THE TÚNEL LA LÍNEA - A CHALLENGE FOR VENTILATION AND SAFETY

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ABSTRACT

The Túnel la Línea in Colombia with its length of 8.6 km will be the longest road tunnel on the American continent. Due to the large number of trucks that will use this tunnel and the exceptional elevation (2500 m above sea level), the Túnel la Línea represents a challenge for the design of tunnel ventilation and safety installations.

The design concept for the Túnel la Línea comprises one tunnel tube for bi-directional traffic and a parallel rescue tunnel. The tunnel will be equipped with a fully-tranversal ventilation system (with two ventilation shafts) in order to provide the highest level of safety in case of a tunnel fire. Other ventilation systems produce a higher air velocity in the tunnel during regular tunnel operation and would therefore delay the detection of the fire and allow the smoke gases to spread rapidly along the tunnel.

The calculation for the fresh air demand was based on the recommendations of PIARC from 1987. In order to guarantee that the permissible maximum values for carbon monoxide and diesel soot concentration are not exceeded, a fresh air volume of approx. 170 m³/(s*km) will be required for the Túnel la Línea. An exhaust air extraction capacity of at least 120 m³/s at the end of each ventilation section would be available in case of a tunnel fire.

With a fully-tranversal ventilation system, fire detectors all along the tunnel, a fire-fighting pressure pipe with hydrants every 125 m, emergency call niches every 250 m, a closed-circuit TV system and emergency exits to the parallel rescue tunnel every 500 m, the Túnel la Línea will be provided with a state-of-the-art safety concept.

Key words: Transversal ventilation system, rescue tunnel, tunnel fire, fresh air demand, safety concept

1 INTRODUCTION

The Túnel la Línea Project is located in the Cordillera Central mountain range of Colombia and consists of an 8.6 km long road tunnel and a parallel rescue tunnel. Construction is scheduled to start during the second half of 2002. Once completed, it will be the longest road tunnel on the American continent.

The Túnel la Línea is part of the road project Ibague - Armenia, with the purpose to improve the existing road connection between Bogotá, Colombia's capital with a population of around seven million people, and Buenaventura, Colombia's main port on the Pacific coast and gateway for Colombia's rapidly growing trade with the Far East. Because of its importance for the country's economy, the road is mainly used by heavy trucks, many of them with 6 axes and a total weight of 52 tons. The existing road is crossing the mountain range at an elevation of approx. 3200 m above
sea level. The Túnel la Línea will be located at an elevation of approx. 2500 m and will reduce the average driving time for trucks by more than 40 minutes.

2 TUNNEL DESIGN CONCEPT

The basic design for the Túnel la Línea comprises one tunnel tube for bi-directional traffic, two ventilation shafts, two ventilation caverns near the bottoms of these shafts as well as a parallel rescue tunnel (min. diameter 4.70 m). The horizontal alignment of the tunnel is slightly curved in an S-shape and has a minimum radius of 3000 m. The vertical alignment shows a constant gradient between the portals of approx. 1 %.

![Figure 1: Túnel La Línea - Longitudinal Section](image)

According to the basic design, the main tunnel comprises the following features:

- two traffic lanes with a width of 4.00 m each, and with a clear height of 4.70 m
- safety walkways (width 0.85 m) at either tunnel side wall
- a fully-transversal ventilation system with both ventilation ducts above the roadway, with fresh air jets every 6 m and exhaust air extraction openings every 96 m
- axial ventilators at both portals and at the ventilation caverns adjacent to the shafts
- emergency exits to a parallel rescue tunnel every 500 m
- niches for emergency stops every 1000 m at both side walls of the tunnel
- two U-turn possibilities at the locations of the ventilation caverns (approx. at the third points of the tunnel length)
- emergency call facilities every 250 m
- a fire-fighting water pressure pipe along the entire length of the tunnel with hydrants every 125 m, supplied by two water storage tanks (one at either portal)
- fire detection sensors along the entire length of the tunnel
- a closed-circuit TV monitoring system
- a radio communication system
- cable ducts underneath both safety walkways
- permanent lighting including an emergency lighting system
- a tunnel control centre at the East Portal (Portal Bermellón)
- a portal building at the West Portal (Portal Galícia)
- a primary (temporary) lining consisting of shotcrete, wire mesh, steel ribs and rock bolts and a secondary (permanent) lining consisting of cast in-situ concrete
- a waterproofing system between the two linings that prevents ground water from entering the tunnel
- two separate drainage systems, one for (clean) ground water and one for (contaminated) road surface liquids
Since the Project Túnel la Línea will be awarded as a Design & Build Contract, the detailed design will be carried out by the Contractor. Changes of the basic design with regard to the excavation method, the ventilation system and the safety concept are permitted within the limits defined in the tender documents.

Figure 2: Túnel La Línea - Tunnel Cross Section

3 VENTILATION SYSTEM

3.1 General

At the Túnel la Línea, trucks and buses count for as much as 70% of the total traffic volume. This traffic mix, together with the high elevation of the tunnel, will result in a considerable fresh air demand for tunnel ventilation.

The Túnel la Línea will require two ventilation shafts with depths between 450 and 500 m. Both shafts will supply fresh air and extract exhaust air from the tunnel tube. These shafts will be located as close as possible to the third points of the tunnel length in order to achieve optimum conditions for the operation of the tunnel ventilation system.

3.2 Traffic Data

According to existing traffic data, the expected traffic volume is 4126 vehicles / day for the year 2007. The corresponding traffic peak per hour, which is crucial for the ventilation design, is equal to
10 % of that value and therefore 412 vehicles / hour. Although traffic volume is expected to increase to more than 7000 vehicles / day in the year 2027, the total emission quantities will be less at that time, due to the improvements in vehicle technology. Traffic for the year 2007 is expected to consist of 63 % HGVs (Heavy Good Vehicles), 30 % passenger cars and 7 % buses. Based on existing traffic data, the average weight of the diesel-powered vehicles (M_D) was calculated with M_D = 21.22 t.

### 3.3 Vehicle Emissions

Various gases such as nitrogen (N_2), carbon dioxide (CO_2), steam (H_2O) and to some degree oxygen (O_2) are emitted by a combustion engine. These gases are, on the whole, not poisonous. Additionally, a number of harmful substances is emitted which can be classified in three categories: products of incomplete combustion, products of over-complete combustion and products from additives and impurities. Especially carbon monoxide and soot are dangerous in road tunnels:

- Carbon monoxide can have a poisonous effect on human beings if it is inhaled in higher concentration or for longer periods. CO is primarily emitted by gasoline engines.
- Soot in higher concentrations impairs the visibility and makes it difficult or even impossible to recognise any obstacles on the roadway. The danger of accidents in the tunnels increases. Soot is primarily emitted by diesel engines.

It is therefore necessary to provide fresh air in longer tunnels to lower the concentration of CO as well as to improve the visibility.

The average emissions of the various types of vehicles are very important. From traffic studies carried out by the local authorities in Colombia it could be concluded that the emissions of the majority of vehicles can be compared with the vehicle emissions existing in Austria around 20 years ago. Therefore, the basic value of the CO emission was assumed with 0.7 m^3/h, veh and the basic value of the diesel soot emission with 16 m^2/h, t. These values had been used in Austria prior to the introduction of the catalysator for the gasoline engines and the implementation of (new) strict emission laws for diesel engines.

The NO_x - emissions of a vehicle strongly depend on the performance efficiency of the engines. Only with extremely high performance efficiencies of the vehicle engines, a substantial NO_x - emission has to be expected. In comparison with the quantity of fresh air required for the dilution of soot emission, the quantity of fresh air required for the dilution of the NO_x - emission is always smaller. Even in the new Austrian Guidelines (RVS 9.262), a calculation of the NO_x - emissions is not required.

### 3.4 Allowable CO-Concentration in Tunnels

Haemoglobin (Hb) is the blood component that transports the vital oxygen through the human body. Only part of the haemoglobin in the blood joins oxygen (O_2Hb), the rest (a small percentage) is unsaturated (Hbu) and does not transport oxygen.

When the air contains CO, the haemoglobin joins the CO to carboxy haemoglobin (COHb) instead of producing O_2Hb, due to the greater affinity between carbon monoxide and haemoglobin. As a result, the amount of haemoglobin transporting oxygen (O_2Hb) is reduced.

The allowable CO-value has been fixed at 150 ppm (parts per million) for tunnels with normal traffic. This value also corresponds to the specifications provided by PIARC [1] (Permanent International Association of Road Congresses). In case of dense, slow-moving traffic the allowable CO-concentration is 250ppm.
3.5 Allowable Turbidity in Tunnels

The soot produced by diesel engines decreases the visibility in a tunnel, making it difficult or impossible to see objects on the roadway in time. The Institute of Combustion Engines and Thermodynamics at the Technical University Graz has carried out research works regarding the effect of soot from diesel engines on visibility. Numerous tests have shown that the allowable extinction coefficient $K$ (indicating the reduction of the intensity of light when passing through a medium containing soot) in fresh air demand calculations should be around 0.007 to 0.008 [1/m]. In some cases the $K$-value can be slightly higher and was therefore set to $K = 0.010$ for the Túnel la Línea. Apart from impaired visibility, a certain amount of turbidity ($k=0.014$) should not be exceeded for health reasons. A tunnel should be closed if this value is reached until visibility improves.

3.6 Fresh Air Calculation

The fresh air demand ($m^3/s$, km, lane) was calculated in accordance with PIARC [1], using the following assumptions:

- Basic value of CO emission [$m^3/h$, veh.]........................................ $q_{CO} = 0.7 m^3/h$ PCU
- Max. permissible CO concentration [ppm CO].......................... $CO_{lim} = 150$ ppm
- Basic value of diesel soot emission [$m^2/h$, t]............................. $q_T = 16 m^2/h$, t
- Mean vehicle weight [t]..................................................... $m = 21 t / truck$
- Admissible diesel soot concentration................................. $K_{lim} = 0.010$ (1/m)

Fresh air demand has been calculated per kilometre of tunnel and for each lane separately. The calculations were performed using the computer program LUME 6c.

A minimum driving speed of 30 km/h was assumed for the downhill lane and of 0 km/h for the uphill lane. The maximum driving speed was determined according to following equation:

$$V_{max} = \frac{80 - 5s}{1 + 0.25s}$$  \[2\]  

$s$ (%) inclination

Normal Tunnel Operation

With the high percentage of HGVs and buses for the Túnel la Línea, soot emission becomes the only decisive factor for the fresh air demand. Although at a speed of 0 km/h the dilution of carbon monoxide (both for the uphill and for the downhill lane) requires more fresh air than the dilution of the diesel soot, it has to be considered that vehicle engines have to be turned off once the traffic flow has stopped. Therefore, the fresh air demand for this case is not relevant for the design. Furthermore it is known that CO-emissions will decrease significantly in the near future. The elevation of the tunnel was considered by using the corresponding altitude factor according to PIARC [1]. For an elevation of 2500 m, this factor is more than 3 times the basis value applicable at sea level.

For the calculation of the fresh air demand for the uphill lane, where sluggish traffic flow and traffic stops cannot be excluded, the air demand for a driving speed range between $v = 0$ and $v = 60$ km/h (approx.) has to be considered (HGVs cannot reach a higher speed in average). The fresh air volume required for the uphill lane was calculated to be $V_B = 100.6 m^3/(s*km)$. The traffic in the downhill lane will flow unhindered. Sluggish traffic flow ($v \leq 30$ km/h) and traffic stops can be excluded. Consequently, only the driving speed range above 30 km/h has to be considered. The fresh air volume required for the downhill lane was calculated with $V_T = 67.4 m^3/(s*km)$. This results in a total fresh air demand $V$ for the Túnel la Línea of:

$$V = V_B + V_T = 100.6 + 67.4 = 168.0 m^3/(s*km) \sim 170 m^3/(s*km)$$
Fire in the Tunnel

In case of a fire in a tunnel with a transversal ventilation system, the operation mode of the ventilation is changed from normal to fire mode. In the fire mode, no fresh air will be blown into the tunnel at the respective ventilation section; smoke gases will be extracted. The crucial factor is the smoke gas volume that can be extracted per second. According to Austrian Standards, it must be possible to extract 120 m$^3$/s of exhaust air at the end of each ventilation section in case of a fire.

A rough calculation showed that the ventilation system for the Túnel La Línea can fulfil this requirement.

3.7 Dimensions and Power Consumption

The Túnel la Línea will have six ventilation sections. Two of them will be ventilated from the two portals, the other four sections from the two shafts. The lengths of the ventilation sections are between 1400 m and 1700 m. With regard to a minimisation of the excavation cross section of the tunnel, the airflow velocities for fresh air and for exhaust air have been limited to 25.5 m/s, resulting in a cross section for the ventilation ducts of 11.3 m$^2$. While the maximum longitudinal air flow velocity inside the fresh and exhaust air ducts reaches these high values only in the vicinity of the ventilators, this is not the case for the shafts. There, the longitudinal air flow velocity remains constant for the entire shaft length and was therefore limited to approx. 18 m/s, resulting in an inner shaft diameter of 8.5 m.

The detailed design for the ventilator stations at the portals and at the caverns is not available at this stage. However, a preliminary estimate shows a required total power for the axial ventilators of approx. 5500 kW. A first estimation of the inner diameter of the axial ventilators for the portal stations and for the sections ventilated from the shafts results in a fan diameter $D = 3350$ mm.

3.8 Operation of the Ventilation in Case of Fire

At the moment when a fire occurs in a tunnel with a transversal ventilation system, it can be assumed that the ventilation system is operating with full power and that the fresh air ventilators and the exhaust air ventilators are working at the same performance level. As a consequence, the longitudinal air flow would be insignificant. The smoke gases would rise almost vertically towards the tunnel ceiling. The ceiling has to be equipped with a fire detection system that can detect and localise the fire very quickly (within 10 to 20 seconds). Immediately after the fire has been detected, a fire ventilation program must start automatically. This program (fire program for the ventilation system, informing fire brigade and ambulance, closing of the tunnel for the traffic, etc.) will be developed during the detailed design.

In case of a fire in a tunnel, it is essential to switch off the fresh air supply immediately in that ventilation section and to switch the exhaust air extraction to full power at the same time. Every 96 m large openings (size approx. 12 m$^2$) with regulators will be installed at the exhaust air ventilation duct. During normal operation, the regulators are adjusted in a way that the same quantity of exhaust air will be extracted through each of the openings. Immediately after detection of a fire, the exhaust air extraction opening next to the fire in direction of the smoke flow will be fully opened by the regulators. All other exhaust air extraction openings of that ventilation section will be closed by the regulators. This will avoid a longitudinal airflow and achieve a concentrated extraction of the smoke in the immediate fire area. As a result, the smoke cannot spread to the rest of the ventilation section, thus enabling tunnel users to escape without difficulties into the rescue tunnel. Together with the start
of the fire program, the jet fans (approx. 8 units), which will be installed inside the rescue tunnel, have to produce an overpressure relative to the main tunnel. This way, smoke cannot enter the rescue tunnel while people are escaping into the rescue tunnel. Instead, there will be a slight airflow from the rescue tunnel into the main tunnel, so that even with open connection doors, smoke will be kept from entering the rescue tunnel.

4 GENERAL TUNNEL SAFETY CONCEPT

A safety concept for a tunnel shall guarantee the safe evacuation of passengers in case of a major accident, e.g. when a large-scale fire occurs in the tunnel. It requires therefore a reliable monitoring system, a safe escape route for passengers, an access road for rescue vehicles, and an efficient and flexible ventilation system.

Safety concepts with safety niches at the tunnel walls where passengers could seek protection from the gases and the heat resulting from large-scale tunnel fires have not proven to be reliable enough. Escape tunnels (transversal to the main tunnel) leading from the main tunnel to the outside are not suitable for the Túnel La Línea due to the topographical conditions of the project area.

The technically best solution for a road tunnel safety concept is of course two separate tunnel tubes with unidirectional traffic in either tunnel tube. This reduces the risk of accidents in the first place and, by constructing cross passages at a regular spacing, provides excellent escape routes for passengers and access routes for emergency vehicles. A longitudinal ventilation system would be sufficient in that case because of the unidirectional traffic. For long tunnels, a concept with two tunnel tubes can usually not be constructed for cost reasons.

Almost all the advantages of the second tunnel tube with regard to safety in case of a tunnel fire can also be achieved with the construction of a much smaller rescue tunnel parallel to the main tunnel. Besides its important temporary function as a pilot tunnel during construction (geological investigation, pre-drainage), such a rescue tunnel will serve as a permanent escape facility for passengers and as an access for rescue vehicles. The rescue tunnel will be equipped with an emergency ventilation and lighting system and will be located at a horizontal distance of 40 - 60 m from the main tunnel, so that it could be enlarged to a second tunnel tube at a later stage, if required.

5 CONCLUSION

The safety concept proposed for the Túnel la Línea comprises a fully-transversal ventilation system, fire detection sensors and a fire-fighting water pressure pipe along the entire length of the tunnel with hydrants every 125 m, emergency call niches every 250 m, a closed-circuit TV monitoring system, and a parallel rescue tunnel with cross passages (emergency exits) at a maximum spacing of 500 m. For a tunnel with bi-directional traffic, this safety concept provides the highest possible level of safety for the tunnel users also in case of a major tunnel fire.

6 REFERENCES

[1] PIARC Committee on Road Tunnels, Brussels 1987