaution.

What legislation in Belgium is concerned with, is that the district of Brussels-Capital, Belgium, ordered a decree that, summarised, limits the average value of the CO concentration (i.e. the averaged value of all the sensors) at 100 ppm and the maximum value of NO<sub>2</sub> concentration at 500 ppb.

Moreover, according to this same official decree, the TLV's applicable for CO and NO<sub>2</sub> are dependent on the travel time through the tunnel.

Figure 1 shows how the TLV of CO is related to the travel time, i.e. the time needed by a vehicle to drive through the tunnel. This diagram is based on the FORBES formula given by Lauwerys, [4],

TABLE 2

$$\log_{10} HbCO(\%) = .85753 \log_{10} CO(\text{ppm}) + .62995 \log_{10} t(\text{min}) - 2.29519,$$

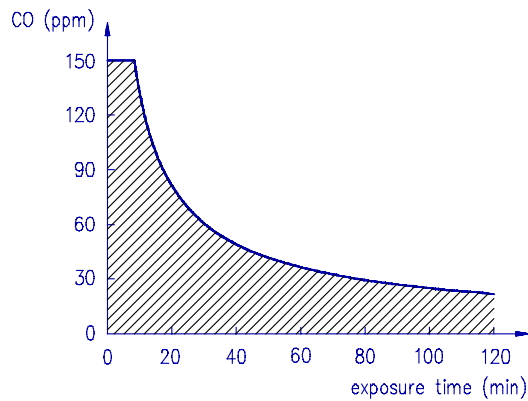


Figure 1. TLV of CO.

evaluated for a permissible concentration of 2.24 % carboxyhemoglobine in the blood.

Defining the values of maximum allowable NO<sub>2</sub> concentrations as a function of exposure time is

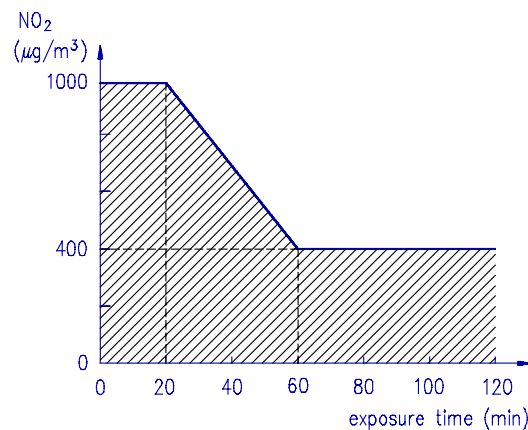


Figure 2. TLV of NO<sub>x</sub>.

much more difficult to achieve, since there are only a few values available for short term exposures (STEL values) and some for 8 hour exposures (TWA values). Guided by the W.H.O., [8], the authorities resolved on enforcing the diagram of figure 2. Acceptable TLV's are situated within the hatched area.

## VENTILATION SYSTEMS

Tunnel ventilation systems can be classified into three basic ventilation schemes, i.e. longitudinal, transverse and semi-transverse ventilation.

### Longitudinal ventilation

The principle of the longitudinal ventilation is to favour the natural draft by acting in such a manner that the mean air flow velocity has a sufficient value. For this purpose, one installs, close to the walls or the ceiling, one or more jet-fans that provide the necessary driving force. This kind of ventilation system is particularly suitable for one way traffic, i.e. the air is blown in the same direction as the traffic goes.

With regard to pollutant concentrations, their maximum values are to be expected at the tunnel exit, or, if several sections are present, at the end of each section. The growing rate is, of course, a function of the amount of emitted pollutants which, for a constant traffic flow may be assumed as being approximately constant.

### Transverse ventilation

Inlet, as well as outlet air, is ducted along the tunnel. It is blown into the tunnel through more or less equally spaced openings (slots) along one of the walls. The vitiated air is sucked off at the

opposite wall also through equally spaced openings and let into a collecting duct. In this manner the air will theatrically flow perpendicular to the axis of the tunnel and thus also to the traffic. Therefore, this ventilation scheme is particularly suitable for all kinds of traffic and for long tunnels. Of course, the air volumes that are supplied and sucked off may be different, which allows for a number of combinations. Since the air moves transversely to the traffic, one can expect that the pollutant concentration over the entire length of the tunnel will be nearly constant, certainly if the longitudinal velocity component of the air flow is reasonably low.

### **Semi-transverse system**

This ventilation scheme could be considered as a combination of both the transverse and longitudinal ventilation system. The fresh air is supplied through openings in the walls or the ceiling, and the vitiated air flows along the tunnel and leaves it through one of the portals according to the combined action of the pressure difference between them and the piston effect. If there is no driving force available that would create a longitudinal velocity component, then the tunnel air flow would be zero in the middle and maximum at both portals. Depending on the extend of a longitudinal driving force (piston effect, wind, and so on ...) the resulting zero point velocity would shift along the longitudinal direction until it leaves one of the portals. Assuming a linear variation of the air velocity, the subsequent pollution concentration will follow a logarithmic function along the tunnel.

It is quite obvious that assuming the traffic flow and speed to be constant, is not very realistic. Nevertheless, the above basic ventilation schemes may give some indications about the suitable locations where the measurement devices should be installed for higher efficiency.

## **SURROUNDINGS**

Due to their confining character, it is beyond doubt that for equally dense traffic, the airborne pollutant concentrations in the tunnel are much higher than the ones on the open road, even in severely polluted cities. Table 3 taken from Haerter, [2], shows some typical concentrations that have been measured in different areas.

The uncontrolled discharge of vitiated air through portals and roof openings or short chimneys may make the pollutant concentrations in the surrounding area exceed the standards. Particularly for longitudinal and semi-transverse ventilation systems, a certain number of solutions to this problem may be applied :

- dilute the tunnel air, just before it leaves the portals, by an adequate fresh air supply,
- provide a chimney through which most of the tunnel air is extracted,
- clean the tunnel air from certain pollutants by off-line precipitating and filter systems (Hennings, [9]),
- design the portal geometry in order to favour the dispersion of pollutants.

In this environmental perspective, several studies have been carried out in order to evaluate the impact of the tunnel air discharge on the surrounding residential areas. So far, three techniques, all successful, have been used :

- local measurement sessions with portable instruments in the vicinity of exhaust grids located in streets or recreation areas (Elisabeth park, de Jamblinne-de-Meux place),
- small scale modelling (Nadel, [10]), a technique that has been used to simulate the dispersion of the CO and NO<sub>2</sub> substances released by an exhaust chimney. For example, in view of determining the location and geometry of an exhaust chimney at the de-Jamblinne-de-Meux place, a 1/200 model has been built. It assisted in evaluating the impact of the resulting



pollution on the surrounding buildings. Three measurement sessions on site, one before construction of the chimney and two afterwards, could confirm the predicted values.

- CFD simulation allows the study of, for example, the influence of the size of a roof opening on the re-entrainment of polluted exit air into the next section of the tunnel. This kind of simulation could give an answer to the question of whether leaving part of a tunnel uncovered is efficient or not, and if so, what the dimensions of the opening should be.

## **BELLIARD TUNNEL**

### **General description**

The Belliard tunnel is an urban road tunnel in the centre of Brussels. It is a complex tunnel, not only because of its length and its several access and exit roads, but also because of its Y-shape. Considered as a single tunnel, this particular Y-shape is due to the assembling of parts of three previously existing tunnels. It links the inner ring road of Brussels with the east of the country through the E40 highway, and with the south of the country toward the E411 highway. Moreover, it serves a local area in Brussels as may be seen on figure 3, and allows access to the independent underground parking areas of two EC-buildings, viz. the Berlaymont and the Conseil buildings.

With its three-lane entrance, the tunnel is an extension of the important five-lane Belliard street. These three lanes, joined by an additional lane from the Conseil parking lot, form a four-lane road in the first part of the tunnel. Then, after some 460m, it splits into two separate two-lane roads. The length between the entrance at Belliard street and the most distant exit i.e. the east portal, is nearly 2 km. The southern branch of the tunnel is much closer to the split, extending only 300m.

The ventilation is of the longitudinal type, but with intermediate air extraction and subsequent fresh air injection. The air flow volumes match at least the fresh air demands in each of the sections of the tunnel. As may be seen on figure 3, there are altogether 13 slots, denoted by  $I_{nnn}$  for an injection slot, and  $E_{nnn}$  for an extraction slot,  $nnn$  being a sequence number, each slot being supplied by a twin fan system. These twenty six fans are all equipped with variable pitch angles.

Since it was not always possible to install fans and injection slots at locations where a preliminary theoretical study indicated that they should be, ventilation needed to be boosted in some parts of the tunnel by means of jet-fans. These are indicated on figure 3 by  $GR_{nn}$ ,  $nn$  being the number of the group of jet-fans. Heavy traffic is not allowed in the tunnel. Therefore, the ventilation has been calculated for an exclusive use by light traffic, of which 10% is assumed to be equipped with diesel engines. For this reason, it is expected that there will be no problems with opacity and only minor problems with  $NO_x$  pollution.

The main criteria and standards for calculating its minimum ventilation capacity form the subject matter of an official ministerial decree, that is already been mentioned.

It is also important to be aware that the ventilation capacity in certain sections has been reinforced to respond to emergency cases, particularly fire hazards. However, this aspect is out of the scope of this paper.

## **MEASUREMENT EQUIPMENT**

Tunnel monitoring systems which operate entirely exposed to the grim tunnel environment suffer a great deal from getting dirty where e.g. the optical surfaces are concerned. This is a

considerable problem, particularly if visibility measuring equipment is involved. The detrimental effects of tunnel washdowns and the constant exposure to suspended exhaust carbons and other particles,



necessitate a large amount of maintenance resulting in a low availability rate. Problems like these have resulted in the equipment having a poor reputation. Any tunnel monitoring equipment must, to a certain extent, come into contact with the tunnel atmosphere.

Some criteria for good measurement devices are :

- \* in the case of tunnels, the most important is certainly their reliability, i.e. the capacity to measure and give out the needed information without failing even after long periods of time. The MTBF should preferably be years, rather than months;
- \* robustness should be preferred to accuracy;
- \* if sophisticated equipment is used, the measurement should be accompanied by a kind of validity status that informs the user on the quality of the information;
- \* Automatic self-checking and calibration will offer an higher level of confidence.

## **Traffic**

### **Flow volume and speed**

Since traffic is *the* source of pollution in a road tunnel, it is obvious, although only recently put in practice, that the measurement of certain traffic parameters has to be considered in the first place. The traffic variables, which are the traffic flow volume, i.e. number of vehicles per unit of time, and the traffic speed in km/h, are measured by analysing the successive pictures of the traffic taken by video cameras. More can be learned in Versavel et al., [11].

However, from the pollution emission point of view, much more useful data would be traffic concentration, i.e. the number of vehicles per km.

A correct prediction scheme of the traffic flow volumes would certainly be the most adequate application in the scheduling of ventilation fans. It is believed that accurate predictions of the traffic flow volume will both reduce ventilation costs and improve air quality. Several algorithms have been developed (Edie et al., [21]) and tried out to predict both flow and speed parameters and to calculate the average travel time. The latter result may also be directly obtained by tracing marked vehicles or license plate recognition, but it needs the implementation of more sophisticated equipment.

Each camera will normally monitor two lanes. The implementation of the cameras is indicated as TC<sub>m</sub> on figure 3.

## **Pollution**

### **CO pollution meter**

This device uses the well proven non-dispersive infrared (NDIR) absorption technique, which is capable of operating on a real time basis. CO absorbs infrared in a very specific manner, producing an absorption spectrum. Infrared radiation is split into two parallel beams, one passing through the sample compartment and one to a reference cell. The differential signal indicating the CO level is converted into a standard 4-20 mA output. Threshold levels can be set via a keypad to trigger alarms to warn of high CO concentrations. Within the useful operational domain, i.e. between 0 to 200 ppm, the accuracy is 10 ppm or 10% of the reading. This accuracy is achieved by using a cylindrical sample compartment that has a length of no less than 3m.

Of interest is its auto-calibration capability, therefore requiring very little maintenance. Besides an analogue output signal from 4 to 20 mA, the device signals a faulty functioning and any transgression of a level setting.

Their location, indicated as CO01 through CO08, may be seen on figure 3.

### **NO<sub>2</sub> pollution meter**

The sensor is based on the physical principle of chemiluminescence : NO molecules are oxidised by the chemical reaction between ozone and NO. This reaction gives a light output that is proportional to the quantity NO<sub>2</sub> being produced and thus also to the initial NO quantity present.

The real NO<sub>2</sub> concentration in the air is calculated by the difference between two measurements obtained by a double application of the aforementioned principle : the sample is split and travels through two separate test-channels. In the first one all the NO is transformed into NO<sub>2</sub> and measured. In the second one, the initial NO<sub>2</sub> is first reduced into NO and then the entire NO content is oxidised and measured. The method is accurate and reliable only if very low concentrations are to be measured (0 to 1 mg/m<sup>3</sup>), but its implementation as a practical measurement technique results in a very sophisticated and expensive instrument that must be handled with care. To our knowledge no such devices have ever been specially designed to be installed in the adverse environmental conditions that exist in a tunnel. Since they are very expensive, only three have been installed. Their locations are indicated on figure 3 as NO21, NO22 and NO23.

The instrument itself is not installed in the tunnel but behind its walls. The actual measurement is done on the basis of samples continuously taken by a small pump system. The full scale measurement range is programmed to be 1 ppm.

### **Flow volume**

#### **In the tunnel**

There is still no reliable method for measuring the air flow volumes in tunnels. Devices based on the ultrasonic principle may provide an acceptable solution to this problem.

The measurement technique uses two ultrasonic devices, each facing the other on the opposite wall of the tunnel, making a line that is at an angle of approximately 45° to the axis of the tunnel. Each of them emits and receives, in turn, a beam of short ultrasonic pulses. The measured difference in travel time between the two beams, is due to the axial velocity component of the air flow, which multiplied by the cross-section is precisely the quantity that we seek to estimate.

Three of such devices, referenced as QT01, QT02 and QT03 on figure3 have been installed. They allow to measure air velocities, averaged on a straight line, in the range of -10 to 10 m/s.

#### **Of the fans**

The air flow rate through the fans is calculated from the velocity pressure measured at the inlet piece of each fan by means of an electronic differential pressure sensor. Since ventilation control involves only flow variations, this method, properly calibrated, was expected to provide satisfactory results. In fact, due to the manner that most fans have been installed within their duct systems, the velocity pattern at their inlet is far from uniform and steady. This problem is still under study.

#### **Opacity**

Smoke concentration often provides the actuating signal in ventilation control. However, since the Belliard tunnel does allow heavy traffic to pass through, visibility problems were not expected. This was later confirmed.

#### **Fire detectors**

Fire detection uses a dual rate-of-rise/maximum-temperature sensor. The sensors are located approximately every 15m along the length of the tunnel. Grouped into so-called zones which correspond roughly to the different theoretically possible fire scenarios, each zone is served by one collective signal line. Therefore, all sensors in the same zone have a common address.

Since this information does not contribute to the environment problematic, no further thought will be given.

## **MECHANICAL VENTILATION EQUIPMENT**

### **Fans**

The fans, altogether 26, are axial, anti-stall fans with variable pitch angle, each equipped with a damper. They are set up in groups of two fans operating in parallel, each pair being controlled as a single operating unit.

The ventilation capacity of each fan has been calculated in such a manner that it corresponds to approximately 50% of the estimated capacity in case of fire. This solution offers, besides maintenance advantages, also the possibility to run alternatively one fan and then the other, mostly at maximum efficiency. The difficulty however, is the transition from one to two fans, and vice versa without disturbing too much the ventilation in the tunnel. This problem has been studied on a small scale model and will soon be published.

The single control unit allows to monitor the different information coming from the fans such as heating problems of the bearings, protection against overload of the motor, the start-and-stop procedures, the opening and closing of the dampers, and the pitch angle settings in order to match the required air flow quantity.

### **Jet-fans**

Since it was not always possible to install air injecting slots where needed, 44 jet-fans, irregularly distributed along the tunnel, were additionally required to ensure a sufficient ventilation capacity at any one of its sections. From the functional point of view, they are subdivided into 11 groups. When full ventilation capacity is not needed, this logical subdivision has the advantage that either one fan within the same group can be started up, so allowing to operate them in turn.

## **MONITORING SYSTEM**

The responsibility of the government to meet legal obligations requires the set-up of a monitoring system that takes account of the need to obtain representative measurements and perform accurate analyses on these data. Carefully designed monitoring programs are also required by engineers who investigate improved environmental control technology, by operators who run the ventilation process and by rescue officers who are in charge of safety.

The frequency of sampling, averaging in space as well as in time, need to be carefully considered. A reasonable monitoring cycle time that comes close to a real time response in relation to the ventilation and pollution process, has been considered to be 1 minute.

The system architecture is depicted in figure 4. Basically it consists of three logical entities :

1. the controlling unit, which is mainly set up by two independent and parallel working supervision automatons, each exchanging data with six programmable datalogging systems, and assisted by an expert system;
2. the left part, which is the set of measurement devices and;
3. the right part, which assembles the fans.

It should not be overlooked that the transmission of the data must also have full attention. There is no point in spending a lot of money in high quality measurement sensors, if too often its output

FIGURE 4

data is lost or its content is distorted during transmission. Therefore, higher level transmission systems i.e. digital telegrams, should be preferred to analogue connections.

## **CONTROL SYSTEM**

### **Problem statement**

As already mentioned, the first objective of a good ventilation system is to provide a safe, comfortable and clean environment inside the tunnel, and minimise the adverse effects outside the tunnel. Therefore, the air quality must comply with existing standards and recommendations. Deviating from these norms inevitably calls alarms to be triggered, and actions to be taken. A correct interpretation of these alarms with subsequent proposals, and, if necessary, the adequate actions on the mechanical equipment according to an in advance prepared scheme, could well be overtaken by an « intelligent » processing unit. This unit, the so-called expert system, extends the capabilities of the monitoring system to a control system.

The objective of the ventilation control is two-fold :

- ⇒ first, it must provide ventilation systems that are economical in routine operation, i.e. adapt the ventilation to the *real* but *minimum* fresh air needs. Adequate air flow rate is indeed a compromise between two conflicting requirements. But on the one hand, the air flow volume must be sufficient to dilute the pollutants emitted by the vehicles. On the other hand, the air flow quantities should be as low as possible to save energy and reduce running costs. Hence, an efficient control system is the one that, at any time, will guarantee these optimal air flow quantities in every section of the tunnel.
- ⇒ second, it must control the ventilation as safely and efficiently as possible in emergency cases resulting from breakdowns, accidents or fire. Fires are unfortunately among the most hazardous situations. In this particular case, it is important that the ventilation system be capable of controlling the direction of smoke motion in order to provide a clear and safe path for escaping and rescuing people, as well as an easy access for the fire brigade (Heselden, [12]).

Any gains from greater operational security are difficult to estimate. However, the energy savings which accrue from optimal management of the ventilation system are obvious. Indeed, for important tunnels the electrical power may well exceed 1 MW per km. A reduction of this amount by only 10%, a figure that seems easily within the reach of a good control system, would allow savings of around 1 million BEF (approximately \$33,000-) per year/km. But, what is even more important is that each kWh saved will undeniably reduce the pollution, whatever kind, at the location where this kWh is produced.

### **Basic considerations**

The knowledge gained through our studies concerning the application of computer controlled processes in the field of mine ventilation (Patigny, [13]), (Jacques, [14], [15]), led us to consider a few basic guide-lines :

- since instabilities in ventilation must be avoided at all times, it is advisable to pay more attention to this aspect than in reaching the optimum. A less optimal, but stable solution should be preferred to any sophisticated control system that tries to follow too closely the fluctuations in traffic and pollution. Moreover, the time lag between pollution build-up, detection and pick-up by instruments, and resulting actions of the fans upon the ventilation, could well take from up to several minutes to a quarter of an hour. Thus, averaging over a

longer time period which would possibly take into account the forthcoming pollution, is a strategy to be welcomed.

- the ventilation of a complex tunnel should always be controlled from a central point of view. Indeed, complex tunnels with longitudinal ventilation behave like networks where, according to Kirchhoff laws, all flow rates are linked (Wang, [16]). Trying to change one of them, inevitably results in disturbing, to a greater or lesser extent, all other flows, and thus also the pollutant concentration. Moreover, one should be aware that, in contrast to single tube tunnels, the pressure distribution in such a network can play a significant role. Mainly for these two reasons, it is vital that, before any action is taken, the potentially disturbed sections be predicted. Proceeding otherwise could result in a kind of "bouncing" game between interacting but not necessarily adjacent fans. The control problem is in fact even more complex, since other aerodynamic sources, such as traffic induced ventilation and natural ventilation, may interfere.
- measured data should always be checked and validated. One must never rely on a single measurement, even if the equipment is ascertained to work properly. Validation could make use of statistical tools and, more important, of information obtained by different measuring techniques. Redundancy and diversification of the measured data are therefore never a luxury !

### **Application to tunnel ventilation**

With these considerations in view, the ventilation control system may make use of the following measurements :

- . concentration of the different pollutants in each part of the tunnel,
- . throughflow of the fans, as well as the flow rates in the tunnel sections,
- . mean speed and traffic flow or concentration in each section,
- . wind velocity and its direction, and,
- . alarm-signals of smoke and fire detectors.

Basically most of these data are provided by the sensors installed in the tunnel for monitoring purposes. Some of the measurements, such as the air flow rates and the traffic data are then combined and used to assess the concentrations of the pollutants by means of empirical laws (PIARC, [17], [18]). In this way, they constitute a first hand estimation of the future pollution.

Others, such as the pollutant concentrations, would be used in a direct manner in order to make sure of the efficiency of the ventilation.

A comparison between the estimated pollution values and the direct measurements, possibly delayed over a certain time, may well provide some sort of validation technique, which would increase the confidence level of the entire control system.

Next, the measurements, if compared to the previously recorded values, can provide information about the rate of growth of the pollution. The latter information is particularly useful to determine the urgency with which the control devices should be programmed to respond. Moreover, it allows to anticipate the up-coming pollution, and may therefore reduce the number of compensating actions over a given time period, and thus the mechanical wear.

Of course, the new set points of the fans are related to the fresh air quantities that one needs to cut the pollution level back below the TLV's for each of the considered pollutants.

Unfortunately, as far as complex tunnel structures are concerned, this relationship between the required fresh air flow rates at any section of the tunnel, and the amount of air to be input by each fan is not linear. Since jet-fans also interfere in these calculations, it becomes obvious that

a reliable numerical model (Jacques, [19]), (Ferro, [20]), is an *essential tool* if ventilation control is to be achieved. Once calculated, the new set points are transmitted to the controller of each fan. They will act on either blade angle setting or rotational speed. In case of jet-fans, these signals usually take only Boolean values, i.e. "on" or "off".

## CONTROL STRATEGY

The required air flow volume of fresh air is usually calculated with the following formula :

$$q = \frac{N_V q_{PL} n_L L}{TLV} 10^6$$

where  $N_V$  is the number of vehicles,  $q_{PL}$  the volume of pollutants,  $n_L$  the number of lanes,  $L$  the length of the tunnel, and where the TLV, in the case of the tunnels in Brussels, is furthermore related to the average travel time of the vehicles.

In the case of single tube tunnels, the control procedure, briefly summarised, would look as follows :

Measured values of a certain pollutant component, e.g. CO, possibly averaged over more than one sensor, are compared with the TLV. This procedure, repeated for each of the pollutants to be monitored, would, by taking the maximum value, determine the minimum required air flow rate in the tunnel by means of the beforementioned formula.

This quantity, possibly increased by a small amount that would account for losses, would determine the duty point of the fan, or, in case of several fans, that of the fan system. Though not linear, this process can easily be operated as if it were. Probably a proportionally working controller could do the job, since time is not a critical variable, and that moreover, the number of fans that may start up within a given time period is limited.

Although the difficulty of working out such an application should not be overlooked, its advantageous feature remains the one-to-one correspondence between pollution level and required fresh air flow volume.

Unfortunately, in complex tunnels this univocal relationship is no longer true (Jacques, [22]). Since complex tunnels consist of several independently ventilated sections, the above expression should be applied to each of them if one wishes, in view of energy savings, to achieve the minimum required fresh air flow volumes. Indeed, the pollution level in any section that must be taken into account, is not only due to the local pollutant emissions of the traffic, but also the one coming in from the upstream section or sections.

Moreover, in a complex tunnel such as the Belliard tunnel, traffic congestion's may occur only in one part of the tunnel, and may unexpectedly disturb or modify the ventilation in other parts where ventilation was supposed to be satisfactory.

The resulting concentration must then be calculated by the following expression :

$$[P]_f = \Sigma q_+[P]_{f+} / \Sigma q_+ + q_{PL} / q ,$$

where  $q$  is the air volume, and where the subscript  $+$  denotes the up-stream sections and the subscript  $f$  refers to the exit of these sections.

Written for each section, it results in a system of equations. Taking further into account that the pollutant concentration  $[P]_f$  must not exceed the corresponding TLV values, i.e. that the difference  $\Delta[P]_f = TLV - [P]_f$  should ideally be zero, the unknown air flow volumes  $q$  would be the mathematical solution, if it were not that the mass conservation law had to be satisfied.

Therefore a certain number of equations need to be added which makes the final system over-determined. According to the applied optimisation criterion, only an approximate solution may be found.

One could, of course take the most critical section and apply the same air flow volume along the entire tunnel. It would mean a non-negligible waste of energy. Since there are several fresh air injecting points available and several adjustable fans that can be operated, there is certainly an optimal distribution of minimum fresh air volumes for which less energy is used while still satisfying the pollution constraints.

However, for complex tunnels the previous one to one relationship is no longer true. There is no way to link a particular measurement, or set of measurement devices, to a particular fan system that would have an exclusive control over it. In fact we are dealing with a multi-variable system. The underlying problem is that a concentration, which is precisely the quantity to be controlled, is a ratio of two volumes, i.e. the pollutant volume to the air flow volume. Therefore, any increase in concentration may be a result of either an increasing pollution or a decreasing air flow volume. Since a variation of a local flow rate may be the consequence of a demand elsewhere, or, could simply be due to a different pressure distribution, induced e.g. by the traffic, an action would only be appropriate if the control unit has been informed as to both these two quantities :

- the flow distribution in the tunnel, and,
- the pollution concentration distribution.

Therefore, an adequate control system must not only be capable of boosting the ventilation where the additional pollution due to congestion is increasing, but must also restore the ventilation in those parts of the tunnel where it has been disturbed.

Simulation with somewhat complex ventilation systems shows that a certain number of these situations may hide traps, and indeed exceed what was thought to be the worst case situation when the tunnel ventilation had been designed.

Lots of computer simulations confirmed the above mentioned phenomena. Additional difficulties, arise with the numerical problem of inverting a matrix which is sometimes near-singular, and the lack of experience with the quality of the newly installed measurement devices.

For these, and other reasons for which there is no room in this paper, the above solution scheme would be far too risky to be applied in the present state of the art. Therefore a different approach to this problem has been elaborated. The basic guidelines could be stated as follows :

- \* since traffic is the source of pollution, it not unreasonable to control its concentration based on the variables which characterise the traffic;
- \* by relaxing optimality of the control function, it would be possible to subdivide the operating domain of the controlling traffic variables into a certain number of smaller domains where these variables stay reasonably constant.

This procedure allows to prepare in advance, by means of numerical simulations, a certain number of tables, each containing the set points of all the fans. These tables are addressed by a combination of the traffic variables.

The advantages are obvious :

- a table may easily be replaced by a more adequate one as experience with the real ventilation proceeds,
  - the software is less complicated and thus guarantees a higher reliability, and,
  - any configuration of the ventilation is entirely predictable and, therefore, can be reproduced.
- These advantages greatly simplify the testing of the software.

Conversely, the weak point of this solution is certainly the lack of any guarantee that pollution never will exceed the TLV's. A built in protection mechanism should prevent this. Besides setting an alarm, the control algorithm will automatically adapt the subdomain boundaries of the traffic variables, if a repeated and significant pollution transgression within a certain time span is noticed.

The four control variables are the traffic concentration variables, i.e. the number of vehicles per km, the average traffic speed, the unbalance between both the exit sections, first where the concentration is concerned, and second where the speed is concerned. All these variables are, of course, time dependent.

Where the concentration is concerned, numerical simulations allow to divide its entire range into five domains. Since speed influences pollution to a lesser extent, only three domains were considered. The unbalance, for both concentration and speed is quantified by values -1 and 1, zero assuming almost equal traffic conditions in both the exit sections.

Since these boundary values had to be determined by simulation, they may not represent the most suitable subdivision. However, there has been no need, till now, to adjust these values.

The combination of the four above defined variables yields 135 ( $= 5 \times 3 \times 3 \times 3$ ) possibilities and therefore may address 135 tables. Each of these tables contains the setting points of all the fans in the system, and therefore clearly defines one operating point of the tunnel ventilation, which would, at least if the underlying model is simulating the reality properly, satisfy the fresh air requirements in each part of the tunnel. In the case of a systematic discrepancy the boundaries of the domains of the traffic variables may, as previously mentioned, be automatically adapted.

One of the real difficulties of this kind of approach are the boundary effects. Indeed, it is almost impossible to study in advance all possible call sequences of the above mentioned tables. Therefore, it will never be sure that no conflicting situations would occur, e.g. starting up a fan that was ordered to stop during the previous control cycle.

However, during the 3 last years that the application ran, we never noticed such a conflicting situation, but this does not prove that there were not any.

## OPERATIONAL EXAMPLE

To illustrate the working and efficiency of the Belliard tunnel ventilation control algorithms, let us describe, with real-time recordings at hand, a situation where the traffic starts to jam.

### Traffic

On the recording of camera TC09R (fig. 5), dated 26 July 95, one can see that, between 17:00 and 17:15, a traffic incident is about to happen : the vehicle flow leaving the Cortenberg section is decreasing slowly and progressively while the number of vehicles entering the tunnel remains constant (see fig.6).

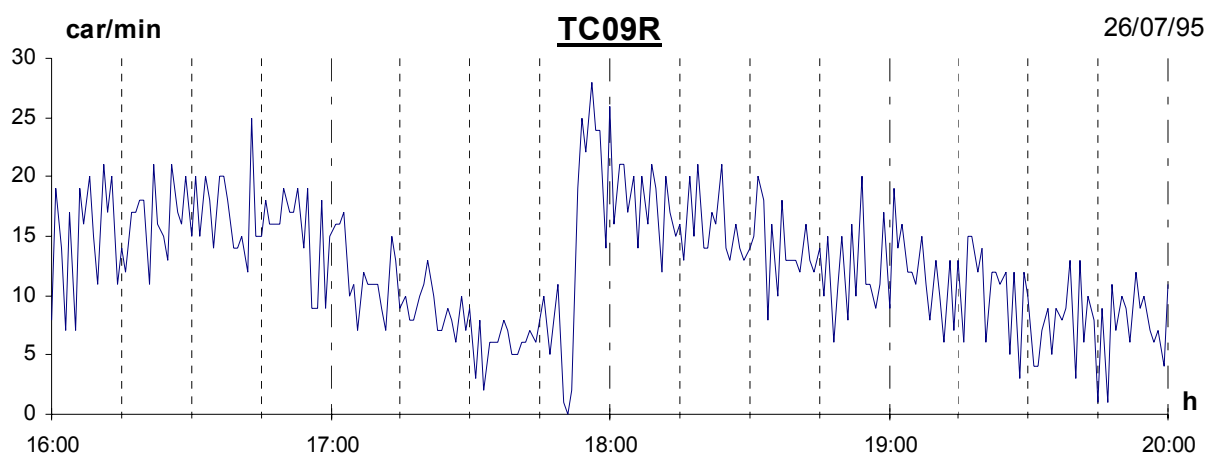


Figure 5. traffic flow at exit of Cortenberg (right lane)

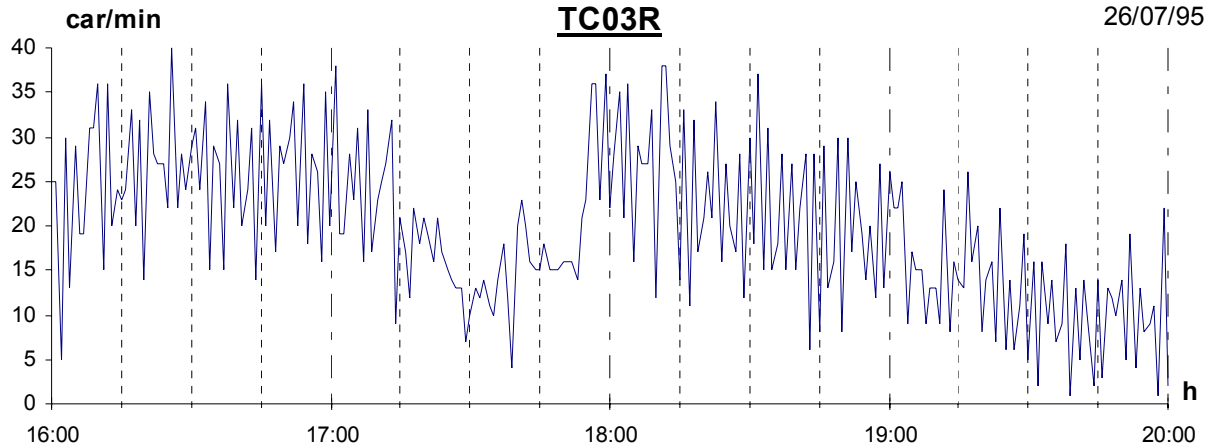


Figure 6. traffic flow at entrance of Cortenberg (right lane)

After 17:14, one can read from the same recording of camera TC03R (fig.6) that the traffic starts also to congest at the entrance of the Cortenberg section. Within 3 min, the average speed has dropped from 77 km/h to 40 km/h, and then further still to 29 km/h. At 17:54, at the same localisation, the traffic jam has suddenly disappeared, and within 3 min the traffic speed has increased from 27 km/h, to 33, and finally up to 62 km/h. The traffic flow on this lane has now dropped from 25 vehicles/min to 15 vehicles/min.

At 17:50, and until 18:01, at the exit of the Cortenberg section, on the left lane, the camera TC09L (fig. 7) shows that the traffic flow has suddenly increased from 11 up to 30 vehicles/min, while it has been interrupted for 2 minutes on the right lane (see fig.5). This shows the end of the incident.

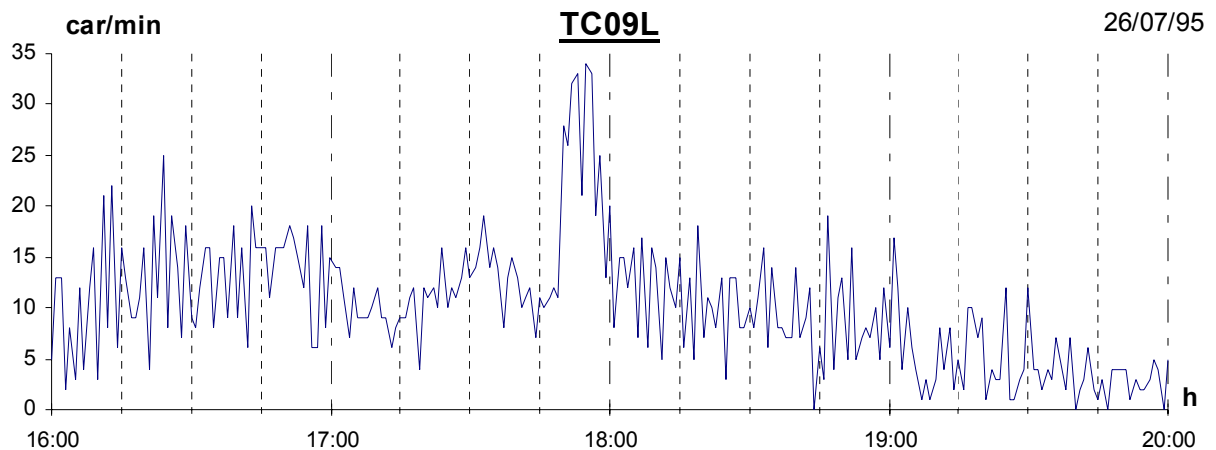


Figure 7. traffic flow at exit of Cortenberg (left lane)

Resumption to the normal traffic speed in the tunnel doesn't take long coming : between 17:53 and 17:56 it goes up from 18 to 62 km/h at the splitting of the sections Schuman and Cortenberg (see fig.8).

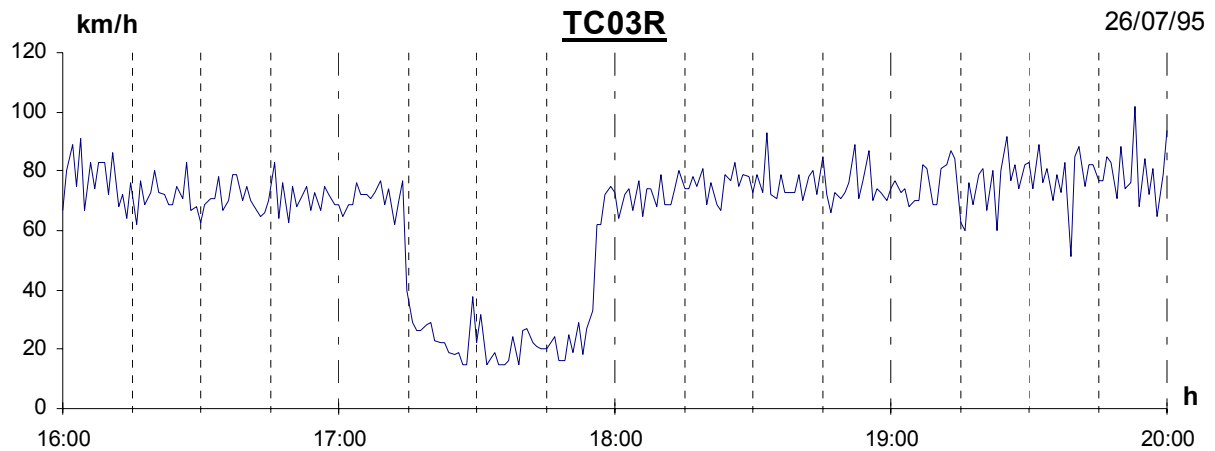


Figure 8. Traffic speed at splitting of Cortenberg and Schuman

The development of a traffic congestion can be explained using the theory of attractors : the traffic speed changes almost instantaneously from one value to another. A minor incident may trigger this phenomenon, in the same way that a slight opposite reaction could make it totally disappear.

### Ventilation

At 17:16, the new traffic situation seems to be identified by the expert system. In order to anticipate the potential risk of an higher pollution level, it is necessary to adapt the ventilation. Therefore, the new values of traffic concentration and speed are used to determine the address of the corresponding ventilation table, the content of which is then sent to the control automaton. The latter takes charge of dispatching the new setting points of all the fans involved by activating their local control units. Four minutes later, i.e. at 17:20, the new ventilation level is achieved.

Between 17:50 and 17:55 the traffic incident is closed. There is no more need for further mechanical ventilation assistance, and thus the fans are switched off. This intervention is clearly illustrated in fig.9, which shows the air flow volume of one of the fans involved, i.e. the injecting fan I015 (see fig.3).

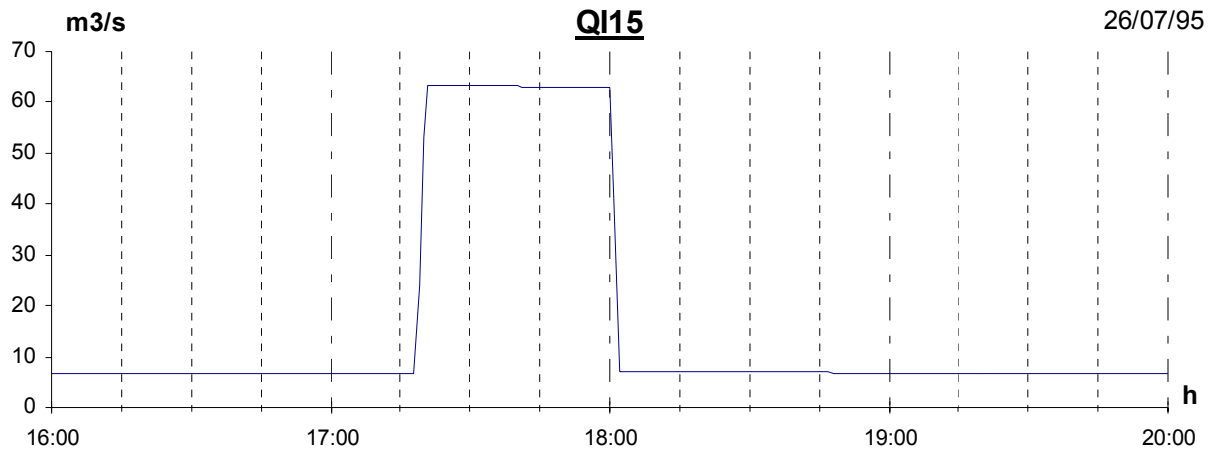


Figure 9. Air flow volume of fan I015

### Air flow volumes

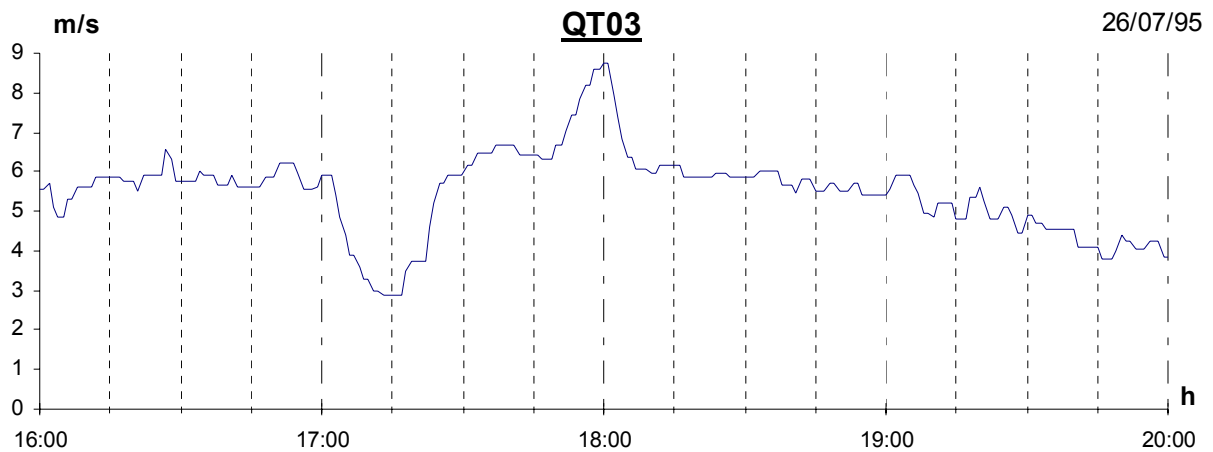


Figure 10. Air velocity at the Cortenberg exit portal

The velocity of the air flow recorded by the ultrasonic device QT03 (see figures 3 & 10) located near the exit portal of the Cortenberg tunnel, is decreasing gradually between 17:02 and 17:11. Clearly it is due to the piston effect of the traffic that slows down from 6 to 3 m/s. After the ventilation has been started up, at 17:20, the velocity went up again to a value of 6 m/s.

After 17:50, the velocity increased up to 9 m/s, then dropped to its normal value at 18:05. This is explained in the first moments by faster traffic and later on, by the switching off of the mechanical ventilation.

### Pollution

Up to a certain point the growth of the pollution is « normal ». This is due to the increasing traffic leaving the city at the end of the afternoon. This is also true for the CO concentration, recorded by the CO07 meter (see fig.11), as well as for the NO<sub>2</sub> concentration, measured by the NO23 meter (see fig.12), both sensors being located near the exit of the Cortenberg section.

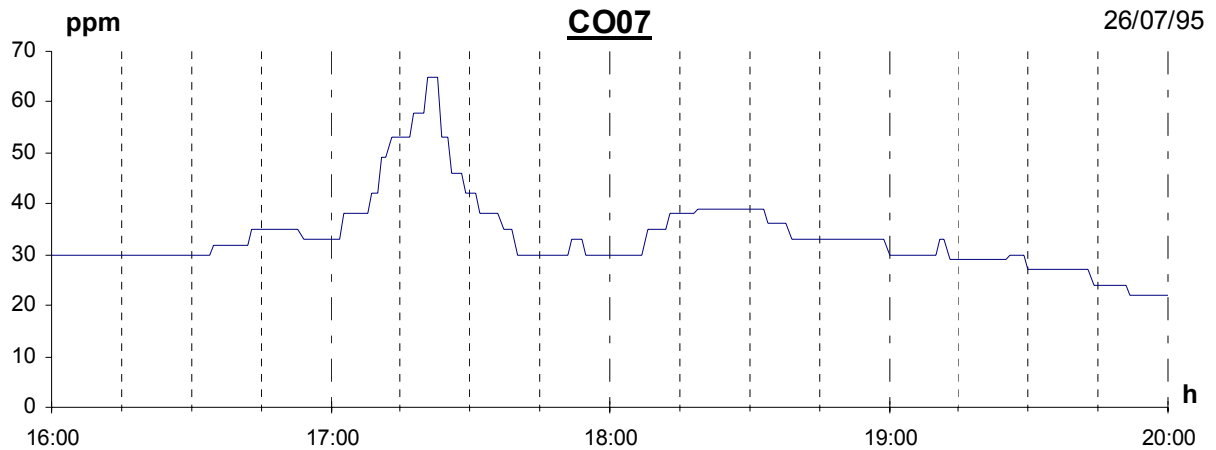


Figure 11. CO concentration near the Cortenberg exit portal

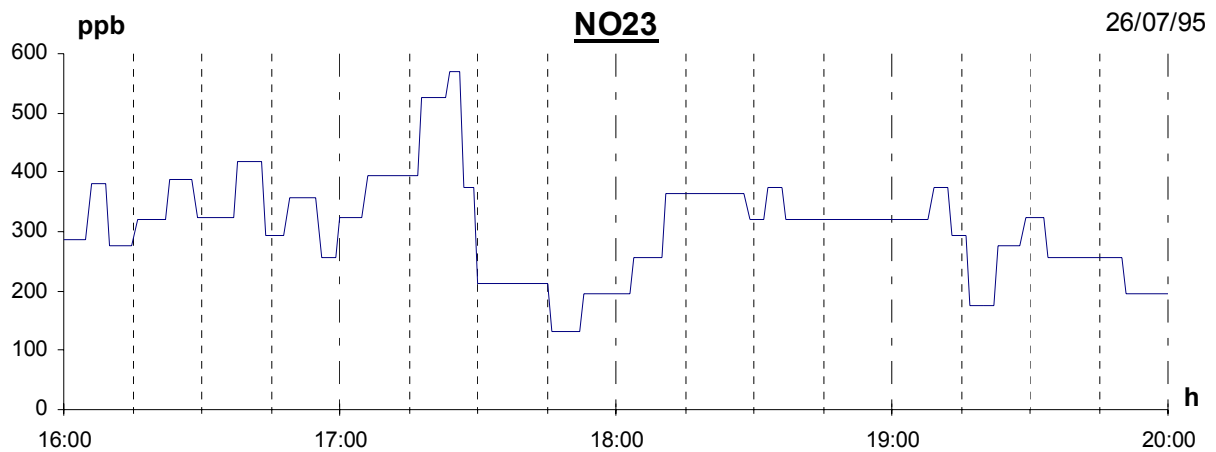


Figure 12. NO<sub>2</sub> concentration near the Cortenberg exit portal

Then, the local pollution concentration at the same location, while remaining small, indicates the beginning of a traffic problem. The pollution increase at the entrance of the Cortenberg tunnel only appears at 17:19. This increase is mainly due to the reduced air flow volume by a smaller piston effect, rather than to the increasing traffic flow.

When the traffic jam starts to develop, the expert system expects an excessive forthcoming pollution and decides to start up the mechanical ventilation. As a consequence, the air velocity in this part of the tunnel is boosted up, so compensating the lack of piston effect. The CO concentration decreases towards the exit while it remains unchanged in the entrance part of the Cortenberg section. In the case of NO<sub>2</sub>, the concentration fades away significantly after the ventilation has been switched on.

By way of conclusion, it is worth noting that the action on the ventilation would not have been as fast, if the recording of the CO concentration, and respectively the NO<sub>2</sub> concentration, was used instead of the traffic information. This is due to the fact that the cause is taken into account rather than its consequence, i.e. the pollution, which is further more dependent on the ventilation itself.

The direct result is, therefore, not only energy saving, but also a much smoother pollution profile.

## **NOMENCLATURE & ABBREVIATIONS**

CCATS	<u>C</u> amera & <u>C</u> omputer <u>A</u> ided <u>T</u> raffic <u>S</u> ensor
CFD	<u>C</u> omputational <u>F</u> luid <u>D</u> ynamics
FID	<u>F</u> lame <u>I</u> onisation <u>D</u> etector
HC	<u>H</u> ydro <u>C</u> arbon
MTBF	<u>M</u> ean <u>T</u> ime <u>B</u> etween <u>F</u> ailure
STEL	<u>S</u> hort <u>T</u> erm <u>E</u> xposure <u>L</u> imit
TLV	<u>T</u> hreshold <u>L</u> imit <u>V</u> alue
TWA	<u>T</u> ime <u>W</u> eighted <u>A</u> verage
VMS	<u>V</u> ariable <u>M</u> essage <u>S</u> igns
VOC	<u>V</u> olatile <u>O</u> rganic <u>C</u> ompounds

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