Experiences on using closed-loop control systems for smoke control

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The main objective of ventilation systems in case of fire is the reduction of the possible consequences by achieving the best possible conditions for the evacuation of the users and the intervention of the emergency services.

In the last years, the required quick response of the ventilation system, from normal to emergency mode, has been improved by the use of automatic and semi-automatic control systems, what reduces the response times through the support to the operators decision taking, and the use of pre-defined strategies. A further step consists on the use of closed-loop algorithms, which takes into account not only the initial conditions but their development (air velocity, traffic situation, etc), optimizing the quality of the smoke control process.

1 INTRODUCTION

Geographical motility is, with no doubts, one of the social aspects that has suffered a strongest growth during the last few years, both national and worldwide. Due to the mountainous geography Spain counts with, it is necessary to develop complex projects where tunnels are a key element.

However, recent fires occurred in tunnels around the world, have raised questions about safety matters what comes into conflict with the necessity of increasing the number and length of this infrastructures.

The transposition of the European Directive 2004/54/CE (1) to the Spanish regulation was finalized with the publication, in 2006, of the RD 635/2006 (2) on minimum safety requirements for road tunnels. One of the key aspects included in this new regulation is the necessity, in most of the tunnels, of automatic ventilation control systems, both in normal operation and fire case.

The main requirements to be achieved by the use of control systems are the reduction in the response time for ventilation activation and the implementation of predefined strategies both for manual and automatic response of fire safety facilities.

However, when trying to establish the criteria for the specification of predefined ventilation strategies, various aspects must be taken into account which range from the type of ventilation system to traffic operation conditions previous to the incident development. Even, in some cases, an appropriate management of fire incidents requires

complex multi-step strategies that must be predefined and implemented in the control systems.
A further step consists on using closed-loop algorithms, which would take into account not only the initial conditions but their development (air velocity, traffic situation, etc), optimizing the response of ventilation equipments.

In this paper, starting from a general overview of the existing recommendations and used methods for smoke control in road tunnels, some theoretical and practical aspects of interest are highlighted. Additionally, some practical examples of algorithms actually implemented in existing tunnels, are described.

Finally, in-situ measurements, related to the topic, which have been obtained from the commissioning phases developed in tunnels under operation, are presented.

2 BACKGROUND

The increasing improving of the tools available for the management and control of the systems and equipments of the tunnels has contributed to the sophistication of the ventilation control systems with the aim of optimizing the operational costs during normal operation and improving the smoke control efficiency in case of fire.

During the last decades, a great amount of resources have employed for the study and development of ventilation control systems **during normal operation**, which included the use of closed loop algorithms and fuzzy logic for the optimization and improvement of the efficiency. Further information on this field can be found in specific reports from CETU (3). However, during the last years, the reduction of the emission levels of the vehicles is reducing the efforts involved in the development of new technologies and methods for the control of the ventilation during normal operation. In this sense, in Spain, the current practice is to implement automatic control systems based on contrasted experiences coming from recommendations from other countries. The activation of ventilation equipments based on measurements of contaminants (mostly CO and opacity) with pre-defined strategies which are based on reference intervals is broadly used.

On the opposite, ventilation control in case of fire is becoming one of the most important topics in the field. Going to the past, the PIARC report on “Fire and Smoke control in Road tunnels” (4) in 1999 already reflected the importance, and lack of unique rules, on the use of active control systems for the operation of ventilation.

From then, several national guidelines have included recommendations on the operation of ventilation systems in incident cases: Austria (RVS 09.03.31) (5), Germany (RABT) (6), France (Circulaire Interministérielle 20-63 dated 20th August 2000) (7) or Switzerland (FEDRO) (8). One common aspect to all of these references is the distinction between the self evacuation phase and the fire fighting phase, and the importance of the longitudinal control of the air velocity in the tunnel, with no dependence on the type of mechanical ventilation system installed, to achieve the desired goals for smoke control.

Taking into account these criteria, different contributions can be found in the literature in what concern to practical application of automatic control system use in road tunnels. Some general recommendations for the implementation and design of algorithms for the control of longitudinal air flow with ventilation can be found in Pospisil et all (9).

A specific solution for the control of longitudinal air velocity, in the case of a transverse ventilation system using a punctual air supply or extraction, is described by Wehner et all (10). In this practical case, the objective is to maintain the confinement of the smoke by the development of a converging velocity, to the fire location and from both sides, of no less than 1.5 m/s. To achieve this goal, numerical simulations of the aerodynamic behavior of the tunnel were developed to determine the air flow rate to be supplied or exhausted by the single point, situated in the middle of the tunnel, during the whole process.

Additionally, Stroppa (11) describes some experiences with longitudinal and semi-transverse ventilation systems concerning the control of longitudinal air flow for smoke control. It is mostly interesting the referred case of a bidirectional tunnel equipped with longitudinal ventilation where numerical simulations using uni-dimensional models were used to define, based in the environmental conditions and traffic situation prior to fire, pre-defined procedures in case of fire. These strategies, oriented to maintain the longitudinal air velocity below certain values, were to be applied to the different ventilation equipments took into account also the values of the mean air velocity inside the tunnel, which is permanently measured.

In another interesting reference, Bettelini et al. (12) describe the solution adopted for the ventilation control system after the refurbishment of the Mont Blanc tunnel, where an automatic logic based on real-time measurements has been implemented with the particularity of the use of mixed ventilation systems (semi-transverse complemented by jet-fans) and the severe conditions caused by the high natural difference of pressure between portals.

With the intention of describing some practical experiences in Spain, in the following, the authors describe in detail the criteria and algorithms developed and implemented for the automatic control of ventilation in road tunnels. It is important to note that the criteria and tools are mainly focused on the evacuation phase, even if some considerations are made on the general approach.

In addition, some results from the evaluation tests are presented as far as the authors consider that the whole process: design, implementation, test and adjustment is the only way to evaluate the reasonable performance of ventilation control system.

3 VENTILATION STRATEGIES IN CASE OF FIRE

As far as numerous references can be found in the literature (4) for the definition of the different types of ventilation systems, it has not been considered interesting to describe them in the present paper.

In addition, it is important to take into account that ventilation strategies to be used in case of fire are not necessarily related to the type of ventilation system in a tunnel. On the contrary, they are strongly related to the operational configuration (unidirectional or bidirectional traffic) and the traffic conditions (free flow or standstill).

In the case of tunnels with unidirectional traffic without congestion, a longitudinal ventilation strategy based on “highly-enough” velocity is the one most widely adopted, which consists in the generation of a longitudinal air flow in the vicinity of the fire, in the same direction than the traffic flow, with the goal of limiting the back layering of the smoke.

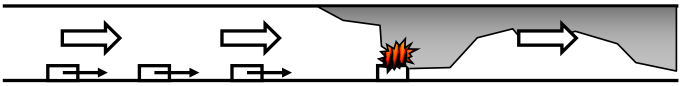

Fig.1. "High" velocity longitudinal strategy for unidirectional free flow traffic

In the case of unidirectional tubes with traffic congestion, a two-stages longitudinal ventilation strategy is commonly recommended which would consist in the generation of a "low" velocity longitudinal air flow until the vehicles stopped downstream the fire has left the tunnel. In a second stage, a "high" velocity longitudinal strategy would be desirable as far as no vehicles, or users, should be situated in the route invaded by the smoke (portal, intermediate exhaust point, etc). The value of velocity to be achieved in the first stage, recommended in the literature, depends on the reference but is usually fixed in values of the order of 1 m/s.

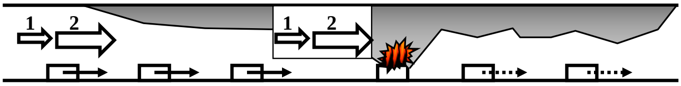

Fig.2. Two stages longitudinal strategy for unidirectional congested traffic

In the case of bidirectional tunnels the two strategies explained before are not longer valid, as far as there will probably be vehicles at both sides of the fire location, what would recommend to adopt ventilation strategies focused on maintaining so long as possible the stratification conditions of the smoke, what is favored by the smoke extraction (if possible), the switch off of the fans that can cause turbulence, and the reduction of the air velocity inside the tunnel.

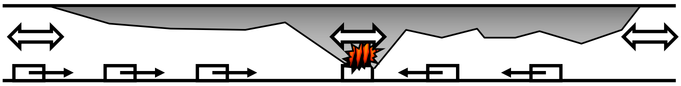

Fig.3. Stratification strategy for bidirectional traffic

It is important to note that the type of ventilation system of the tunnel (capacity, exhaust availability, remote control dampers, etc) will contribute to achieve the smoke control objective but that the way the system is operated depends on the strategy adopted (which can not be unique but depending on the traffic conditions or operation situation). For example, high velocity strategies can be adopted for transverse ventilation systems based in the activation of different ventilation sections as shown in the references cited in the precedent paragraph.

4 CHALLENGES FOR DESIGN OF VENTILATION CONTROL SYSTEMS

During normal operation the main goal of the ventilation control system is to reduce the operating costs while maintaining acceptable air quality levels inside the tunnel. In some cases, the high emission levels require high air velocities in the tunnel which, in case of fire, are totally contraindicated. In other cases, the environmental (natural draught) or traffic conditions (piston effect) can cause this undesired situations that must be managed as soon as a fire incident appears (or is expected to appear).

Consequently, it is of the outmost importance to handle the quick transition from normal operation to the emergency mode, which includes from the point of view of the ventilation system, the following steps:

1. Normal operation
2. Automatic incident detection
3. Ventilation safety response
4. Location and validation of the fire
5. Predefined ventilation response plan
6. Follow-up and correction (if necessary)
7. Emergency service strategy
8. Return to normal operation

All these stages must be implemented in accordance to the general emergency response plans so, coherence between the different equipments activation can be guaranteed.

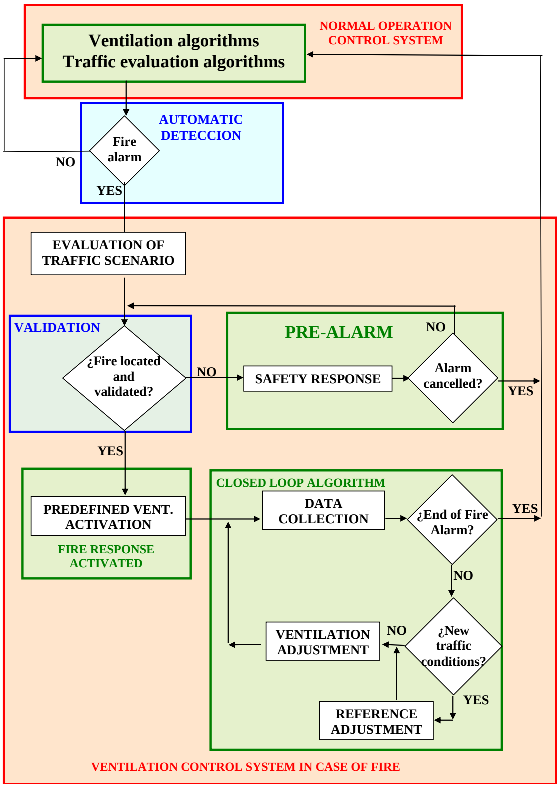

Fig.4. General overview of the ventilation control system stages

However, when facing the design of the algorithms to be implemented in the control system, all these steps must be clearly detailed and defined into specifications documentation.

Sometimes, the lack of a clear definition or missing concepts reduces the efficiency of the algorithms and even, can produce undesirable consequences.

In this sense, some typical problems that must be considered include:

- Reception of multiple automatic alarms: once an incident occur, the great amount of alarms that are received from the different equipments installed in the tunnel can interfere in the activities of the operator. For example, in the case of the AID (Automatic Incident Detection) system, the queue formation upwind the traffic stop point generates multiple alarms in areas far from the fire situation.

  This aspect can be undesirable if the automatic preconfigured actions come into conflict with the right strategy (for example, the alarms on high opacity can be associated to the activation of the ventilation what can be in conflict with the fire strategy).
- Excessive demand of information from the operator: when designing the interface human-computer application, the excessive request of information must be avoided and, if totally necessary, priority criteria must be established.
- User failure protection: even if sometimes it is not possible to guarantee that the actions taken by the operator are correct, a great amount of mistakes can be avoided without complex means (for example, the use of 'double confirmation' messages for fire alarm cancellation as are used in standard applications)
- Lack of operators training: as far as, fortunately, fire situations are not common during the operation of the tunnel, it is necessary that the operators can receive permanent training in the management of the application, general concepts, expected behavior, practical cases, etc. In some tunnels, very good experiences are being obtained with the use of training 'simulators', where the use of the graphic interface screens for fire situation can be used reducing the 'surprise' of the operator to new situations.

It is obvious to say that most of the mistakes that can be found in the control applications are not due to the complexity of the problem but to "theoretical approaches" which can be handled with good practice and experience. On the other hand, it is important to note that the development of these applications require clear criteria, detailed specifications, considerable implementation efforts and rigorous test procedures, what in practice means scheduled time and financial provisions to be considered.

5 STUDY CASE 1: UNIDIRECTIONAL CONGESTED TUNNEL

5.1 Infrastructure description

The tunnel of study has two independent unidirectional traffic tubes of about 2000 meters length. The proximity of an urban area produces a highly unbalanced traffic distribution what causes standstills in the morning and evening commuting times.

The ventilation system is longitudinal with jet fans uniformly distributed through the tunnel, although according to the new Spanish regulation in the close future the tunnel will be refurbished and the ventilation system modified.

Due to the high traffic levels and its length, the supervision level of the tunnel is high (with a dedicated control center) and different safety systems which includes among other equipment, fire linear detector, CO and turbidity sensors, anemometers inside the tunnel, loudspeakers system, barriers, AID and CCTV systems.

5.2 Normal operation of the tunnel

During the normal operation of the tunnel the control system is permanently monitoring the CO and turbidity levels inside the tunnel; and a closed loop algorithm based on intervals is the one in charge of operating the jet fans.

In order to maintain optimal ambient conditions inside the tunnel, and depending on the measured level of contaminants, a predefined number of jet fans will be connected (in the same sense as the traffic) to dilute the contaminants. In order to minimize the time fluctuations on the measurements, a temporal smooth is applied on each sensor. Finally, based on the smoothen values obtained during each integration period, a representative value is determined and its value used on the decision taking.

At the same time, and to improve the response of the system in case of fire, an automatic control system to analyze the traffic situation was implemented based in the alarms given by the AID system as well as the gauging spires. The traffic state is consequently monitored, not to act on the ventilation control system during the normal operation but to determine the traffic situation previously to the incident occurrence.

5.3 Fire scenarios

In case of the reception of an automatic fire alarm or when the fire alarm is activated by the operator, the control system turns automatic and immediately into a fire mode. The alarm generation is not only related to the fire detectors or the CO and turbidity sensors, but also to the alarms generated by the AID. In addition, the system evaluates not only the levels for the CO and turbidity sensors, but also the strong temporal fluctuations.

With all this information a “Detection Index” is calculated, which indicates the most probable fire locations. This information is shown to the operator through the user interface to help him in the decision taking process. The criteria to calculate the detection index is the following:

- The position of the fire, defined as the “sections” situated between two consecutive cameras
- Each automatic alarm of the tunnel is associated to one or more sections, based to a predefined pattern
- On each type of alarm a weighting factor is applied according to its capacity to react before a fire (but not necessarily related to its reliability)
- For each section the system evaluates periodically the value of the detection index, ranging from 0 (no alarms) to 100 (all alarms).

Once the detection index value for any of the sections is higher than a preconfigured value, pre-alarm is generated and the control system automatically applies a predefined procedure (pre-alarm mode). In this case, the procedure stops the ventilation in both tubes to avoid the de-stratification of the smoke during the early stages.

Depending on the value of the detection index, i.e. the number of alarms simultaneously received in the same section, two different situations can be found:

- If the detection index value is very high (several alarms or one highly weighting alarm received in the same section) the fire response procedure (including tunnel closure) is automatically initiated within 30 seconds (without human intervention)
- If the detection index value is high, the fire response procedure is not initiated until manual validation from operator is completed (but ventilation remains stopped with visual and acoustic alarms activated)

Once the fire confirmation is produced, the start up of a predefined number of jet fans is required, to achieve a reasonable flow in the same direction than the traffic.

For the definition of the number of jet fans to be activated one-dimensional numerical models were used taking also into account the location of the fire, to avoid the use of jet fans in the vicinity of the fire, but also the results given by the traffic evaluation algorithm that is continuously running during normal operation, either to achieve high air velocity (fluid traffic) or to maintain low velocities to help the vehicles, situated downstream the fire, to leave the tunnel.

In the non-affected tube some jet fans are connected in the opposite direction to the traffic flow in order to prevent the smoke recirculation from the incident tube.

An additional tool has been implemented in the control system to evaluate the traffic conditions in the downstream area based on the information gained from the AID system. Due to the reduced reliability of the information provided by the cameras in case of fire, it was decided that this system only provides a proposal to the operator about the traffic situation during the emergency who is responsible to modify the reference velocity for the activation of the automatic control system.

5.4 Closed loop longitudinal air flow control system

Unfortunately, even if the predefined number of jet fans used in the first response allows reasonable air velocity conditions in the tunnel (which in practice is extremely hard to achieve), during the development of the fire incident, there exist numerous effects that will modify the air velocity, i.e. the chimney effect due to the gradient, the change in the climatologic conditions or the piston effect due to the traffic.
Consequently a second stage must be considered to control of the longitudinal air velocity, which requires closed loop algorithms with the objective of maintaining the control on the longitudinal air flow what should facilitate the users evacuation.

For the case study presented, the two main parameters that have been taken into account for the design of the algorithm are the air velocity inside the tunnel and the target air velocity. On one side, the air velocity in the fire location is calculated as the average of the values given at every instant by “representative” anemometers, taking into account that the measurements of some of the installed anemometers would be influenced by the jet fans flow and the smoke layer around the fire

On the other, the target air velocity is fixed taking into account the traffic state downstream the fire location (3.5 m/s for a fluid traffic, 2 m/s in case on dense traffic and 1 m/s for congested traffic). However, given the uncertainties associated to the air velocity measurement equipments, a range of velocities instead of a fixed value has been adopted. The amplitude of this interval is however reduced while time progresses (see figure 5). It is important to note that the ordinates axis is not the value of the velocity measured but the difference between the measured air velocity and the reference value. The reason for this representation is to use a ‘difference velocity’ from the reference value determined by the traffic conditions. Other additional criteria that are included in the algorithm definition is a delay time after ventilation activation to avoid flow instabilities during the fan start up times.

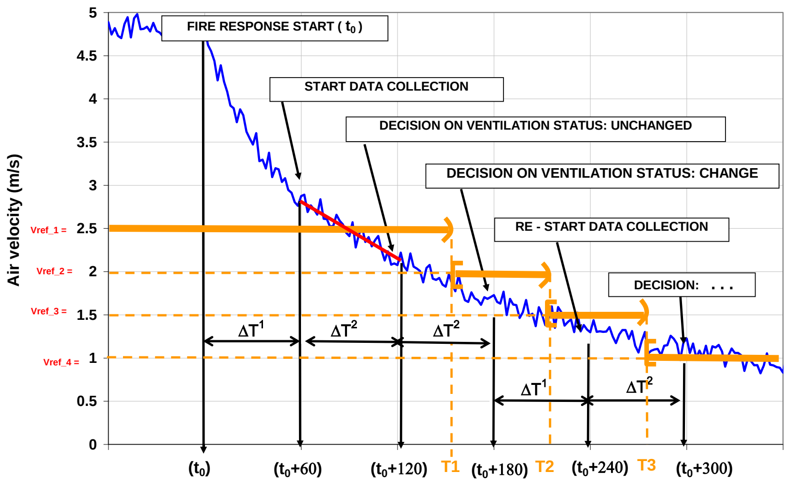

Fig.5. Methodology diagram for the closed-loop algorithm

The implemented algorithm follows a predictive-corrective logic, based on the average air velocity in the tunnel and the trend shown during the control intervals. Both magnitudes are evaluated at the end of each control periods by a linear adjustment to try to avoid the random temporal fluctuations (see red line in the decision figure). The algorithm estimates the value of the velocity expected (V_{est}) to occur at the end of the time interval and the slope of the linear regression curve (m).

Finally, from the values obtained for the control variables, the decision on the number of jet fans to be connected is taken based on pre-programmed charts with predetermine actuations (see next table) which depends on the velocity estimated comparison to the reference interval and the sign of the slope of the linear regression (m).

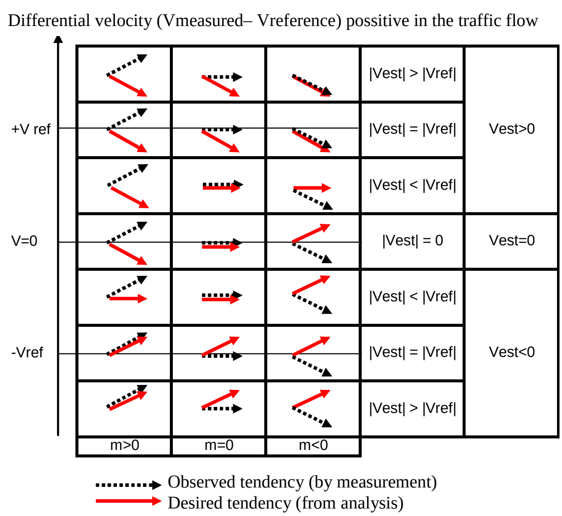

Fig.6. Scheme of the close-loop logic applied.

6 STUDY CASE 2: BIDIRECTIONAL TUNNEL

6.1 Infrastructure description

The tunnel of study is a bidirectional tunnel of around 5200 meters length. The ventilation system installed is of the type semi – transverse reversible, organized on 4 ventilation ducts of around 1250 meters with two ventilation stations one in each portal. Each of the stations houses 2 fresh air and 2 extraction fans (reversible): one pair for each section.

The fans have an air flow exhaust capacity of about 140 m^3/s in 600 meters, for emergency case. The ventilation ducts, located above the traffic zone, are equipped with dampers situated every 50 meters and prepared to supply fresh air into the tunnel and also to extract smoke from it in case of fire,. To help the longitudinal smoke control, in case of fire, 9 jet fans have been placed in the central part of the tunnel (around 200 meters without ventilation ducts). These jet fans can be switched, one by one, depending on the inside tunnel conditions.

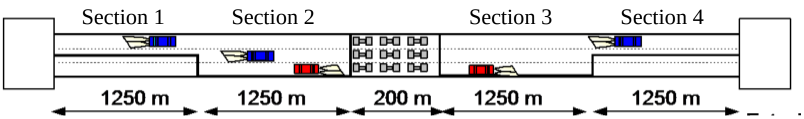

Fig.7. Configuration of the tunnel ventilation system.

Due to its singular characteristics, below an important mountain and with a difference of height between portals of almost 200 m, important differences of pressure between the portals have been measured, which recommended to improve the longitudinal control of the air in case of fire.

6.2 Normal operation of the tunnel

During normal operation, all the ventilation sections supply fresh air along the whole tunnel length by all the dampers that stay open. The ventilation for the fresh air flow can work under different regimes depending on the CO and turbidity levels inside the tunnel.

In addition, during normal operation another automatic system is used to estimate the pressure differences between the portals, due to its important role during the initial ventilation actions in case of fire. The estimation of the pressure difference between the portals is obtained from indirect measurement of the air velocity in the tunnel, the knowledge of the functioning point of the fans and measurements on the traffic parameters in the tunnel. For that, real time calculations are used to evaluate the aerodynamic equilibrium equation:

$$\Delta p_{jet} + \Delta p_{friction} + \Delta p_{traffic} + \Delta p_{ext} = 0$$

Where the different terms represent the pressure variation values given by the fans, the friction (wall, singularities, etc), the piston effect due to the traffic and finally the difference between the portals, which is the unknown part of the problem. The equation is evaluated with averaged values of traffic, air velocity, etc. and the resulting magnitude smoothed to reduce the fluctuations resulting from the uncertainties on the calculation process. The algorithm estimates this value permanently while the tunnel is in normal operation and, in case of fire, the value used for the ventilation activation, to avoid the disturbance of the measures in the preceding minutes, is the corresponding to the values calculated 20 minutes before the alarm activation.

Taking into account the expected uncertainties coming from the calculation procedure and the measurement systems, the results obtained with the implemented algorithms can be considered acceptable when comparing with direct measurements obtained with high sensibility barometric stations located at the portals (see fig 8).

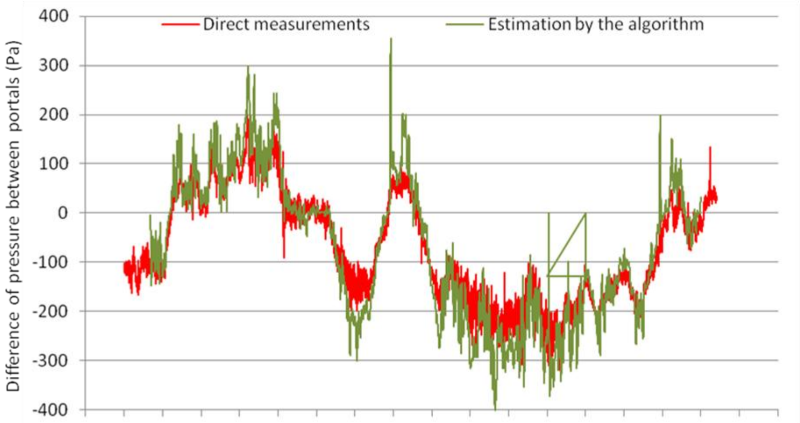

Fig.8. Comparison of estimation by algorithm and direct measurements of the difference of pressure between portals.

6.3 Fire scenarios

In case of an automatic fire detection (by the linear detector, the CO or turbidity sensors) or a manual one given by the operator, the control system turns automatic and immediately into a fire mode, activating the “pre-alarm” or first response phase that consists on the stop of all the ventilation equipments while waiting for the fire confirmation. During this phase the operators must localize the alarm origin using the CCTV system in order to validate it or not. In the case that there are no operators in the control room a pre-programmed routine will automatically turned into the fire mode.

Once the fire is confirmed, the predefined actuation depends on the fire position and the pressure difference between the portals calculated during the normal operation of the tunnel before the incident occurred. This first response on the ventilation system consists on the extraction of the smoke through the dampers opened in the ventilation sections above the fire. The other ventilation sections are used to help to control de longitudinal flow to confine the smoke around the extraction location.
At the same time, depending on the pressure difference between the portals a predetermined number of jet fans is connected, which has been determined by numerical models and validated through in-situ tests.

6.4 Longitudinal air flow control system

As was mentioned in the previous case study, a second stage is needed to achieve a reduction of the longitudinal air velocity in the fire location.

In the case of study, where a semi-transverse ventilation system is used, the longitudinal control is more complex than for a longitudinal ventilation system, because not only depends on the external pressure conditions, the traffic and the stack effect but also on the fire location and the regime of the ducted ventilation system.

Another difference with the previous case is that, in this case, the goal of the algorithm is to achieve a reduced air velocity in the fire location (improving the efficiency of the ventilation extraction and allowing a converging velocity around the fire point).

The procedure to determine the air velocity in the vicinity of the fire location is based on the following steps:

1. Determination of the longitudinal flow distribution layout by determining the real working conditions from each of the ventilation sections
2. Measuring the air velocity with the anemometers situated inside the tunnel (in this case, 13 units)
3. Adjustment by a least squares method of the theoretical longitudinal air velocity pattern to the real air velocity values obtained with the tunnel anemometers
4. Estimate the air velocity value in the fire point using the adjusted distribution

By this process a reasonable approximation of the air velocity at the fire point in each moment is obtained (see the next figure).

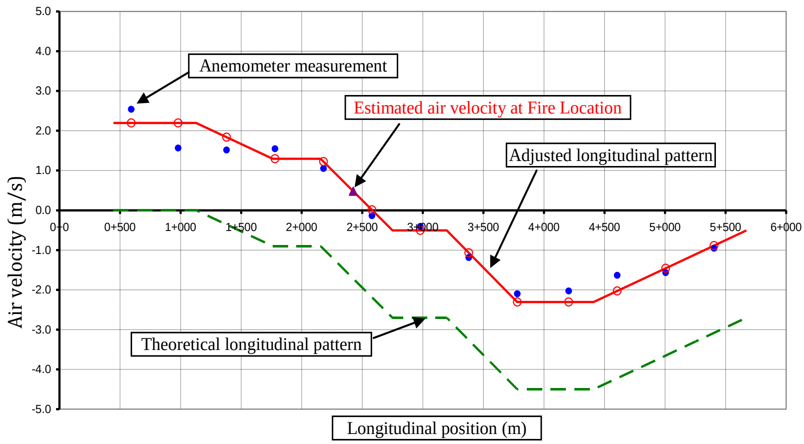

Fig.9. Procedure for the estimation of the air velocity at the fire location

Once the air velocity at the fire location is obtained, the methodology used in the previous case study can be used.

6.5 Verification tests

To verify the behavior of the control systems of the tunnel before its opening, a test campaign was carried out with in-situ measurements and under no traffic conditions. From the different results obtained it is of special interest the case of the test represented in figure 9 where a malfunction of the normal operation algorithm (for the evaluation of the pressure difference) was being evaluated. This scenario involved a very unfavorable situation what highlighted the capability of the algorithms. First of all it must be noted that, even if the air velocity at the beginning of the test (due to natural counter pressure) was high it was decided to switch on 4 jet fans in the same direction that the air flow (at the same time as the initial operation on the exhaust system was activated).

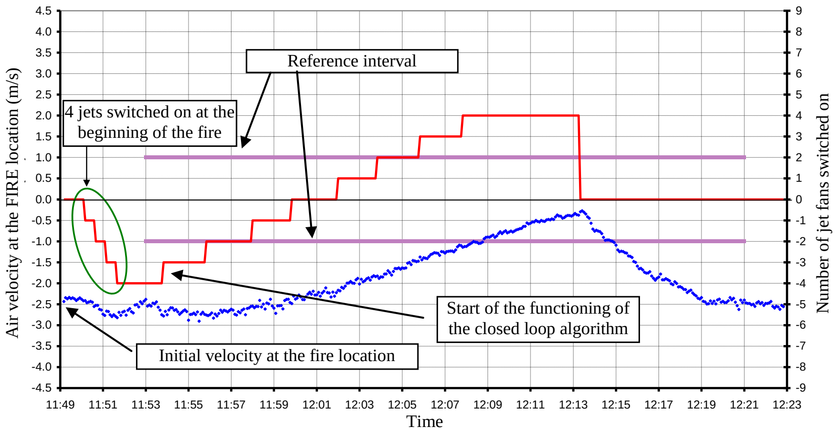

Fig.10. Results obtained from in-situ tests of the control ventilation system

Once the first response was forced the closed-loop algorithm should 'repair' the mistake coming from the operator decision and automatically estimate the decisions on the jet fans to reduce the air velocity in the fire location.

In the figure can be seen how the automatic actions over the jet fans modify their state turning them off one by one before connecting the right number of them (4 in this case) in the other flow direction. Once the estimated velocity is within the reference interval (fixed in this case in 1 m/s for both directions) the automatic system maintained the number of jet fans with no further activations.

In figure 11, obtained during another test, a comparison between the estimated air velocity and the measured values in the fire location can be seen. As far as, in this test, the initial activation of the ventilation was done in agreement with the estimated pressure difference, immediately after the activation of the fire sequence, the longitudinal are velocity came to very low values which were maintained, as expected, during all the test until the activation of a longitudinal strategy was set to take the smoke out through the portal.

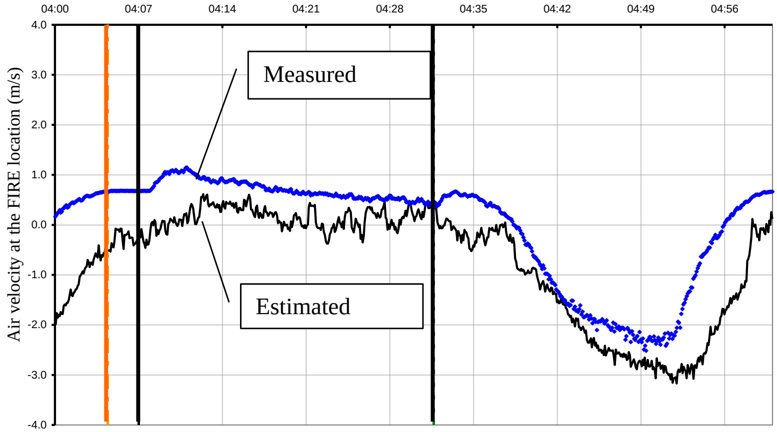

Fig.11. Measured and estimated velocity in the fire location

7 CONCLUSIONS

The research on ventilation control methodologies and algorithms, for application into road tunnels, is focusing more and more on fire situation instead of normal operation. This fact is being reflected in the national and international regulations and guidelines.

However additional research and development efforts seem to be necessary to improve the design, specification, implementation and testing of ventilation control systems.

On one side, software applications should be capable to deal with more and more sophisticated systems where, in some cases, complex algorithms are required to take into account the ventilation characteristics, environmental conditions and traffic evolution.

On the other, additional efforts should be dedicated to evaluate the application of closed loop ventilation algorithms in real tunnels, what would permit the optimization of the response of the ventilation system in case of fire

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