Safety in tunnels: innovation and tradition

A. Focaracci
Prometeoengineering.it srl, Rome, Italy

SUMMARY: After ten years from the tragic accident of the Mont Blanc, to which the accidents of the Gottard and Tauri are followed, after five years since the European Directive 54/2004/CE came into effect, it is possible to make a balance on the evolution of the methodologies of quantification of the risk and the technologies of fittings applied to the safety in tunnel. From the point of view of the development of plant design technologies, new systems have been produced and able to increase safety in tunnel: supervising and communication systems, exodus facilities and fireproof protection, that the normative in force identifies as the most effectives.

1 INTRODUCTION

The new regulations, both at European and national level, on safety in tunnels when in service has provided an innovative response to the need to make a substantial improvement to safety, strongly demanded by public opinion following the serious accidents that have occurred in recent years (Mont Blanc, Gottard, Frejus).

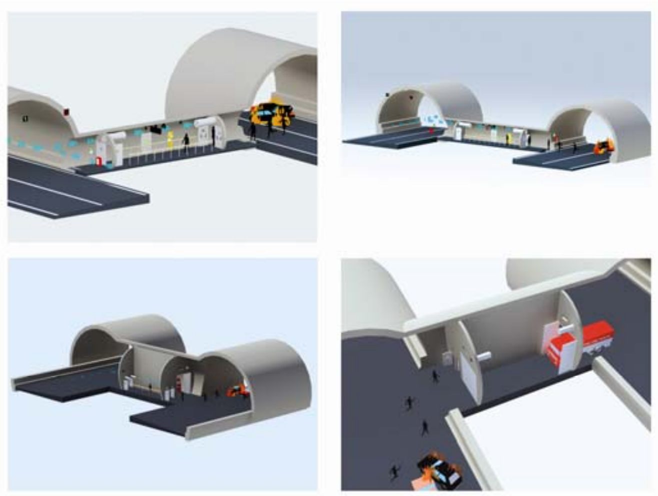

Figure 1 Emergency scenarios in tunnels

The new regulatory framework adopted the new design approach based on quantitative and qualitative assessment of risk. The necessary basis was thereby created to start a huge programme of action to improve safety in road, mainline and metropolitan rail tunnels based on engineering assessments and not on the feelings of "experts" or even worse, dictated by the emotional response to the serious accidents that had occurred.

The main legislation in question is EC Directive 2004/54/EC "on the minimum safety requirements for tunnels in the trans-European road network", which requires safety measures to be based on systematic consideration of all aspects of the system, i.e. the infrastructure, operation in service, users and vehicles. The directive also lays down compulsory regulations for all underground infrastructures with a length of greater than 500 m. It identifies safety objectives, identifies a set of safety parameters to be observed, sets groups of minimum safety requirements to be satisfied, recommends a systematic approach to safety design and identifies risk analysis as the instrument to use to determine the safety level of a tunnel.

The purpose of EC Directive 2004/54/EC is to ensure a minimum sufficient level of safety for road users in all tunnels in the trans-European road network. In the event of an accident, the consequences must be addressed with effective protective measures so that the users involved can reach safety and, at the same time, all those directly involved can react immediately to avoid further damage.

The most feared of accidents from the viewpoint of the safety of tunnel users is without doubt fire, due to the severity of the consequences. The fumes and toxic gases that develop at high temperatures remain at dangerous levels even at a distance, creating difficulty not only for those already present inside the tunnel, but also for rescuers when they arrive.

Safety inside tunnels is therefore a complex subject and therefore capable of generating fields of research that are equally varied and complex, based in particular on the following:

– the behaviour of users in emergencies;
– the characteristics of the infrastructure (type of construction, escape routes, portals, etc.);
– in service operating characteristics: the type and functioning of the systems, including safety systems, installed (fire prevention, ventilation, lighting).

The formulation of safety designs for many new or existing tunnels has led therefore to the development of a large number of innovative solutions. Attention has been focused on measures to facilitate evacuation and on the systems installed. An illustration is given of the main technological innovations employed with regard to compliance with the safety requirements contained in the European directive:

– **Emergency exits (54/2004/EC § 2.3):** "*allow tunnel users to leave the tunnel on foot and reach a safe place… (…). Examples of such emergency exits are*:
  - *direct exits from the tunnel to the outside;*
  - *cross-connections between tunnel tubes;*
  - *exits to an emergency gallery;*
  - *shelters with an escape route separate from the tunnel tube.*
– **Evacuation lighting (54/2004/EC § 2.8):** *"such as evacuation marker lights, at a height of no more than 1,5 m, shall be provided to guide tunnel users to evacuate the tunnel on foot, in the event of emergency";*
– **Ventilation (54/2004/EC § 2.9):** *"a mechanical ventilation system shall be installed in all tunnels longer than 1,000 m with a traffic volume higher than 2,000 vehicles per lane."*
– **Water supply (54/2004/EC § 2.11): "***shall be provided for all tunnels. Hydrants shall be provided near the portals and inside tunnels at intervals which shall not exceed 250 m."*.

2 TECHNOLOGICAL INNOVATION: TO INCREASE SAFETY IN TUNNELS

2.1 *Measures to facilitate evacuation: emergency exits*

2.1.1 *The Suspended Emergency Escape Route*

An enclosed walkway suspended from the crown of a tunnel, constitutes a particularly effective evacuation system.

The suspended emergency exit is a walkway that is large enough to provide an easy escape route. Access to it is along connecting stairways sited inside side chambers or at parking areas.

Figure 2 The Suspended Emergency Exit

The walkway is trapezoid or rectangular in shape and it is fixed to threaded bars or bolted plates. The structure is in concrete or steel and it is protected with materials designed to resist high temperatures such as mortars, plasterboard or similar materials. The exit to the walkway may be near the tunnel portal, where special areas are set aside and equipped for emergency rescue operations.

Access to the suspended emergency exit may be provided by constructing the stairway to the prefabricated structure inside the cross section of the tunnel, where it has been widened, and by equipping that area with the necessary emergency systems directly, or alternatively it may be constructed inside chambers cut out of the side of the tunnel. The former solution is advantageous from a cost viewpoint, while the second allows greater volumes of space to be obtained in which an electrically operated elevator can be installed.

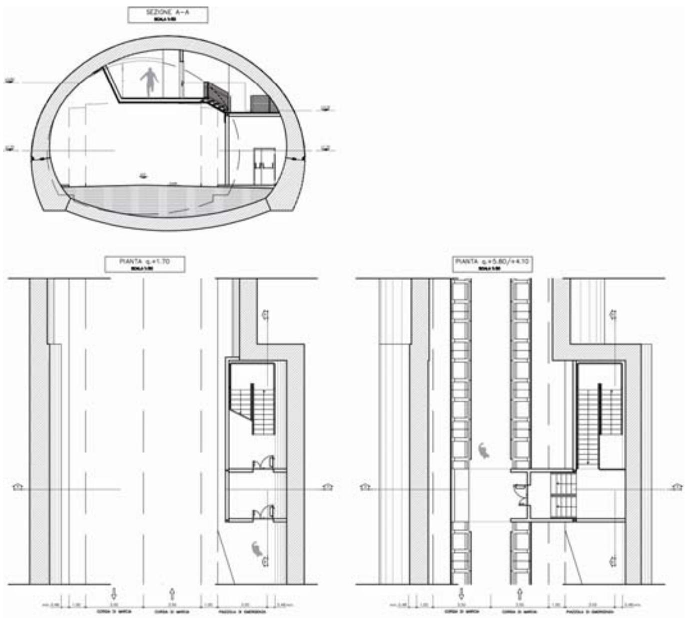

Figure 3 Access inside a section of the tunnel

The walkway is therefore designed to fully meet requirements for the emergency evacuation of tunnel users, because it is fully enclosed (prevents the passage of flames, gas and smoke), thermally insulated (it limits the transfer of heat) and conserves its structural integrity (it will maintain its structural integrity for at lease 120 minutes in a fire). In other words it constitutes an REI 120 structure to all effects and purposes.

This structure provides the following advantages over conventional solutions:

– industrialised construction: the prefabricated components are produced under controlled conditions in a workshop and are subsequently assembled and fitted on site;
– low production costs: the suspended enclosed walkway is an alternative to the costly excavation operations required for other solutions. Excavation is only required for the side chambers which give access to the walkways;
– rapid installation: anchor bolts are fitted in advance in the crown of the tunnel, while the structure is already pre-assembled on the ground with threaded bars and the steel reinforcement grid for the Fireshield mortar. The next stage consists of raising the structure and temporarily fixing the units together and to the crown of the tunnel. The last stage consists of placing the layer of Fireshield mortar which provides protection against fire.

This design solution for escape routes can also be used in existing tunnels with no escape routes for compliance with regulations. Often the size of the cross section of these tunnels is too small and the level of the road must be lowered.

The operations in the tunnel can be easily performed by alternating one-way traffic on one lane, thereby reducing inconvenience for road users to a minimum.

The construction work can be performed on an entire lane using a number of cutters, i.e. machines used to remove the existing road surface and foundation, in series, with the relative means for removing the rubble and the tunnel invert backfill.

This solution can be performed in a series of construction stages:

1) lowering the level of the road on one lane by excavation. Road traffic flows alternating one-way on the other lane;
2) A new road is laid. Behind it, anchors are installed in the crown and the individual prefabricated segments of the suspended emergency exit are assembled. Road traffic continues to flow alternating one-way on the other lane;
3) lowering the level of the road on the other lane by excavation. Road traffic flows alternating one-way on the other lane;
4) once excavation is completed normal road traffic is resumed in two directions on two lanes.

The construction stages with the possible site organisation are illustrated in the figures that follow, both for the existing cross section and where the tunnel has been widened for parking areas. When the new road surface is being laid, water drainage systems together with systems to collect liquids from the road can be installed behind the lining along with the relocation of systems installed in the crown.

It is therefore an innovative solution designed to save the lives of tunnel users in the event of a serious fire. It requires certification by a highly qualified independent third party which tests both the statics characteristics and the REI 120 functions specified by the relevant standards.

A full scale test was therefore performed inside the S. Croce Tunnel on the “Strada dei Marmi” at Carrara. The testing for certification was performed by the Energy Department of the Polytechnic of Turin, which designed and supervised all the tests on site.

Numerical simulations were performed beforehand designed to assess the environmental conditions during the test, to establish the levels of ventilation and to conduct finite element analysis of the prefabricated segments.

Figura 4 The suspended emergency exit during the fire test

The fire resistance and insulation test was performed by heating the outer surface of the escape route operating two oil burners for 120 minutes and measuring the following:

– the temperature of the outer surface of the escape route at the nozzles of the burners;
– the vertical distribution of the temperature inside the escape route;
– the distribution of the temperature inside the different layers of the floor and the walls of the escape route;
– the temperature of the internal walls of the escape route;
– temperature of the threaded bars;
– the rate of flow of air inside the escape route;
– the concentration of carbon monoxide inside the escape route;
– the opacity of the air inside the escape route;
– the increase in the length of the threaded bars;
– displacement of the joints between the prefabricated segments.

2.1.2 *Prefabricated cross-connections*

A protected escape route is a zone used for the evacuation of people in safety and therefore it must be:

– sufficiently well-lit;
– kept free from fumes and at a higher pressure than the tunnel by means of natural or forced ventilation;

– separate from the tunnel by means of structures and doors with REI 120 certified fire resistance compartmentation.

One of the most important passive safety measures that can be employed for emergency escape routes in tunnels with two tubes is to provide lateral connections between them, known as “cross-connections”.

When a fire occurs in one of the two tubes, the cross-connection must prevent the passage of air-fume mixes from the tube in which the fire has occurred to the other tube. In this case the fire-free tube must remain in service for the exit of traffic in transit at that moment, for the passages of people evacuating the tube affected by fire and for the arrival of rescue teams. The evacuation route consists of the following sequence:

– the tube affected by the fire;
– the cross-connection;
– the tube not affected by the fire;

The design of the prefabricated cross-connection originated as an answer to that requirement and was then also improved and perfected with the construction of new tunnels.

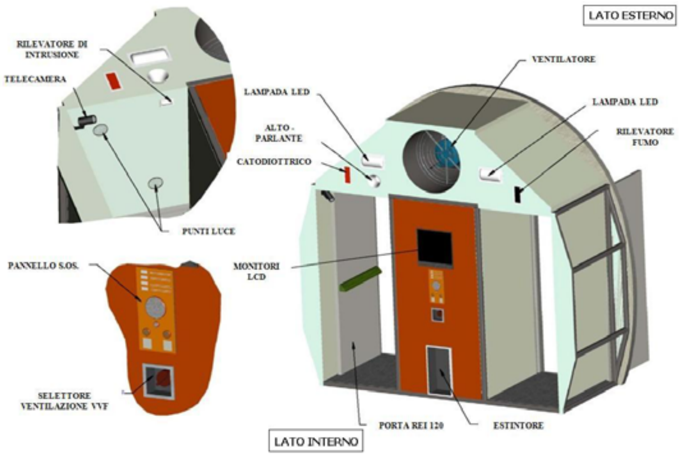

Figure 5 Detail of a cross-connection module

The module consists of a prefabricated box structure shaped to allow maximum precision for its insertion into the “cylinder” of the actual cross-connection.

The wall of the module which faces onto the tube is constructed to provide REI 120 class certification fire resistance. It contains housings inside it for two doors for pedestrians, again to REI 120 standard, and for one axial ventilator. Once the module is installed at the correct depth inside the cross-connection, the cavity between the prefabricated structure and the walls of the cross-connection are sealed with fireproof material in order to ensure the same uniform fire resistance.

The internal part of the module consists of a closed part for the electrical equipment and a semi-cylindrical structure above it to the same depth. The wall facing onto the tube, the part housing the electrical equipment and the semi-cylindrical section are held in one fixed single structure by a metal frame of structural steel or another fire resistant material appropriately shaped which extends to the full height of the module.

The walls which enclose the housing for the electrical equipment are fitted with air vents and the can be removed for maintenance access inside.

Each cross-connection has two twin module units placed sufficiently far apart to allow an internal floor area between the two to contain an appropriate number of persons in compliance with the regulations to consider the area a temporary safe place.

Prefabricated cross-connections fully satisfy the requirements for the safe evacuation of users, because they possess characteristics of compartmentation (prevents the passage of flames, gas and fumes), thermal insulation (limits the passage of heat) and function conservation (they conserve their structural integrity for at least 120 minutes in the event of fire). In other words they constitute an REI 120 structure to all effects and purposes.

The prefabricated cross-sections must possess all the necessary characteristics for the safe evacuation of users and are therefore equipped independently of the tube of the tunnel, with:

– REI 120 doors;
– electrical board;
– UPS;
– SOS emergency station;
– lighting system;
– CCTV system;
– ventilation system;
– loudspeaker system;
– fire and fume detection systems;
– luminous signs.

2.2 *Evacuation lighting*

2.2.1 *LED technology*

After a fire develops and therefore after fumes have spread along the tunnel, the lighting rapidly darkens in the crown of the tunnel, and therefore evacuation lighting and safety signs are essential for people to be able to reach safety and escape.

The adoption of LED lighting provides adequate lighting along escape routes which is always greater than 2 lux even under unfavourable conditions. Furthermore, extra LEDs are installed at emergency exits to ensure they are easily identified by tunnel users who must evacuate the tunnel.

Uniform lighting when visibility is poor in the presence of a fire, combined with standardised information indicating the escape routes to follow, provides a better perception of the route to follow to reach a safe place, because it reduces the reaction times of tunnel users.

2.2.2 *LED guide barrier*

Safety lighting must allow users to reach safety by means of escape routes and therefore it must enable users and rescue workers to identify fire fighting equipment and emergency stations. Generally LED lighting must be installed on both sides of the tunnel with the dual function of lighting walkways next to the barriers themselves and indicating the direction to take along the tunnel in emergencies. The safety lighting must ensure the following:

– clear and unambiguous indication of the escape routes, provided by the physical and luminous guide of the lights;
– illumination of the escape routes;
– identification of safety equipment for use by users;
– indication of the direction to take to move away from the fire.

The innovative solution employed is that of a guide barrier with an LED element housed inside it with the dual function of lighting walkways next to the barriers themselves and indicating the direction to take along the tunnel in emergencies.

Figure 6 Guide barrier with LEDs incorporated

Ground lighting is provided by a yellow-amber LED which must furnish average lighting of 5 lux for a minimum luminous band of 90 cm within which the minimum illumination must not be less than 2 lux. This band must start within 30 cm. from the foot of the guide barrier. The sign that indicates the direction to take is furnished by the illumination in sequence of groups of 3 green LEDs, oriented in such a way as to be directly visible to pedestrians. There are 7 groups of green LEDs every 3 m. along the guide barrier. The groups are lit in sequence (one on and seven off) in order to produce a perceived velocity of apparent movement of the green LEDs of 7-8 metres per second.

Under normal conditions the green LEDs are off.

In emergencies operation of the sequential lighting is controlled by the supervision and control system of the tunnel. The direction of the sequential lighting (ahead or backwards) and therefore the direction to be taken along the tunnel is decided by the supervision and control system of the tunnel. In the event of an emergency, the sequential green LED lights indicate the direction to take to move away from the critical point where the accident occurred.

2.3 *Ventilation*

The design of tunnel ventilation systems must produce a configuration capable of ensuring the following:

– the dilution of vehicle emissions within the tunnel under normal service conditions (health ventilation);
– the environmental compatibility of the structure,
– the management and control of fumes in the event of accidents identified as serious (emergency ventilation). Innovative fans possess high aeraulic efficiency and are fitted with electronic controls for the velocity of rotation by means of an inverter installed in them.

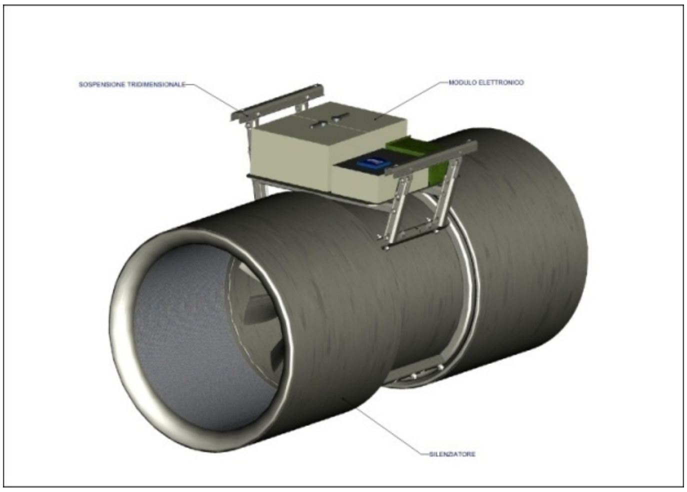

Figure 7 High efficiency fans with inverter

The increased efficiency of the fans is provided by the design of the blades with a wing profile which allows faster rotation and by the fluid dynamic design of the fan wheel-electric motor unit.

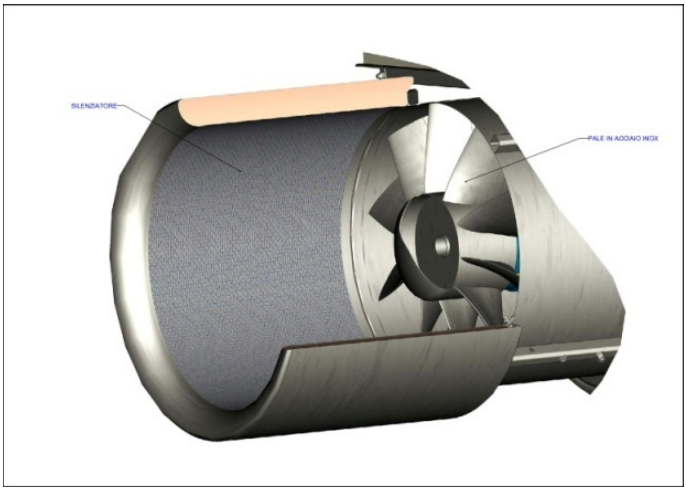

Figure 8 Detail of the fan wheel

Innovations in the materials and design field have also produced great improvements in the electrical and electronic components of the machines.

The new generation fans provide the following advantages:

– elimination of harmonics in the power lines;
– lower costs for all the electrical components (wiring, switches, electrical boards, generator units, ducting, transformers, etc.);
– increase in the power factor to greater than 0.96.

– control of velocity with the elimination of potential counteraction phenomena between fans installed in parallel which cause a loss of output;
– reduced braking and direction reversal times;
– elimination of blade corrosion phenomena;
– reduced energy consumption for the same performance;
– elimination of the ventilator electrical connection cabinet;
– reduction of the costs for the lower rated power.

Under fire conditions the fans allow the flow rate of the air in the tunnel to be controlled to encourage the layering of fumes and to control the flow rate over time in the tunnel in order to limit back-layering and to contain increases in the heating power of the fire caused by high air ventilation flow rates.

This control is effective in the initial stages of a fire before rescue workers arrive because of electronic protection systems installed in the ventilators.

Conventional systems are controlled by switching the fans on and off, which is a limitation due to the time taken to start them up and to the range of control provided which diminishes with the number of fans installed. The limitations of this system of control are even greater in two-way tunnels where the direction of the ventilation must be reversed depending on the quantity of the traffic in each direction. Continuous adjustment allows simultaneous operation of all the fans and subsequent continuous adjustment on the basis of the quantities of traffic and the concentrations of pollutants.

2.4 *Water supply*

2.4.1 *Automatic fire fighting systems with the use of distributed monitors*

The ability to intervene with high-powered robotic fire fighting systems in the first moments when a fire starts furnishes considerable advantages with important results in terms of saving the lives of tunnel users:
– it prevents fires from developing and increases the chances of containing them or putting them out;
– flashover is delayed;
– the production of toxic gases is delayed.

This can be achieved by positioning motorised monitors controlled remotely by special software and by control centres when required in place of regulation fire hydrants.

The system is based on tried and tested fire fighting technology with remote controlled hydro-foam monitors, widely used throughout the world to put fires out in high-risk industrial plants.

Figure 9 Robotic monitor

Intervention and control stations are located at regular intervals (usually every 42 metres) along the walls of tunnels. They consist of a remote controlled monitor with a capacity of 1,000 litres per minute fitted with a motorised valve, an electrical board, flame detectors and visible light and infrared video cameras.

Figure 10 The fire fighting system in action

3 REFERENCES

Focaracci A.2004. Nuovi orientamenti in tema di normative di sicurezza per gallerie stradali e ferroviarie, *Gallerie e Grandi Opere sotterraneo* n 73 , Agosto 2004 Bologna Patron Editore

Cafaro E., Focaracci A., Guarascio, Stantero L. 2006, Quantitative Risk Analysis for Tunnels, *Tunnel Management International Conference Torino, Maggio 2006.*

Focaracci A. 2006. Relazione del Presidente del Comitato C.3.3 sulla gestione delle gallerie stradali, XXV *Congresso Nazionale Stradale AIPCR Napoli 4-7 ottobre 2006*

Focaracci A. 2007. Progettazione e realizzazione della sicurezza nelle gallerie stradali e ferroviarie , *Strade & Autostrade* 1-2007 Milano EDI-CEM srl

Focaracci.A. 2007 . Progettare la sicurezza - Italian Risk Analysis Method , *Le strade* 4-2007 Milano La Fiaccola srl

Angelozzi E.; Bandini C.; Doferri Vitelli M.; Focaracci A.; Grassi F. 2007. Il progetto del potenziamento appenninico, *Le strade* 6-2007 Milano La Fiaccola srl

A. Focaracci ; Tozzi G. 2007. L'applicazione del D.Lgs. n 264/2006 alle gallerie di Autostrade per l'Italia (ASPI), *Le strade* 11-2007 Milano La Fiaccola srl

Focaracci A.; Cafaro E. 2009. Lo studio del livello di rischio di una galleria, *Strade & Autostrade* 1-2009 Milano EDI-CEM srl

PIARC Committee on Road Tunnels:

"Fire and Smoke Control in Road Tunnels", 1999

"Road Tunnels: Emissions, Ventilation, Environment; 1999

ISO 13387 – 1999 Fire Safety Engineering Parts 1-8, 1999

NFPA 502 - 2004 Standard for Road Tunnels, Bridges and other limited access highways, 2004

IEC,1995 - International Standard 60300 –3 – 9, Risk Analysis of technological systems, Geneve, 1995

NFPA 551 -2004 - Evaluation of Fire Risk Assessments, 2004

MHIDAS (Major Hazard Incidents Data Service), UK Health and Safety Execution, July 2004