BASICS IN TUNNEL VENTILATION CONTROL

E. JACQUES
Department of Mechanical Engineering, Université catholique de Louvain, Belgium
jacques@term.ucl.ac.be

ABSTRACT

Where the introduction explained briefly the benefits that could be drawn from an efficient ventilation control system, this paper aims at giving a general survey of the needs and the difficulties encountered when applied to routine ventilation. It also focuses the attention on elements that already have to be considered at the early stage of the project. These elements should enable the designer to decide whether a ventilation control system would be suitable or not. Particular aspects which are not necessarily difficulties but should not be overlooked, are also put forward.

The paper goes successively through the control principles that may be applied to classical ventilation systems in single tube tunnels and in mixed ventilation systems. It touches on difficulties with multiple fan systems and ventilation systems with more than one fresh air supply unit.

The control loops, whether they would be automatically or manually operated, may use as actuating variable measured quantities that are either concentration values of one or more contaminants or traffic characteristics. A more optimal solution would be a combination of both.

Particular attention is drawn to all aspects concerning the quality of the input data and their information content. The choice of certain control variables is also discussed.
It should be understood that the paper does not address the particular aspects of fire and smoke control which is a topic on its own.

KEY WORDS

VENTILATION CONTROL / ECONOMY / PREDICTIVE MODEL / POLLUTION / TRAFFIC

1. INTRODUCTION

Energy is undoubtedly now more than ever a major concern. Ventilating tunnels entails substantial energy costs. Except for a few particular cases where air is being reconditioned inside the tunnel, reduction of pollution is commonly obtained by increasing the input amount of fresh air. In fact, the concentration of any pollutant expresses itself as the ratio of the volume of this pollutant divided by the volume of air that is available. Both quantities are usually considered per unit of time.

The volume of pollutants produced by traffic is, of course, in the first place a function of the category of vehicles, their density and the average traffic speed. Density is the number of vehicles per unit of length. Category denotes the type of vehicle that can be either a personal car, a truck, a light van, etc.

Most tunnels are not equipped with a system that would act directly on the entering traffic flow. Therefore, the tunnel operator has very little hold on the total volume of pollutants that is produced in his tunnel and that is, moreover, variable in time. The only manner he has to limit the pollution concentration to an acceptable level is by supplying more fresh air and thus by boosting the available mechanical ventilation system. Of course, in periods of low traffic he should decrease or even stop the ventilation. The optimum would be that he ensures, at any time, there is just enough fresh air in every section of the tunnel. This operation of regulating the ventilation needs an ongoing surveillance and would, therefore, be carried out by a process controller at least as reliably as by a human being.

Controlling the ventilation is only beneficial if there is an economical balance between the increased capital and maintenance costs of additional equipment on the one hand and lower energy consumption on the other. Where long and heavily used tunnels are concerned, it is not exceptional having energy expenses that exceed € 10 000 /km/month. Reducing these costs, if it were only by 10 or 15 %, would certainly pay off.

But, even if financial calculations would show a profit, the technical difficulties of implementing an efficient control system should not be overlooked. These difficulties are all the more overwhelming that the more the complexity of the tunnel increases. Complexity may result either from the geometric layout of the tunnel or from the ventilation system itself, but often both aspects are intrinsically linked.

2. OUTLINE OF THE PAPER

The paper aims at giving a general survey of the needs and the difficulties encountered with tunnel ventilation control in routine operation. It provides elements to decide whether a ventilation control system would be suitable or not and draws the attention to particular aspects and difficulties that should not be overlooked.

The paper goes successively through classical ventilation systems in single tube tunnels, with or without mixed ventilation systems. It also touches on the difficulties that arise with several independent air supply stations due to a more complex layout of the tunnel.

However, the paper does not address the particular aspects of fire and smoke control. This is a topic on its own.

3. OBJECTIVES OF VENTILATION CONTROL

The first objective of ventilation control in normal operation is primarily the reduction of energy consumption. No doubt, adjusting fan speeds to comply with variable traffic conditions could introduce marked savings. Although ventilation control entails additional capital investment costs, they are relatively low compared to the overall equipment budget and could have a pay-back of a few years. Indeed, pollutant sensors and surveillance systems are already part of the everyday equipment in a tunnel. Traffic sensing devices are installed in heavily used tunnels and are likely to become part of the standard tunnel equipment in the near future. The major additional investment costs would then only be due to development, implementation and maintenance of the control system itself.

A second objective appears when dealing with complex tunnel systems. Besides an economical one, the objective here is to ensure in each of the sections of a tunnel and at any point in time, air volume rates are within health and safety standards. This concern entails the need for a discriminatory control of the separate sections of a tunnel without adverse interference effects between them.

4. VENTILATION CONTROL SYSTEM

The ventilation control system is like any control system, an arrangement of components that are related in such a manner so as to direct or regulate a process. Depending on the level of automation, one may recognise ventilation control systems that are :

- fully manual, i.e. where an operator watches either pollution or traffic behaviour by sensors or cameras and decides himself how to set the ventilation accordingly,
- semi-automatic, i.e. where the controller suggests a change in ventilation but the decision to activate it, is up to the discretion of the operator, or
- automatic, i.e. where one or more processing units, on basis of collected information adapts the ventilation to satisfy a reference set point.

Either the control task is an easy one like "pollution goes up, supply more air" or "pollution goes down, decrease or stop ventilation", and any controller will be able to do this task more steadily than a human being.
Or the control operation is more complex because several fans or separate ventilation sections are involved. In that case, it makes it far more difficult for the operator to take the right decision, if not the optimal one.

Therefore, for routine operation, a well designed controller should be preferred to manual interventions. However, the control system must be designed in a manner that it allows the operator to regain full manual control whenever he needs to, for instance in case of hazards such as fire, accidents, toxic gas release, etc.

The most important characteristics of a well designed control system for routine ventilation should include :

- Stability of the ventilation that translates itself in a smooth and steady adaptation in time and also in space if more complex or mixed ventilation systems are concerned ;
- Reliability through simplicity of both software and hardware components that set up the entire control system ;
- Robustness by which the system is tolerant to limited or temporary data drop outs caused by failures of sensors or any transmitting equipment ;
- Efficient in its function as a control tool i.e. maximum comfort for minimum operating costs.

4.1. Control method

Classical control is a series of ventilation corrections in response to changing environmental conditions in a tunnel. The major shortcoming of this method is obviously its "running-behind" characteristic that tries to correct a bad situation rather than to avoid it. A too simplistic approach or design may also lead to an unpredictable number of start and stop operations of the ventilation equipment which would certainly have an adverse effect.

A better alternative method would be one whereby conditions in a tunnel can be predicted. After measuring the parameters that describe the traffic, a control unit would assess the total quantity of pollutants produced, calculate the air flow rate that is necessary to dilute them and return the economical fan settings. The advantages of this approach include a greater stability of the ventilation and its capability to anticipate the upcoming pollution (Ichikawa et al., 2000 ; Jacques, 1999).

Obviously, both approaches can be combined. One solution would be to use both data, i.e. pollutant concentration measurements and the ones that are predicted by monitored traffic characteristics. A weighed combination of these values would provide the actuating variable (Ohuchi et al., 1994). A different solution would be to use one of these two data as a surveillance information : either the system would set an alarm if the discrepancy between the two values were excessive and call for a manual intervention if these alarms are too frequently set, or, in a more sophisticated version, would correct the actuating variable by using a so-called reconciliation model.

Generally, if disturbing elements due to e.g. fluctuating wind conditions or variable bi-directional piston effect dominate, it is not obvious that a feedback pollution based control loop would be more efficient than an open loop predictive method. Stability criteria, limitations on the number of start and stop operations of a fan, response time of sensors, quarter hour peaks, etc., would in any case restrict the number of ventilation correcting operations within a certain time span, for example at maximum three or four settings per hour. Because of these constraints, it is turns out that classical feedback control is poorly suited for tunnel ventilation control where energy savings being aimed for. This is all the more true if this method were to be applied to a tunnel that has several independent ventilation sections.

The control algorithms and tools necessary to develop a ventilation regulator are beyond the scope of this paper. Note that besides classical solutions which include feedback (Mizuno, 1997), feed forward and predictive models (Ichikawa et al., 2000), more unconventional techniques such as fuzzy logic (Katijima et al., 1997) or genetic algorithms (Ichikawa, 1998) have been applied in a few cases.

4.2. Input data

At this point it is important to recall that no control system, whether automatically or manually operated, would ever function satisfactorily if the quality of the measured input data was poor. What must be understood by quality will be looked at under the heading "Quality of measured information".

For most known ventilation control systems the controlled variable is CO-concentration, except for these tunnels where traffic has a significant percentage of heavy duty vehicles with diesel engines ; here visibility is also a major concern.

However, CO-concentration as controlled variable becomes more and more questionable due to the advanced technological developments in catalytic exhaust pipes. For example, recordings in the Cointe highway tunnel ([1]) where traffic speed is limited to 80 km/h show that the CO-concentration stays as low as 5…7 ppm, in spite of high traffic volumes (60 to 70 thousand vehicles/day) and mechanical ventilation being switched off. However, this observed CO-concentration does not necessarily mean that the air quality complies within all other health standards.

---

[1] Liège, Belgium

4.3. Representative pollutant

In order to obtain an effective control system for all known harmful pollutants, the controlled variable should be a representative pollutant. Being "representative" means that this specific pollutant would act as a kind of reference tracer, the concentration of which would indicate the most toxic or dangerous situation. Without entering into the chemical complexity of exhaust gas production by engines and their possible interaction with the atmosphere, it is common knowledge that some components are e.g. produced in relatively larger quantities at low vehicle speed, others at high speed.

A way to cope with this difficulty would be to calculate for each concerned pollutant an average volume rate that is emitted by a typical fleet driving through the tunnel at a certain speed. The ratio of the average concentration of each of the pollutants to their respective threshold limit values (TLV) would yield a toxicity factor. These factors are plotted versus speed. The curve through all the maximum values would then represent the most unhealthy, probably virtual pollutant as a function of speed. This curve, put in correlation with real-time measured concentrations of pollutants such as CO, NO_x/NO_2 and particles, could be used to determine the required air volume rate that dilute all considered agents in an acceptable manner.

4.4. Maximum value versus time-averaged value

From a medical point of view, it is known that some contaminants become harmful when their concentration in the air exceeds a tolerable maximum value. For other components it is rather the quantity of the substance PL that matters. In the latter case the average concentration is calculated as $[PL]_m = \frac{1}{t}\int_0^t [PL]\,dt$, where [PL] is the instantaneous concentration that the driver experiences during his travel through the tunnel and t the time that he is exposed to. Indeed, the harmful quantity that he inhales is more important due to the fact that it takes him more time to drive through the tunnel. Strictly speaking, for this category of contaminants permissible concentration levels should then be expressed as a function of cumulative exposure, and not of local peak values.

A well designed ventilation control system should take this phenomenon into account. Intrinsically, introducing this concept of cumulative exposure or dose has a stabilising effect on the regulator. The inconvenience, however, is that the control logic needs to be assisted by a calculating unit since this information can no longer be retrieved from a single pollutant sensing device.

4.5. Traffic characteristics

Because traffic is the direct source of pollution, the idea of using traffic parameters as primary input information rather than the resulting pollutant concentrations is straightforward. Parameters such as speed, flow and occupation can be measured reliably. Derived information such as traffic density, i.e. number of vehicles per unit length, and vehicle category is directly useful because it enables one to have a fairly good estimate of the total number of vehicles that are present at any one time in the tunnel.

But, since the worst contaminant concentration provides or should provide the controlled variable, the traffic parameters must in any case be linked to pollutant emissions. For each category of vehicle one needs to know the amount and the composition of the exhaust gases. Abundant literature on this matter exists but the weak side of this kind of information is still that the data have mostly been obtained on test benches for typical or standardised driving cycles. These driving cycles are often not the ones encountered in tunnels. Fortunately, most tunnels impose their own typical driving cycle and, therefore, it is possible after a certain follow-up period to correlate with rather good confidence, traffic parameters with pollutant volume emissions inside this tunnel.

The set of actual measured traffic parameters enables the processing unit of the controller to calculate, on a statistical basis, the volume rates of each of the emitted contaminants. At this point one is brought back to the above mentioned scenario, but with one major advantage : the predicted values of the most dangerous contaminant can now be used to calculate the required fresh air volume rate instead of the single measured one.

It is worthwhile noting that this traffic based control system can be simplified by one more step. Indeed, after a set up period, knowledge of the air flow rates is no longer needed because the duty point of the fan system may be linked directly to a well defined combination of the traffic parameters.

The advantages as well as the inconveniences of this open loop approach have already been outlined and discussed in (Jacques, 1999). However, one major advantage should be recalled : a traffic based control system has the ability to anticipate ventilation actions since the system may incorporate measured information of the traffic before it enters the tunnel. It may even take traffic forecasts into account where experience shows that similar traffic patterns recur on a periodic basis, for example daily or weekly.

4.6. Quality of measurements

A sensor may be accurate and even be frequently calibrated, it does not necessarily guarantee that the retrieved data informs correctly about the process that one is trying to control. For example, a contaminant concentration may be measured at a location where the air is now and then stagnant or re-circulating and, therefore, would provide a biased information about the real concentration in the air that flows through the tunnel.

Quality of information means, therefore, that the measured values have been checked on validity and likelihood. The next example may clarify this point or idea. In a longitudinal ventilation system it is expected that pollution concentration increases from the entrance portal towards the exit of the tunnel. If one considers three CO-sensors along its axis it would be expected that the middle one shows a value somewhere in between or close to one of the two others. A significantly exceeding or high value would probably be explained by a failure or an exceptional cause, as already experienced, for example, in the Leopold II tunnel (Brussels, Belgium) where the exhaust pipe of a maintenance truck stayed for a while close to a CO-sensor. This very local and temporary phenomenon must not in any way and without prior questioning boost the entire ventilation.

5. APPLICATIONS

The degree of sophistication of a control system depends strongly on the type of tunnel and the kind of ventilation method it has to deal with.

At this point it should be understood that the ventilation systems surveyed next are defined from their operational point of view and not as they were initially designed or built. For instance, a ventilation system with transverse capabilities may be used in routine operation as a semi-transverse system and, will therefore, be considered here as a semi-transverse one.

5.1. Single tube tunnel

5.1.1. Longitudinal ventilation

If the tunnel is a single tube, either one-directional or bi-directional and longitudinally ventilated, the air flow rate is in principle one and the same all along the tunnel. This means that the control system has to deal with one ventilation set point at a time.
Controlling the pollution level is then a matter of providing fresh air at a rate consistent with the comfort of the tunnel user. If Q_a is this diluting rate and Q_{PL} the produced volume rate of pollutant PL, the volumetric concentration [PL] is theoretically equal to Q_{PL} / (Q_a + Q_{PL}), practically to Q_{PL} / Q_a .

In continuous and steady traffic flow conditions, the air volume rate required would be the one that satisfies the constraint $[PL] = [PL]_b + Q_{PL} / Q_a \leq TLV$, where $[PL]_b$ is the background or initial concentration of the considered pollutant PL in the air and TLV (Threshold Limit Value) its maximum tolerable concentration.
Obviously, this dilution requirement must be true for any pollutant. The highest requirement will then determine the fresh air volume rate that complies with health and safety standards.

Three points are worth being highlighted at this stage :

1. It should be clear that the highest required air volume rate for a given traffic flow is not continuously determined by the same contaminant, because the produced quantity of a particular pollutant is mostly dependent on the vehicle speed and the driving behaviour, this dependency being generally non-linear.
2. The equation may be applied separately to two or more contaminants within the same space as long as these contaminants do not react with each other.
3. The determined air volume rate Q_a is not necessarily the one that must be ensured by the fans. Traffic induced ventilation and natural ventilation could contribute, but the opposite is also true. For example, traffic induced ventilation in bi-directional tunnels may cause inverse and variable meteorological conditions which could now and then exert an adverse influence.

Furthermore, if traffic volume is significantly changing throughout the day it generates transient pollution conditions in the tunnel. A more realistic model that takes into account the pollution situation that existed during the previous control cycle, should then be applied :

$[PL]_{t+\Delta t} = [PL]_t + \frac{Q_{PL}}{Q_b} + Q_a \frac{\Delta t}{V}([PL]_{i,t} - [PL]_t) \leq TLV$, where Q_a is the air volume flow rate, Q_{PL} the volume production rate by traffic, V the tunnel volume, $[PL]_i$ the initial pollution concentration in the air, t the time and Δt the inverse of the control frequency.

Whatever approach is adopted, i.e. permanent or transient, the minimum ventilation rate Q_a must be linked in some way to the actuating signal, i.e. the number of fans that need to be operated. This fan operating procedure could be achieved by a human operator, but a well designed automatic regulator would probably be more reliable.

However, many more aspects need to be taken into consideration when developing and implementing an efficient control system. They are :

- nature of the pollutant and the way it should be taken into account, i.e. either as a peak value or as a time averaged toxicity level,
- quality of the measurements, and their spatial distribution along the tunnel,
- time delays due to transition periods between different ventilation levels,
- limited power availability in case of mechanical or electrical failure,
- avoidance of quarter hour peaks, etc.

Moreover, some longitudinally ventilated tunnels are equipped with a local exhaust system that is designed to extract the polluted air before it leaves the exit portal. The airflow direction may then additionally be controlled by reversible jet fans in this exit section of the tunnel. Obviously, in this configuration the ventilation system has at least two independent fan units to be controlled and, as such, it must be addressed as a multiple fan system.

5.1.2. Transverse ventilation system

5.1.2.1. One ventilation facility

If the tunnel has only one ventilation facility, i.e. a facility with only one fresh air flow output although it may contain more than one fan ([2]), the control problem may be handled in a similar way as the one in the case of longitudinal ventilation. In a full transverse ventilation system a simple model shows that the average concentration, as a function of time, is ruled by the expression $[PL] = Q_{PL} / Q_a (1 - e^{-Q_a t})$ where Q_a is the air volume rate supplied by the fan facility and t the time.

Thus, only one air flow rate has to be considered, although it may change over time. The ventilation control problem can, therefore, be approached in a similar manner as the one in the longitudinal one. Again, the natural and traffic induced ventilation will make the system more difficult because the air flow rate in the tunnel would be no longer identical to the flow rate produced by the fan facility. The resulting ventilation flow rate in the tunnel is in fact a combination, variable in time, of a transverse and longitudinal system, or of a transverse and a semi-transverse system if the exhaust is regulated independently.

Concerning the choice of the input control variable and the quality of the measured data, the ideas are quite similar to the ones previously developed for the longitudinal ventilation. In the presently concerned case the input variables may also be either one, pollutant concentration or traffic identification, or a combination of both. Either choice, it is important to stress, once again, that quality of the measured input information is the key element in making the control system work correctly.

5.1.2.2. Two or more ventilation facilities

If there are two or more ventilation facilities that could be operated independently and that supply fresh air in the tunnel by different ducts and openings, one may have to choose which one to operate.

At maximum ventilation demand, provided that the overall power had been correctly dimensioned, there should be no problem since all the fans are prompted for maximum capacity.

But in all other cases, the air flow rate could probably be supplied by one or more fan units or by a weighed combination of them. Tunnels of a certain length have mostly two or more

[2] It is implicitly understood that the exhaust fan station has an identical air flow output

ventilation sections served by independent fan units or stations. Numerical simulations show that in case of partial ventilation load, different supply combinations may exist for a particular air flow rate requirement in the tunnel. However, these combinations are not all equal from the energy consumption point of view. An efficient control system should then use those fans that maintain the overall energy consumption at minimum without violating the air quality standards.

5.1.3. Semi-transverse supply ventilation system

5.1.3.1. One ventilation facility

A semi-transverse supply ventilation system can be considered as creating a longitudinal ventilation flow where the volume rate increases steadily along the tunnel. If one considers that two successive fresh air blowing openings along the tunnel are ΔL meters apart and that it may be assumed that the supply volume rate Q is distributed equally over n openings so yielding ΔQ = Q/n , one may write that the concentration of pollutant PL in section i+1 is approximately :

$$[PL]_{i+1} = \frac{[PL]_i Q_i + Q_{PL} + [PL]_b \Delta Q}{Q_i + \Delta Q},$$

where Q_i is the volume flow rate up to section i, Q_{PL} the volume rate of pollutant PL produced by the traffic and $[PL]_b$ the background concentration (mostly negligible) in the intake air. This equation shows that the pollution increases so that the maximum concentration may be expected close to the exit portal of the tunnel. In this case, the control procedure is similar to the one applied in a longitudinal ventilation system.
One should be aware that this model implies a flow direction from the entrance towards the exit of a one-directional tunnel. This is mostly the case since ventilation should only be switched on when traffic is important which then generates a sufficient piston effect.

But in empty as well as bi-directional tunnels, the air may leave at both portals and at rates that are variable in time. The balance between these volume rates depend mainly on the external meteorological conditions and/or on the direction of the predominant traffic flow. Economical ventilation control in this latter case becomes, if possible at all, so challenging that it is beyond the scope of this paper.

5.1.3.2. Two or more independent supply units

Similar to what has been explained for transverse systems, where the designer was also faced with the necessity of having to choose between one or more air supply units in case of a reduced ventilation requirement. The COINTE tunnel is an illustrative example of a semi-transverse system with two separate ventilation sections served by two independent air supply units. But, because this tunnel is additionally equipped with jet fans, its operation will be described in the next paragraph that concerns mixed ventilation systems.

5.2. Mixed ventilation systems

5.2.1. Longitudinal ventilation with intermediate or local air renewing

This system is obviously a mixed system as seen on figure 1. Any pollution excess recorded by the meters calls for more fresh air in the tunnel. A priori, this increment of air flow rate can be achieved either by a few jet fans of the first group (represented left on the figure) or by a few of the second group (right on the figure), or by the combined exhaust and SACCARDO injector system. On top of this, one can imagine that there are also different combinations of these groups that must yield an acceptable pollution level.

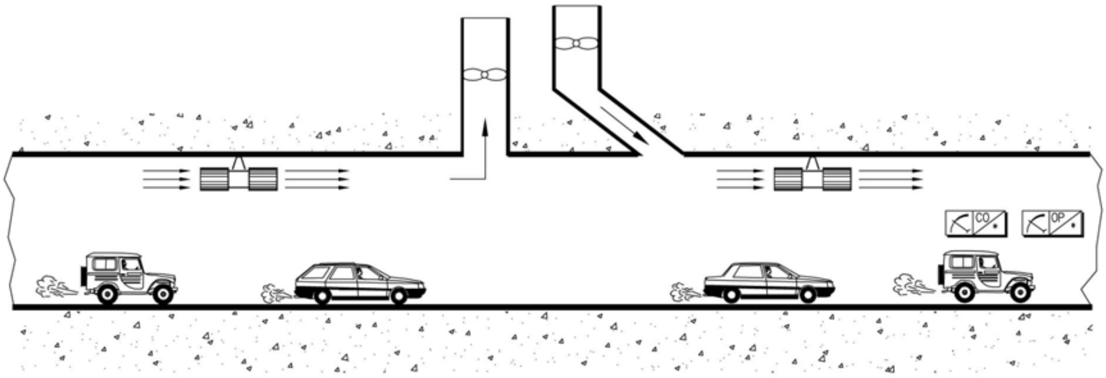

Figure 1 - Longitudinal ventilation, SACCARDO system

As may be expected, numerical simulations show a different energy consumption for a few of these fan combinations while almost the same air quality was maintained at the point where the instruments are located. This does not necessarily mean that the pollution elsewhere in the tunnel shows a similar profile.

This example may give an idea of the complexity of such a control system. Computer simulations for the 2.5 km-long Leopold II tunnel ([3]) that has basically four similar schemes in series, show that the energy differences may be significant.

But, apart from any economical aspect, one can imagine that these results would have looked differently if the traffic had been variable, not only in time but also along the tunnel. If traffic density and speed change only in one section, for example, due to the existence of a lateral exchange road, the resulting emission rate and piston effect will both change in that section. As a resulting effect, the pollutant concentrations in the considered section would change but not always in an expected manner. Moreover, since all tunnel sections are part of the same network, it is likely that changes in pollution concentrations may also occur in adjacent sections. It would, therefore, be the job of the controller not only to adapt the fresh air flow in the concerned section, but also to restore the initial situation in each of the sections where it has been disturbed.

Generally, the objective of ventilation control here is not exclusively to minimise energy consumption but there is a second concern : to supply the air in the entire tunnel in such a way that an acceptable quality of air is ensured in all of its sections.

5.2.2. Semi-transverse ventilation system with enforced longitudinal component

The COINTE tunnel may be considered as a representative example of a mixed ventilation system. It combines a semi-transverse system that extends over the main part of the tunnel with a longitudinally enforced flow by jet fans.

5.2.2.1. Geometrical layout

The COINTE tunnel is a twin bore across a hill in the city of Liège, linking two highways in Belgium. Each tube has two lanes. Since this highway link crosses the core of the city,

[3] Brussels, Belgium

the bored tubes (each around 1.3 km long) extend on both sides by a covered section of approximately 150 m long. These extensions give access to local areas and bring the total length of this tunnel up to 1.6 km.

5.2.2.2. Ventilation system

The ventilation, initially designed only for the bored section of the tunnel, is a semi-transverse system with two independent ventilation units, one at each end. As seen in figure 2 that is a schematic representation of one tube, each of the two fan facilities, i.e. V_1 & V_4 , supplies the tunnel with fresh air over half of its length, the airways being separated by a (closed) median damper located in the middle of the fresh air duct. The fresh air is then blown into the tunnel by vents, approximately 10 m apart, located at road level.

The covered extension sections of the tunnel with their lateral access roads required an additional local ventilation equipment. A longitudinal system with jet fans has been installed there. As a result of this choice, the ventilation of the entire tunnel is operated by a combination of two systems which are not independent, but they rather interact. Indeed, limited airflow rates could be provided either by the semi-transverse system or by the jet fans, or a combination of them.
Additionally, an independent extraction system has been designed to discharge most of the polluted air through an exhaust shaft (marked as CHERA chimney in figure 2,) before leaving the portals.

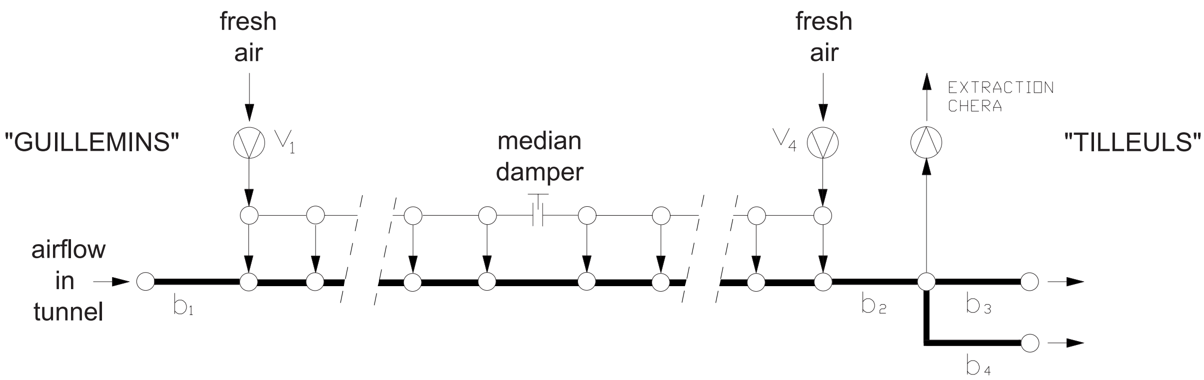

Figure 2 - Equivalent hydraulic scheme of the fresh air circuit in the AMONT tube.

5.2.2.3. Operating the ventilation

The combination of two independent fresh air supply fan facilities, one extraction system and several jet fans, yields a fairly complex ventilation system to operate.

Since both tubes in the COINTE tunnel are reasonably identical, only the AMONT tube will be taken as an example to show the kind of complexity that may arise if an optimum operating of the ventilation is aimed for.

Fresh air is brought into the tunnel by fans V_1 and V_4 . It is distributed along the tube through openings every 11 m. Jet fans in sections b_1, b_3 and b_4 can be operated independently in order to boost the air flow along the tunnel. Besides enforcing the longitudinal flow, these jet fans can also be used to balance the airflow rate between the two parallel roads that are exits b_3 and b_4 .

5.2.2.4. Measurements

The quantities that are measured and available to the controller concerned :

- traffic parameters i.e. speed, density and category of vehicles,
- pollutant concentrations, these include CO and NO_x concentrations and opacity, and,
- environmental quantities such as temperature, atmospheric pressure and airflow rate in the tunnel.

5.2.2.5. Objectives of the ventilation controller

The ventilation controller of this application needs to reach a double target, i.e. controlling the air quality in all sections and minimising the energy consumption.
In spite of simplifying assumptions, the design of this controller will still reveal some tough and challenging aspects.

For a start, it will be assumed that :

1. The traffic is fluid and at constant speed, at least during the time period between two cycles of the controller. It turns out that these assumptions match quite well with the every day reality.
2. For any given traffic speed, the pollution will normally build up along the tunnel and reach its maximum value at both outlet portals. If additionally one assumes that the traffic volume is distributed between the exit roads b_3 and b_4 in a well known and constant proportion, e.g. 80 and 20 % respectively, it suffices to watch the pollution concentration or opacity metering at either one exits b_3 or b_4 .
3. One further step into simplification would be to watch the pollution at exit of section b_2 (before splitting) rather than at either one exits b_3 or b_4. Indeed, at this point vehicles have already travelled 90 % of their path through the tunnel.

Focussing now only on the CO-concentration in section b_2, the job of the controller would be to maintain this concentration within an acceptable margin of the required TLV. Exceeding by too much this value would not be tolerated for health reasons, being too low would mean energy loss.

The exercise is then to find out by simulation what the optimum fan combination would be that satisfies the TLV requirement. Indeed, either one of the two fan facilities may contribute more or less to produce the necessary fresh air volume in b_2 , and this contribution is different if one or more jet fans are put in operation.

By systematically running all the possible fan combinations that yield the same CO-concentration while keeping in mind that e.g. the efficiency of a fan may change with its duty point, one can associate an energy cost to each of these ventilation configurations. After repeating the calculations for several CO-concentrations, a graph may be set up where the CO-concentrations are plotted versus the energy cost (see figure 3). Note that this method could be applied for any other pollutant, but the graph would most certainly look different.

One may observe that for a given CO-concentration, the graph shows a minimum and maximum cost and a certain number of in between values. They all depend on the fan combination that has been operated. Obviously, a ventilation control system would be efficient if it runs the fan combination that corresponds to the most left dot on the horizontal line of CO-concentration considered as being the TLV.

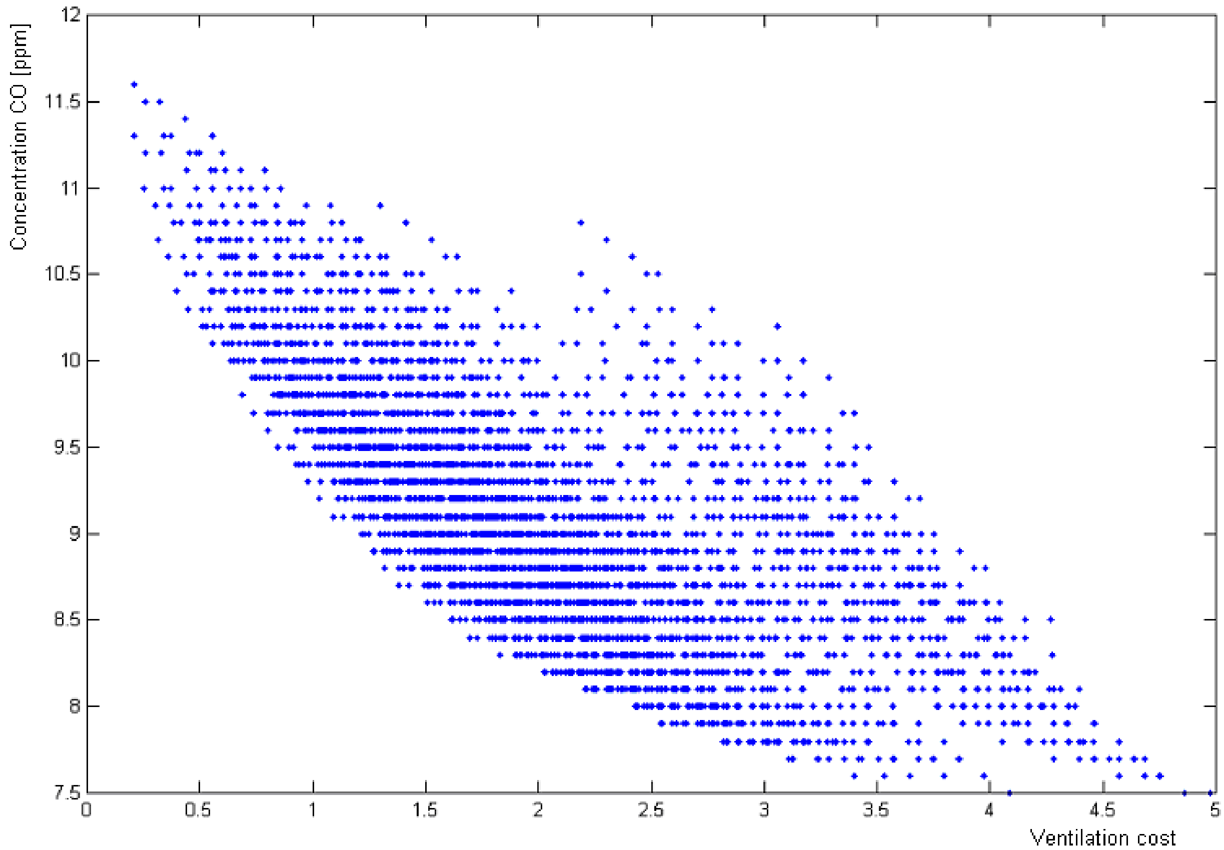

Figure 3 - Example of "pollution-cost" relationship

However, it should be emphasised that one has still more difficulties to overcome :

- The graph in figure 3 has been calculated for one traffic pattern. If traffic parameters change so will the look of the cloud within this figure ;
- Since jet fans operate only in a on/off mode, the next traffic pattern may well entail an optimum fan combination for the next control cycle that is different from the actual one. The problem then is to ensure a smooth transition between successive fan configurations without having to stop and start too frequently the same fan. This implies again a choice between either stopping certain fans and starting up others, or giving in on the optimum criterion by using the same fans but at different duty points.

It is beyond the objective of this paper to develop any solutions for this control problem. It is only demonstrated here to draw the attention to all the difficulties that may arise. It is meant as a hint towards designers who should evaluate thoroughly the future operating costs before they start to implement a mixed ventilation system.

5.3. Complexity by geometrical layout

Some tunnels, mostly urban tunnels, have important links to lateral access or exit roads. The complexity results from the fact that one or more of these links have their own independent ventilation system. In some cases, of which the BELLIARD ([4]) tunnel in is a representative example, the complex layout results from the interconnection of already existing tunnels. Each of these tunnels kept more or less its own ventilation system. A schematic representation of this BELLIARD tunnel may be found in (Jacques et al., 1997).

[4] Brussels, Belgium

The extent of the difficulty of controlling ventilation in these tunnel structures results not only from the multiplication or addition of the fan facilities but also from the underlying network structure. Solving the problem of an adequate air flow distribution in networks is already not an easy task to achieve. But optimal fan settings that are subject to several pollution constraints in different sections of the tunnel present us with such an assiduous problem that there does not seem to be a generally applicable solution available yet. Indeed, solutions obtained by mathematical optimisation techniques are not always directly applicable (Jacques, 1991).

To understand the real nature of the challenge, one must be aware that by modifying on purpose the airflow rate in one section, flow rates in other sections may change unintentionally, thus causing disruptions to the local pollution concentration balance that previously existed. Trying to restore them one after the other could result in a kind of "bouncing" game between interacting but not necessarily adjacent fans.

The control problem is in fact even more complex because the pressure distribution in such a network can play a significant role. Other aerodynamic sources such as traffic induced ventilation and natural ventilation may interfere. It is far beyond the scope of this paper to go deeper into this subject. If necessary, please refer to (Jacques, 1991).

6. CONCLUSIONS

- Where one-directional single tube tunnels are concerned, economical ventilation control is basically not a very difficult task to carry out since the operator or the automatic regulator has to deal with only one air flow rate at the time. For medium and long tunnels, this effort certainly has interesting advantages.

- Where ventilation control in complex tunnels are concerned, the human or automatic regulator has to deal with several air flow rates. Besides economical considerations, the system must also ensure or maintain a sufficient air quality within all sections of the tunnel. This concern entails the need for a discriminatory control of separate sections at the same time without adverse interference effects between them. For this latter reason, local pollution feedback must be avoided.

- For most tunnels air quality is assessed by measuring the CO-concentration and, where necessary, the air quality in terms of visibility. These measured quantities are usually also the controlled variables. Where traffic information is available it can be used separately or additionally as an actuating signal in the control process. Each of these approaches have their own advantages and inconveniences :
  - Pollution actuated control systems have the advantage of maintaining directly the pollutant concentration below a tolerable level. But they have the inconvenience of doing it on a single measurable pollutant concentration, mostly CO, that might no always be representative of the real pollution. Where visibility is the controlled variable, a feedback loop could be adopted, provided that the tunnel does not show a complex structure.
  - Traffic actuated control systems have the advantage of being independent of any problem with pollutant concentration measurements but have the inconvenience of needing more equipment and certainly a lot more models and control software to be developed.

- ➢ Whatever the control system adopted, validation of all input data is essential. Moreover, for pollution actuated controllers, the designer should focus on a pollution contaminant that is "representative" of the various harmful components in the tunnel air.

- ➢ Before building a tunnel with a more or less complex geometric layout, the designer must be aware of all the implications that his construction might bring along once control of the ventilation is aimed at. Especially in urban areas it is tempting to build tunnels with several lateral access roads or even to interconnect existing tunnels thus creating a real underground network. The designer must be aware that because of high energy costs, he will be faced with the necessity to reduce them sooner or later and thus be forced to develop a efficient ventilation control system. Then the real challenge shows itself, not mentioning all the difficulties that may arise for mastering fire and smoke movements.

REFERENCES

Ichikawa A., Vardy A.E. (2000) A ventilation simulator for road tunnel control, , 10th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Professional Engineering Publishing Ltd., Bury St Edmunds & London, UK, pp127-149.

Ichikawa A. (1998) The application of genetic algorithms to road tunnel ventilation control, PHD thesis, University of Dundee, Scotland, UK, 202 pages.

Jacques E. (1999) Ventilation control based upon directly measured traffic characteristics, XXIst World Road Congress, PIARC, Kuala Lumpur, Malesia, CD-KL, 8500 pages.

Jacques E., Possoz, L. (1997) Some experience with ventilation control based on traffic data, Tunnel Control & Communication, 2nd International Conference, Ed. A. Vardy, Amsterdam, the Netherlands, pp 235-251.

Jacques E. (1991) A solution to the optimal setting of airflow-control devices in a ventilation network, Proceedings of the 5th US Mine Ventilation Symposium, SME, Littleton, Colorado, pp 411-418.

Jacques E. (1991) Numerical Simulation of Complex Road Tunnels. Aerodynamics and Ventilation of Vehicle Tunnels, Elsevier Science Publishers Ltd., England, pp 467-486.

Katijima K., Koyoma T., Ota Y. (1997) Practical performance of fuzzy control system for the semi-transverse ventilation system of the Tokyo Port Tunnel, Tunnel Control & Communication, 2nd Int. Conf., Ed. A. Vardy, Amsterdam, the Netherlands, pp 235-251.

Mizuno A., Okubo T. Is ventilation control for longitudinal system difficult, Tunnel Control & Communication, 2nd Int. Conf., Ed. A. Vardy, Amsterdam, the Netherlands, pp 99-110.

Ohuchi T., Shigehara N., Koyama T., Ota Y. (1994) The new control system of tunnel ventilation for Tokyo Port Tunnel, Proceedings of the 1rst International Conference on Tunnel Control & Communication, ITC Ltd, Basel, Switzerland, pp 461-472.