 DOI: 10.3217/978-3-85125-883-7-31

RISK-BASED VENTILATION DESIGN STUDY FOR THE LA LINEA TUNNEL

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ABSTRACT

With a length of 8,650, the La Linea tunnel is the longest road tunnel crossing the central Andes mountain range in Colombia, with one tube for unidirectional traffic, connected via several cross passages with the parallel rescue tube. In 2016, at the beginning of the study, the civil works were concluded and the tunnel equipment had to be defined. According to relevant regulations and guidelines, the tunnel would require a transversal ventilation system. However, in the tunnel were no provisions for the implementation of such a ventilation system, respectively an intermediate ceiling for an air duct. In the ventilation study, different ventilation concepts were investigated. The aim was to identify the most appropriate ventilation system for normal operation and in case of fire. The equivalency of each alternative ventilation system including additional required risk-mitigation measures was investigated by a detailed quantitative risk assessment study. Thereby, the Austrian Tunnel Risk Model (TuRisMo) according to RVS 09.03.11 was used as a decision-making tool for the ventilation design and other safety-related aspects. The results obtained from the quantitative risk assessment study as well as the ventilations study show that the longitudinal ventilation system is the best and most suitable ventilation concept for the La Linea tunnel.

Keywords: Tunnel risk assessment, transversal and longitudinal ventilation system, road tunnel, decision-making tool.

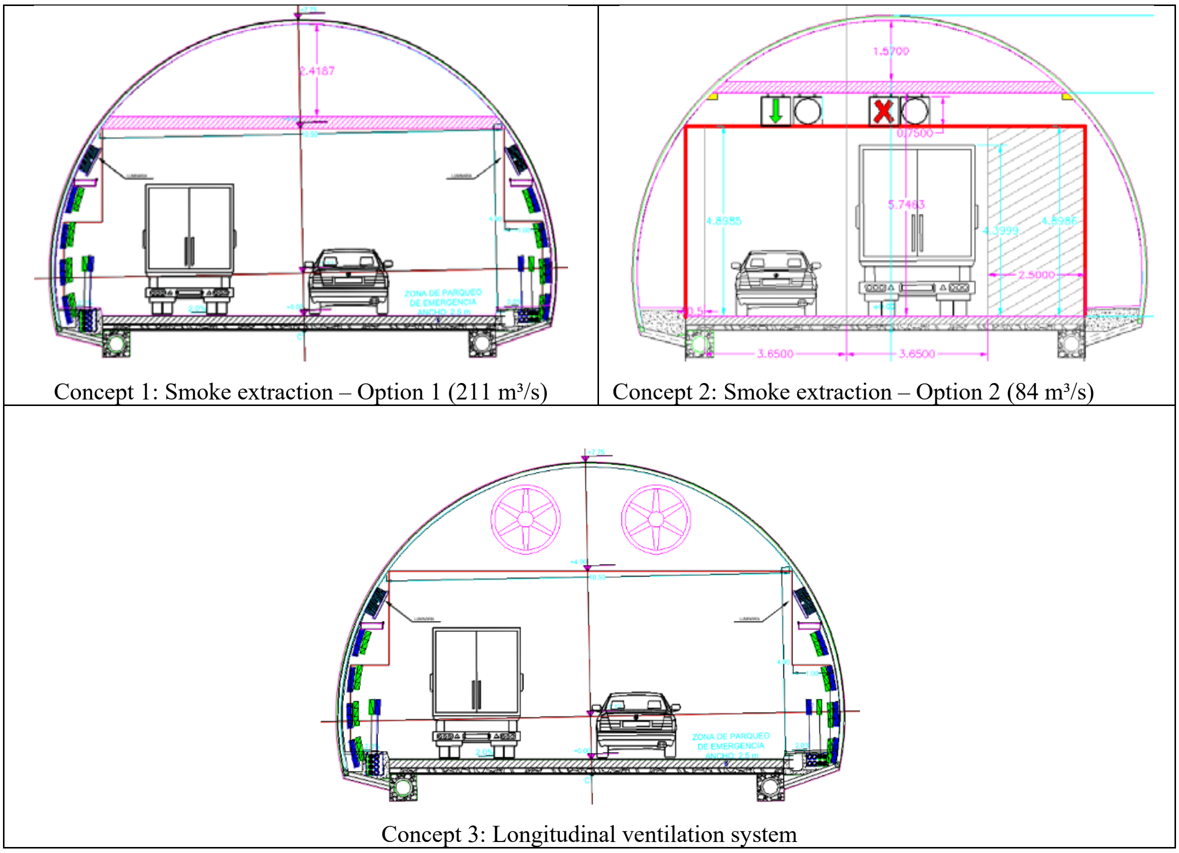
1. INTRODUCTION

The La Linea tunnel is the longest tunnel of the 24 tunnels which are part of the project “Crossing the central mountain range”. The 8,650 m long tunnel system has one traffic tube for unidirectional traffic which is connected via 16 cross passages (connecting galleries) with the parallel rescue tube. The traffic is operated in uphill direction at a slope of 1%. The tunnel is at an average altitude of about 2,450 m above sea level and is part of a main transport route of the country. The predicted traffic for 2036 is approximately 5,747 vehicles per day.

The La Linea tunnel has a long design history since the 1990 decade: Several different options for a ventilation system have been studied and proposed. Finally it was intended to implement a semi-transversal ventilation system. At the beginning of this study in 2016, the tunnel was in the final phase of construction, with finalized civil works, without equipment and installations at this stage. Normally, the decision on the ventilation system is taken in an early planning phase, because it provides an important basis for defining the requirements for the design of the civil structures of a tunnel (like tunnel cross section). In particular, the implementation of any smoke extraction system requires the provision of a properly dimensioned air duct (for smoke extraction) in the upper part of the tunnel cross section. However, as the project was already in an advanced stage of realization, the cross section could not be modified any more. These boundary conditions provided considerable constraints for the decision on the ventilation system.

2. INITIAL SITUATION

As the project was already in an advanced stage of realisation, the cross section could not be modified anymore. Referring to the key design parameters for fire for a semi-transversal ventilation a cold exhaust flow rate of 211 m^3/s would be required (see Figure 1 – concept 1). In principle the existing tunnel cross section would provide sufficient space above the traffic clearance gauge to achieve this design objective, but then no space would be available for the implementation of the planned overhead signalling system (according to international state of the art and regulations – see for instance RVS 09.02.22 [1] – the lane dependant traffic signs must be positioned on top of its corresponding lane). Vice versa, providing the space required for the installation of the overhead signalling system would reduce the capacity of the smoke extraction system to 84 m^3/s, which would impede its efficiency considerably (see Figure 1 – concept 2).



Concept 1: Smoke extraction – Option 1 (211 m³/s)

Concept 2: Smoke extraction – Option 2 (84 m³/s)

Concept 3: Longitudinal ventilation system

Figure 1: Alternative ventilation concepts feasible in existing tunnel profile

Therefore, a detailed quantitative risk assessment model was used as an decision-making tool to investigate different possible ventilation systems and define the most appropriate ventilation design and other safety-related aspects.

3. TWO DIFFERENT APPROACHES TO TUNNEL SAFETY

According to international best practice (see for instance PIARC reports "Risk analysis for road tunnels" [2], "Current practice for risk evaluation for road tunnels" [3]) two different approaches are applied to guarantee a satisfying level of tunnel safety, which are as well relevant for the selection of important safety systems like tunnel ventilation: (a) The (traditional) prescriptive approach, based on technical design guidelines, providing technical specifications of the safety features of a tunnel; the underlying safety principle of this approach postulates, that a tunnel is sufficiently safe, if these technical specifications are met. However, even if all requirements are fulfilled there is a residual risk, which is not specifically addressed in this approach; and (b) the (innovative) risk-based approach, based on a structured, harmonised and holistic safety analysis of the whole tunnel system, considering all safety-relevant specific characteristics of an individual tunnel. A tunnel is considered as sufficiently safe, if predefined risk criteria are met.

These two approaches shall be used as complementary elements of tunnel design (see PIARC report "Current practice for risk evaluation for road tunnels" [3]). These two different approaches are as well established in up to date international tunnel regulations, like the EC-Directive 2004/54/EC [4]. The EC-Directive 2004/54/EC on Minimum Safety Requirements for Road Tunnels is a regulatory framework which is mandatory for all EU member states; it has been implemented in the national legislation of all countries. The EC-Directive 2004/54/EC defines in Annex I a list of mandatory safety measures, also addressing ventilation aspects; defines in Article 13 the requirement for a risk analysis; and establishes the principle of compensation: if a prescriptive requirement cannot be met for relevant reasons, this can be compensated by alternative measures, if it can be demonstrated by a risk analysis, that at least the same level of safety can be achieved. National guidelines may be stricter and more detailed, but must be within this frame work.

4. RELEVANCE OF TUNNEL LENGTH WITH RESPECT TO DECISION ON VENTILATION SYSTEM

4.1. EC-Directive

In the European Directive 2004/54/EC [4] there are no general length limitations for unidirectional tunnels with longitudinal ventilation systems. The only length limitations for longitudinal ventilation (>1000m) refers to traffic parameters – bidirectional traffic or unidirectional traffic with regular congestion (due to traffic overload). The traffic study for the La Linea tunnel [5] confirms, that even in the long-term perspective the expected peak hour traffic will be clearly below the capacity of the tunnel. In all future peak hour scenarios investigated the level of saturation will be clearly below 50%. Additionally, in the risk assessment study requirements are defined (regarding the position of the toll station) to award building up of a queue of vehicles in the tunnel exit zone, which may reach back to the tunnel exit portal. Hence, the basic conditions for the implementation of a longitudinal ventilation system in La Linea tunnel are met.

4.2. National guidelines

In some European countries there are national tunnel design guidelines – in addition to the EC-Directive; in many cases, these national guidelines are older than the EC-Directive. Some of these guidelines have length limitations for the application of longitudinal ventilation systems in unidirectional tunnels. The main reason for these limitations was that in the past the fresh air supply during normal operation due to the high emission level of old vehicles could be a limiting factor, because the maximum permissible air velocity in the tunnel could be exceeded.

In Austria – like in some other European countries - there is a set of national technical guidelines (RVS) relevant for elements of civil tunnel structure and tunnel equipment (including ventilation). These guidelines are continuously updated, implementing new findings and developments. In older versions of RVS 09.03.11 [6] the application of longitudinal ventilation systems for unidirectional tunnels was limited to tunnels shorter than 3,000 m. In an update

(2014) of national guidelines (RVS 09.02.31 [7]) these limitations have been adapted as follows: In general, RVS 09.02.31 suggests for unidirectional tunnels longer than 5,000 m a semi-transverse ventilation system. However, an alternative ventilation system is permissible, if the equivalency is confirmed by means of a risk analysis. These regulatory definitions define the requirements for risk assessment as well as the conditions for the acceptability of a longitudinal ventilation system from a risk-based perspective: In the risk assessment it has to be demonstrated that the risk of the tunnel with longitudinal ventilation (including additional risk-mitigation measures required) is equal to or less than the risk of the tunnel with semi-transversal ventilation; thus defining the semi-transversal ventilation as reference case relevant for risk evaluation.

4.3. Technical aspects

In addition to the regulatory aspects, also technical aspects have to be considered when designing a ventilation system for a (long) unidirectional road tunnel.

Fresh air demand

The fresh air demand depends on the emissions of the vehicles in the tunnel. The number of vehicles in the tunnel is a function of the hourly traffic volume and the tunnel length. The longer the tunnel, the more vehicles are inside the tunnel at the same time. Hence, a long tunnel requires more fresh air than a short tunnel.

The amount of fresh air itself is no restriction for any ventilation system. However, guidelines like the PIARC, NFPA, the German RABT or the Austrian RVS limit the maximum longitudinal air velocity in the tunnel. Since a high fresh air demand causes a high longitudinal air velocity in the tunnel, the maximum amount of fresh air is indirectly also limited by the velocity limitation. Therefore, the application of ventilation systems with a fresh air supply via the tunnel portals like a longitudinal ventilation system or a semi-transverse ventilation system has limits. Thus, for long tunnels with a high fresh air demand a transverse ventilation system may be required for normal operation. In case of the La Linea Tunnel it could be demonstrated that the required amount of fresh air allows to apply a longitudinal ventilation system (see chapter 6)

Pressure loss caused by wall friction

The friction between the flowing air and the static concrete walls causes a pressure loss, which has to be overcome by the ventilation system. The pressure loss rises if the length of a tunnel/exhaust duct gets longer and if the cross section gets smaller. In case of a longitudinal ventilation system a long tunnel causes a higher pressure loss than a short tunnel. That is why a long tunnel requires more jet fans for reaching a required air velocity than a short tunnel. However, the application of a longitudinal ventilation system is not restricted by the required amount of jet fans. For a semi-transverse ventilation system there is a pressure loss in the main tunnel and in the exhaust duct. The longer and the smaller the exhaust duct, the higher is the pressure loss along the duct while extracting air and the higher is the pressure difference between the exhaust duct and the main tunnel. The maximum permissible pressure difference between the exhaust duct and the main tunnel is limited by guidelines for technical reasons (e.g. by the Austrian RVS 09.02.31 to 3,000 Pa). This limitation restricts the application of a semi-transverse ventilation system

4.4. Safety Aspects

From the safety perspective only fire incidents are relevant for the decision on the ventilation system. The EC-Directive as well as national guidelines limit in general the application of longitudinal ventilation systems to unidirectional tunnels which do not have congested traffic (with some exceptions under specific conditions – see chapter 4.1 and 4.2). This regulation refers to the fact, that in case of a fire incident, vehicles in front of the fire should be able to leave the tunnel without problems, if the traffic is not congested. In this respect two different scenarios for congested traffic need to be distinguished:

- **Congestion due to traffic overload:** Stop-and-go traffic caused by insufficient capacity of the tunnel itself or road sections downstream of the incident location. This type of congestion excludes the application of longitudinal ventilation for longer tunnels.
- **Evolving congestion after a previous initial event**: Congestion caused by an initial event, like vehicle breakdown or collision. This type of congestion may happen in every tunnel and cannot be excluded. Therefore, this type of congestion is not meant by the regulatory requirements mentioned above.

However, both congestion types lead to different fire scenarios with different probability of occurrence, exposition (number of vehicles potentially affected) and preconditions for smoke propagation. Especially in the latter, there is an influence of tunnel length. Hence, the consequences of this scenario need to be specifically addressed in a quantitative risk assessment study.

5. RESULTS OF RISK ASSESSMENT STUDY

Taking the conditions and requirements defined in chapter 3 as basis, a quantitative risk assessment study was performed for the La Linea tunnel. For that, the Austrian Tunnel Risk Model TuRisMo (defined in RVS 09.03.11 [6]) was applied, following the principles defined by PIARC for the risk assessment process.

The risk assessment study was performed for the 3 ventilation systems shown in Figure 1. The risk evaluation was carried out using a relative approach: The tunnel options which shall be investigated were compared to the risk value of an idealised reference tunnel defining the "reference risk profile" (see Figure 2). Following the definitions in the ventilation design guideline RVS.09.02.31 [7] for the decision on the ventilation system of La Linea tunnel, the reference tunnel is a tunnel with a semi-transverse ventilation system with a exhaust flow rate of 211 m^3/s (see chapter 2) – an ideal case, without taking into account possible consequences of space requirements in cross section.

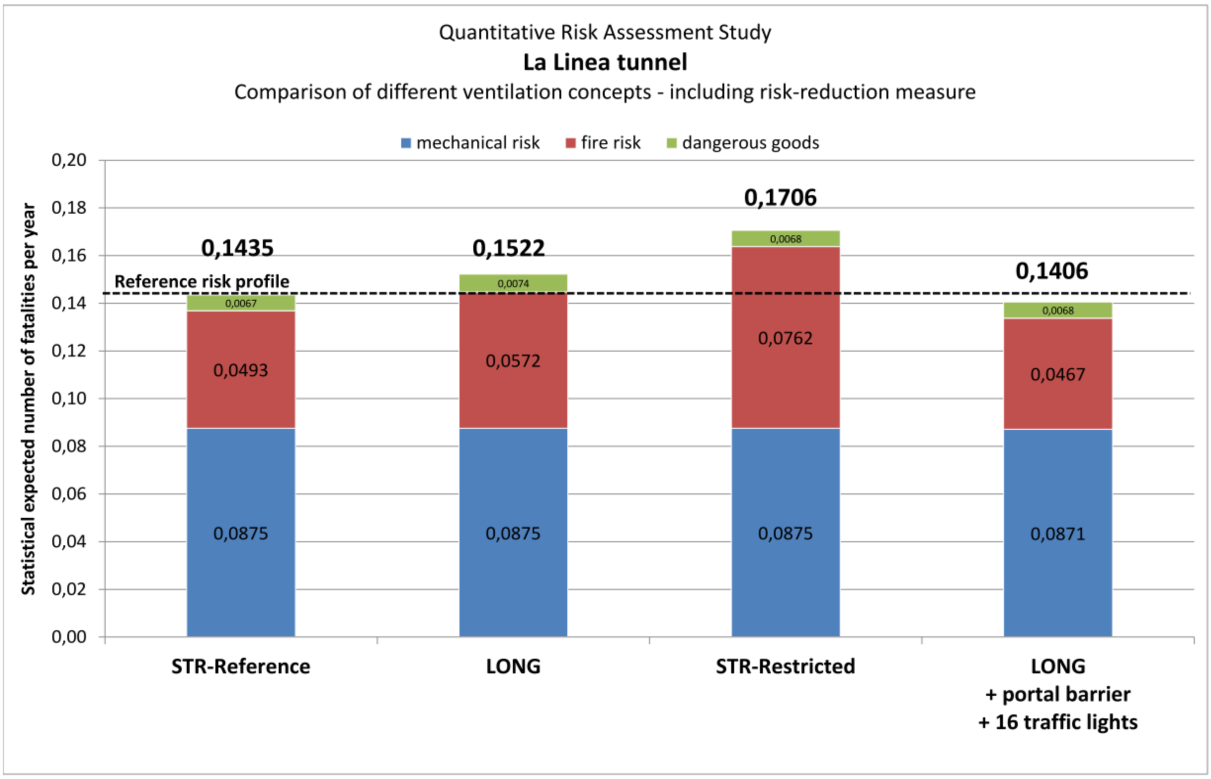


Figure 2: Quantitative risk assessment study – final results

These results can be interpreted as follows: The optimum semi-transverse smoke extraction system (Concept 1: "STR-Reference") defines the reference risk profile. A realistic but restricted semi-transverse smoke extraction system (Concept 2: "STR-Restricted"), taking into account the space requirements, considerably exceeds the reference risk profile (due to high fire risk as a consequence of a restricted smoke extraction capacity). The longitudinal ventilation system (Concept 3: "LONG") slightly exceeds the reference risk profile due to a slightly higher fire risk.

Therefore, additional risk mitigation measures are required to allow the use of a longitudinal ventilation system from a risk perspective. A more detailed analysis of the fire risk of Concept 3 revealed, that a relevant share of risk is due to secondary fire scenarios (influence of tunnel length – high number of vehicles still moving in the tunnel – increased likelihood of secondary collisions and fires). Hence, the additional measures are proposed to reduce this specific part of the risk: stop vehicles in tunnel as soon as possible by implementing additional traffic barriers at the tunnel portal and 16 traffic signals throughout the tunnel – thus, reducing exposition of vehicles to a potential fire. During the adaption of the Austrian tunnel model TuRisMo respectively RVS 09.03.11 both, the time for vehicles to stop in front of a red light as well as a in front of a traffic barrier were discussed. Based on the experience of Austrian tunnel operators it takes approximately 30 seconds to stop in front of a red light. When using a traffic barrier it was assumed, that this time is reduced to zero. Of course, the time to detect the incident and react has to be added (e.g. 60 seconds). Due to the faster stopping time less vehicles enter the tunnel and less people are exposed in case of a fire. In addition, traffic signals inside the tunnel stop vehicles in regular distances and increase the distance of people to the fire location. Since the traffic signals (and additional vehicle queues) are located next to the emergency exits, the evacuation time in the tunnel is increased. The results show that this specific measure was able to reduce the risk of the tunnel with longitudinal ventilation below the reference case.

6. RESULTS OF FRESH AIR DEMAND CALCULATIONS

The amount of required fresh air depends on the traffic volume through the tunnel. Hence, the fresh air demand is the same for all ventilation concepts. As with a longitudinal ventilation system the fresh air supply underlies some limitations (due to tunnel length), this requirement is crucial for the assessment of the feasibility of a longitudinal ventilation system. Hence, an investigation of the fresh air requirements to meet the air quality limits in the tunnel, which is necessary for carbon monoxide (CO) and visibility in the conceptual ventilation design, and result in a minimum flow rate has been performed. Particle emission rates are used for the calculation of fresh air to meet the visibility limits. The NO2/NOx concentration is not considered for the fresh air demand, what is state of the art for European and North-American road tunnels. The reason for the neglect of the NOx concentration is it's irrelevance for short term exposure. The fresh air calculation defines the minimum flow rate and is set up for different speeds for CO and turbidity. Due to the increasing number of vehicles equipped with catalytic converters. CO emissions have decreased. Therefore, in most cases the visibility due to particulates (exhaust and non-exhaust) is relevant for the ventilation design.

Under the assumption of a traffic control system that can limit the minimum collective vehicle speed to 10 km/h, the design flow rate for normal operation was calculated to 211 m³/s. This flow rate is equal to a longitudinal air velocity of 2.8 m/s. The design flow rate for maintenance operation is calculated by applying a limiting value of 0,003 m-1 according to PIARC and is 375 m³/s. Due to the high fresh air demand for maintenance operation, maintenance works shall be performed during low traffic hours to avoid too high air flow rates. The minimum required air velocity in the tunnel according to the PIARC for normal operation is 1.5 m/s. According to the guideline NFPA 502 [8] maximum air velocities in the traffic tunnel during normal operation should be less than or equal to 11 m/s. Hence, the fresh air demand can be provided without exceeding maximum velocity limits. According to the calculation results all vehicle speeds down to 10 km/h can be handled by the ventilation system. The calculation results are summarized in Table 1

Table 1: Required jet fans for normal operation

collective vehicle speed	**number of required activated jet fans**	
[km/h]	**traffic scenario with max HGV-percentage**	**traffic scenario with maximum traffic**
≥50 km/h	self-ventilated	self-ventilated
40 km/h	self-ventilated	4
30 km/h	2	6
20 km/h	6	10
10 km/h	11	14

7. SUMMARY AND CONCLUSIONS

A risk assessment study was performed in order to investigate and quantify the influence of different ventilation systems on the risk, and used as a decision-making tool on the ventilation design. The study compared an reference smoke extraction system (=fulfilling all guidelines) with a realistic smoke extraction system and a longitudinal ventilation system. The results show, that from a safety point-of-view the realistic smoke extraction system (taking into account the space requirements in the La Linea tunnel) considerably exceeds the reference risk profile and cannot be taken into consideration. Furthermore it was demonstrated, that the fresh air supply of La Linea tunnel can be guaranteed by an adequately designed longitudinal ventilation system.

Besides the safety aspects the longitudinal ventilation system is superior to the semi-transverse ventilation system regarding the following: the reliability of the system; the simple ventilation control; the power consumption during emergency operation and therefore a less costly energy supply system; the combination with a simple and effective pressurization system for the rescue tunnel; the testing and commissioning effort; the required space for overhead traffic signs; the investment costs.

The results obtained from the quantitative risk assessment study as well as the ventilations study showed, that the proposed longitudinal ventilation system is the best and most suitable ventilation concept for the La Linea tunnel. Therefore, that was the system that finally was implemented and operates with no issues since September 2020.

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