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Ventilation and Risk Control of the Young Dong Rail Tunnel in Korea

Fathi Tarada, Rudolf Bopp, Samuel Nyfeler
HBI Haerter Ltd., Consulting Engineers, Switzerland

Kwang-Soo Jegal, Deog-Su Kim
Daewoo Corporation Engineering & Construction, Korea

ABSTRACT

At 16.3 km in length, the Young Dong Rail Tunnel will be the first long rail tunnel in Korea. This paper reviews the design of the ventilation and risk control systems undertaken by the successful Daewoo Consortium, starting from the definition of the relevant design criteria for both normal and emergency operation, and ending with detailed specifications for the civil and mechanical components, including a rescue station and three air exchangers for the purging of diesel emissions. The engineering analyses employed included Quantitative Risk Analysis, Computational Fluid Dynamics and one-dimensional aerodynamic calculations of the entire tunnel system.

1 INTRODUCTION

In October 1999, Korea National Railroad announced the award of a design-and-build contract for the construction of the 17.8 kilometre long Young Dong Railroad Relocation Project to a consortium led by Daewoo Corporation. The project includes 16.3 kilometres of new, mixed traffic, single track, rock tunnel in the mountains of eastern Korea. The tunnel, to be driven by drill-and-blast methods, features a large radius loop to give the required gradients between Dong-Baek Mountain Station and Do-Ge Station.

The winning tender design was prepared by Seoul-based consultants led by Yooshin Engineering Corporation, with specialist consultancy services provided by the Halcrow Group in association with HBI Haerter Ltd. The Halcrow/HBI Haerter team provided technical assistance with geotechnical interpretation, tunnel design, construction methods, construction management, hazard and risk studies, track-slab design and construction methods, and ventilation and risk control.

The unique nature of the Young Dong Rail Tunnel, being by far the longest such tunnel project to be carried out in Korea, led to ventilation and risk control being given a high weighting within the list of criteria through which the competing tenders were evaluated. This paper therefore focuses on the development of the ventilation and risk control strategy, from the establishment of appropriate design criteria to the design of the individual components.

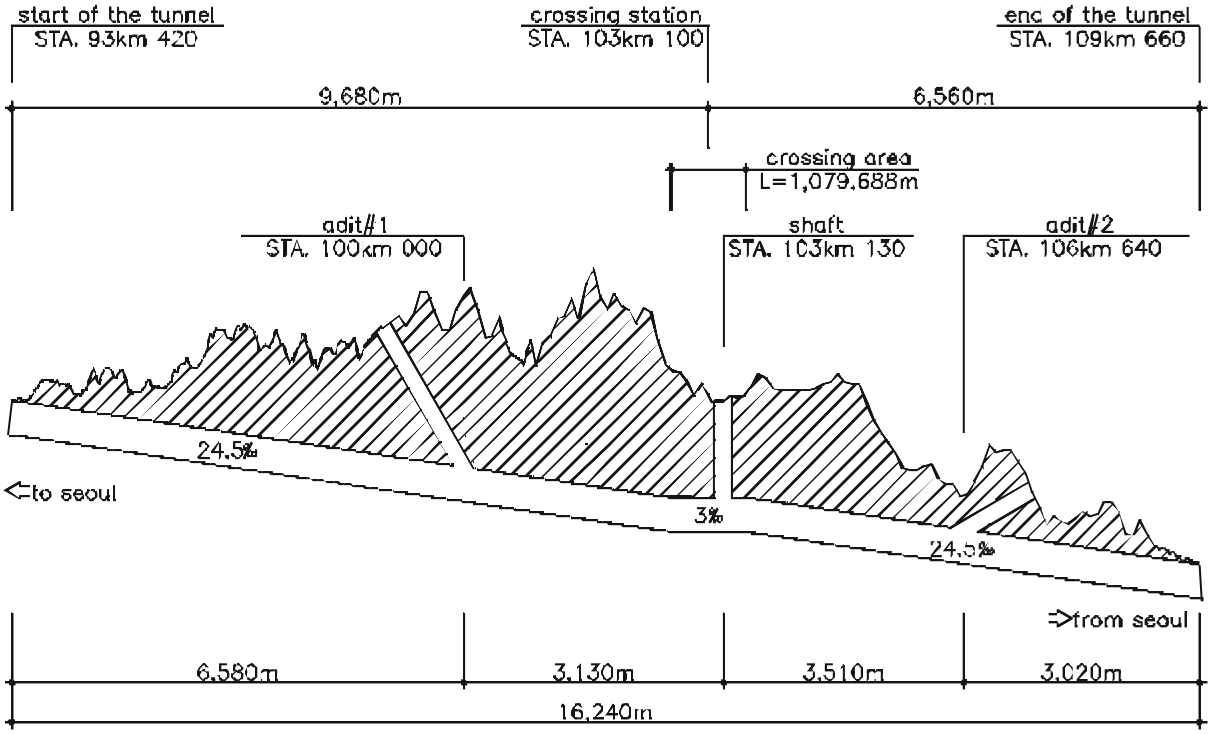

Fig. 1: Overview of the Young Dong Rail Tunnel

2 DESIGN CRITERIA

2.1 Risk Control Design Criteria

The Young Dong Rail Tunnel will be the first long railway tunnel in Korea, and hence the criteria with respect to risk control were carefully chosen for this project, with a view to establishing a good precedent for future rail tunnel projects in Korea.

The basic methodology used to analyse the total railway risks was Quantitative Risk Analysis, as depicted in Fig. 2. This included a top-down procedure (analysis of existing accident statistics for Korea National Railroad), a bottom-up procedure (estimation of the impacts of safety measures) and an event tree analysis. The output of the event tree analysis were curves on a frequency-consequences diagram (Fig. 3). These serve to display total railway risks using the number of fatalities as a risk indicator.

The frequency-consequences diagram is divided into three zones:

- The lower zone contains risks whose product of frequency and consequences are relatively low and are hence irrelevant for the design of safety systems. This lower zone is upper-bound by the 'line of irrelevance'.
- The middle zone contains risks which may be relevant for the design of safety systems. This intermediate zone is sandwiched between the line of irrelevance and the line of acceptance.
- The upper zone contains risks whose product of frequency and consequences are relatively high and are hence unacceptable. Safety systems must be designed so as to avoid this zone.

The lines of irrelevance and acceptance were set to the standards required of new European rail tunnels, in order to provide high levels of safety for the travelling Korean public.

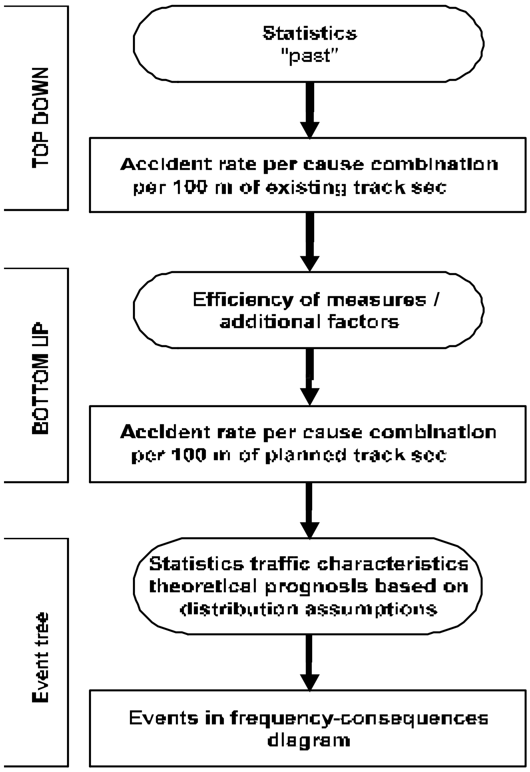

Fig. 2: Quantitative Risk Analysis Methodology

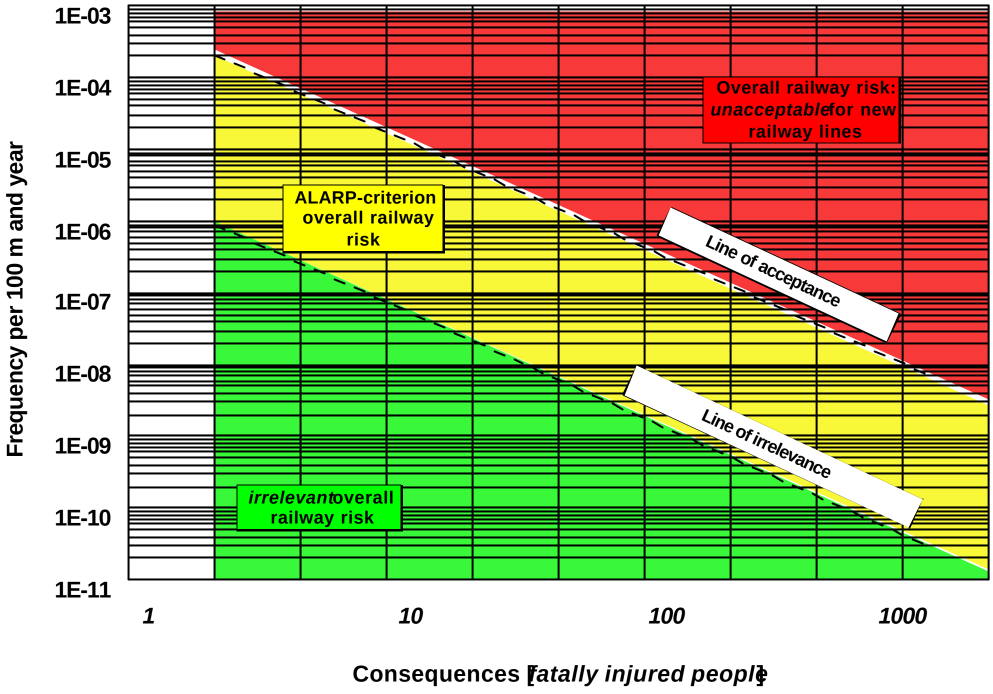

Fig. 3: Protective Goals for Total Railway Risks

2.2 Ventilation System Design Criteria

The design criteria for the ventilation system were developed after careful consideration of many issues, the primary ones being:

Diesel emissions

The rail traffic through the tunnel will include a substantial proportion (around 20%) of diesel-hauled locomotives. The identification of the gaseous contaminants (NO_x, CO) within the diesel emissions as well as their limitation to acceptable levels in the passenger carriages is therefore an important safety requirement. Secondary considerations arising from diesel emissions included the requirement to limit the temperatures at the locomotive and air-conditioning system intakes and to provide reasonable forward visibility for train drivers. The engineering calculations took the variation of emissions and heat rejection with throttle position (notch position) into account.

Fire scenarios

The primary requirements for the emergency ventilation system derive from smoke control considerations, i.e. that the smoke can always be driven in the required direction without any significant backlayering, even when thermal buoyancy forces are acting.

Design Criteria for Safety

Design Criterion	Recommended Value	Reason for Recommendation
NO_x concentration (critical contaminant)	28 ppm for journey times of up to one hour (with 5.2% of NO_x as nitrogen dioxide, as measured by Charlwood et al (1992)).	Bendelius (1999) proposes limits of 5 ppm for NO_2 and 37.5 ppm for NO for a one hour exposure. The limit for NO_x containing 5.2% NO_2 by volume was calculated using Haber's rule (Purser, 1995).
CO concentration	• 100 ppm under normal operation. • 30 ppm during maintenance work in tunnel.	• 100 ppm normal operation limit as recommended for fluid and congested traffic by PIARC (1995) • 30 ppm limit during maintenance as recommended by PIARC (1995), and by the Swiss Accident Prevention Institute (1997) for an 8 hour working shift.
Minimum velocity to be generated by emergency ventilation system over a stopped train	2 m/s in running tunnel.	Prevention of smoke backlayering - smoke should be driven in a clearly defined direction whilst passenger escape is arranged in the opposite direction.

Design Criteria for Operation and Maintenance

Design criteria	Recommended value	Reason for recommendation
Maximum air velocity in tunnel	10 m/s	To ensure the safety of maintenance workers in the tunnel.
Maximum air velocity in ventilation shaft	20 m/s	To limit the pressure drop across ventilation ducts.
Visibility	$0.007\ m^{-1}$ in running tunnel.	PIARC (1995) recommendation - exceptional congested traffic, standstill on all lanes.
Maximum pressure fluctuation during a train journey.	±3kPa change within 4 seconds.	Draft UIC recommendation for aural pressure comfort in single-track rail tunnels without sealed carriages (European Rail Research Institute, 1997).

Table 1: Design criteria for ventilation system

3 QUANTITATIVE RISK ANALYSIS

A Quantitative Risk Analysis was undertaken in order to estimate the overall railway risks both with and without a rescue station. As indicated by Fig. 4, the risk profile in the absence of a rescue station lies significantly above the line of acceptance, indicating the need for a rescue station in the Young Dong Rail Tunnel. The final engineering design included a rescue station beneath the central shaft as well as rescue areas at the bases of the two adits (see next Section).

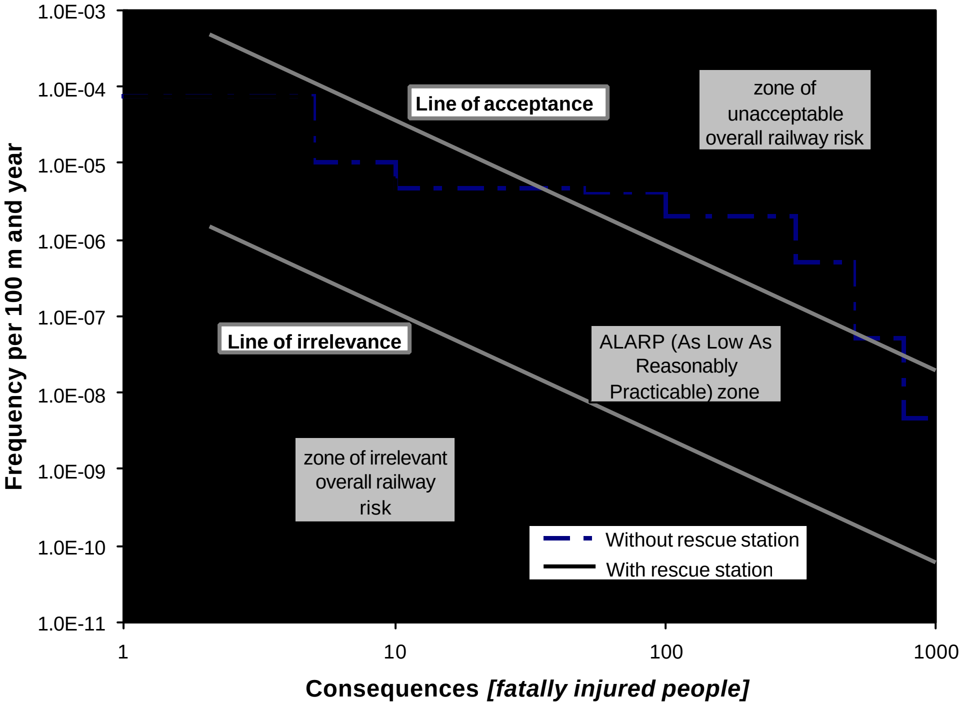

Fig. 4: Frequency/Consequences Diagram for the Young Dong Rail Tunnel

4 EMERGENCY VENTILATION SYSTEM

4.1 Emergency Concept

In an emergency case of a train fire, the train would leave the tunnel whenever possible. This is the most efficient measure to reduce the risk to passengers and staff.

At train speeds of between 36 to 77 km/h, typical journey times of 13 to 27 minutes are to be expected through the Young Dong Rail Tunnel. The emergency running characteristics of the trains are such that only 15 minutes of train travel during a fully-developed fire can be expected. Should a fire break out on a train during its journey through the tunnel, the danger exists that such a train cannot continue to the next portal and would therefore have to stop in the tunnel. Under these circumstances, it is important to provide a protected escape route for passengers and railway personnel, by providing a rescue station.

The location of the rescue station was set so as to provide approximately equal travelling times from both portals. Since the uphill train speeds are lower than the downhill train speeds, the rescue station was placed closer to the lower portal than the upper portal.

4.2 Emergency Rescue Station

Fig. 5 shows a plan view of the rescue station. Both the running tunnel and the side tunnel are connected to a split ventilation shaft, through which separate fans can either supply or exhaust air. In a fire emergency, one set of fans directs smoke out of the affected tunnel whilst the other set protects the non-affected tunnel from the effects of heat and smoke.

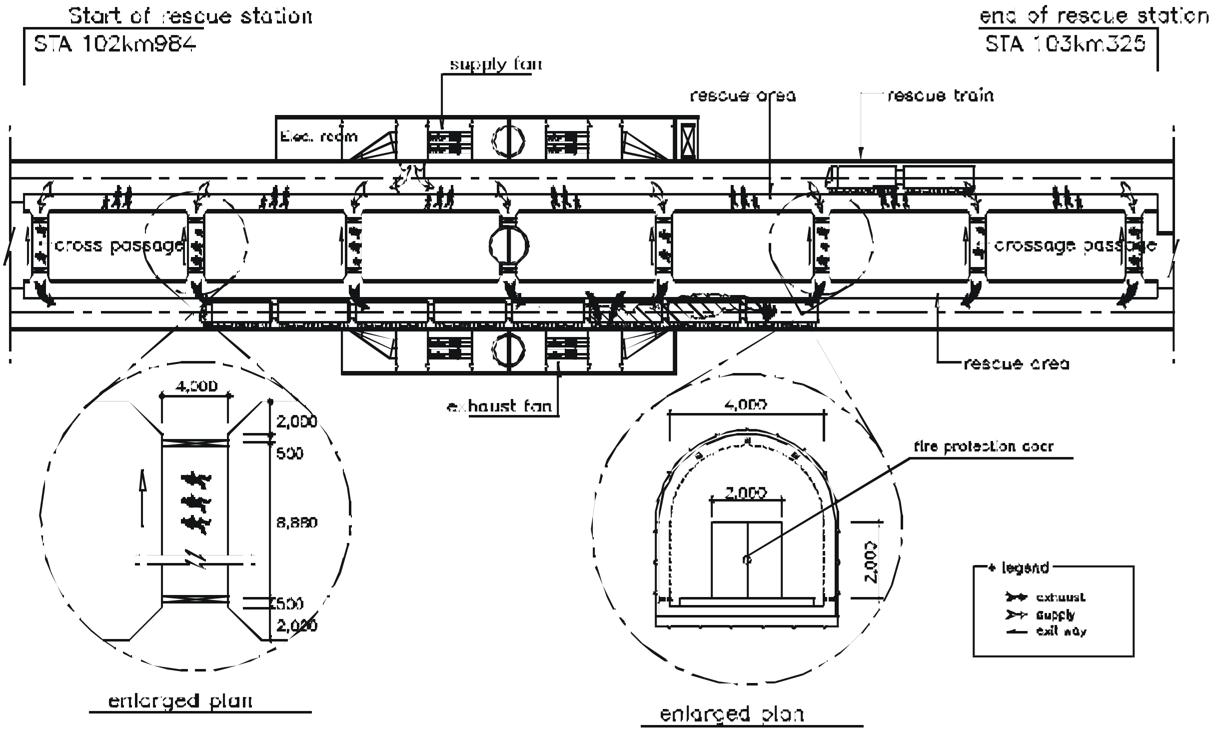

Fig. 5: Rescue station in the Young Dong Rail Tunnel

Within both tunnels in the rescue station, platforms of 3 m width was designed. The two platforms are connected by eight cross passages spaced 47 m apart. These cross-passages allow passengers and staff to escape quickly from one tunnel tube to the other. This arrangement is inherently symmetrical and is therefore suitable for the possible next phase of the Young Dong Rail Tunnel construction with two separate single-track tunnels.

4.3 Requirements for Emergency Ventilation System

The primary requirements for the emergency ventilation system derive from smoke control considerations, i.e. that the smoke can always be driven in the required direction without any significant backlayering. They can be expressed as follows:

At an arbitrary position in the running tunnel:

- A minimum of 2 m/s flow velocity should be generated in either directions at any point in the running tunnel.

In the rescue station and rescue areas

- A minimum flow velocity of 2 m/s should be generated through all the open doors in the cross-passages between the incident tunnel and the crossing loop tunnel (or escape zones at the rescue areas).

- Fresh air should be entrained at a rate of at least 2 m/s at both ends of the platform tunnel, such that smoke cannot escape from the emergency station. This is to ensure that the crossing-loop tunnel and the running tunnels remain free from smoke.

Other important requirements relate to

- **Robustness** of the smoke control strategy: the same strategy should cover the vast majority of expected cases. This is required because the information relating to a real fire situation may be late, inaccurate or not available at all.
- **Flexibility** of the ventilation system: the same ventilation equipment should be capable of covering all fire scenarios.
- **Simplicity** of the smoke control strategy: in a stress-filled fire scenario, complexity may lead to the wrong decisions being made, which can make matters worse, not better for passengers and staff.

The above requirements were to be satisfied despite the presence of strong thermal buoyancy effects in the tunnel, due to a difference of 370 m in the portal elevations.

4.4 Calculations for Emergency Ventilation

In order to develop a concept for the emergency ventilation system that would satisfy the requirements outlined above, one-dimensional aerodynamic simulations were carried out for the entire tunnel network using ThermoTun, developed by Prof. Alan Vardy of the University of Dundee, UK.

Fig. 6 shows an example of the calculated flow velocities in the case of a fire emergency in the rescue station, which satisfy the design requirements set out above.

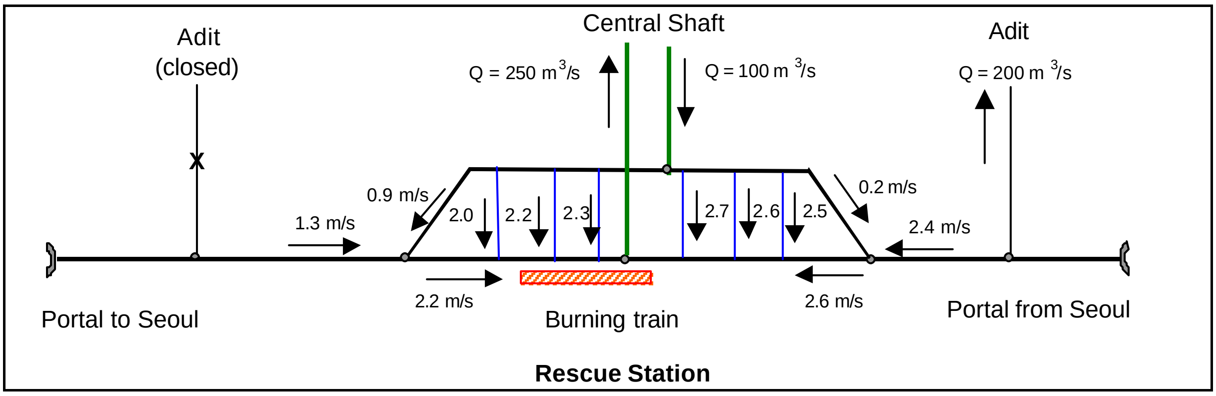

Fig. 6: Example of emergency ventilation strategy in rescue station (not to scale)

In order to confirm the one-dimensional aerodynamic calculations of emergency conditions, three-dimensional Computational Fluid Dynamics (CFD) calculations were also carried out both in the running tunnel and within the rescue station, using the commercially available Fluent code. Fig. 7 shows the results of one of the CFD computations in the rescue station, which indicates that the smoke is contained within the affected platform tunnel, hence satisfying the design requirement.

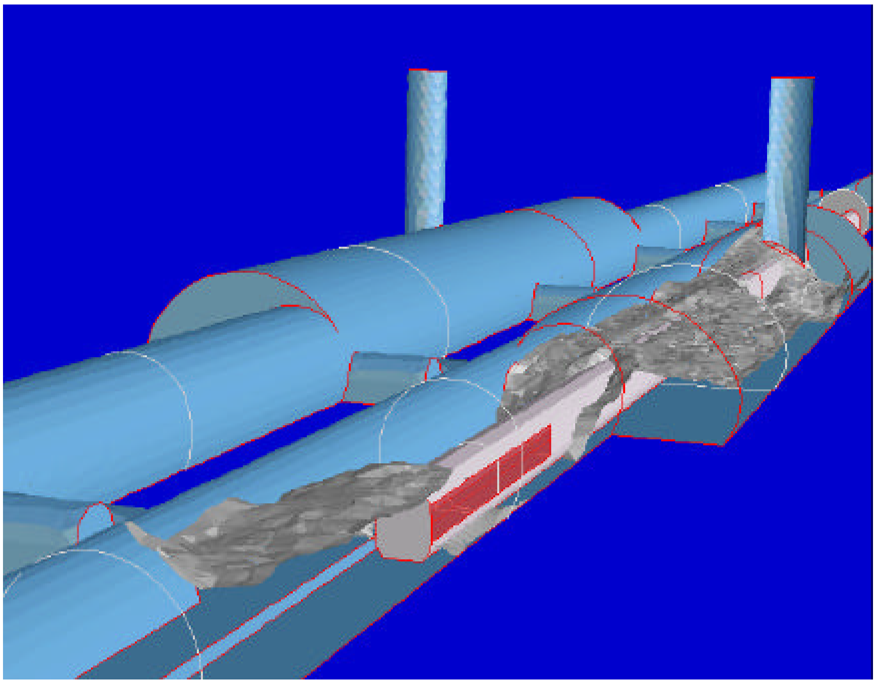

Fig. 7: CFD computation of smoke propagation in the rescue station

5 NORMAL VENTILATION SYSTEM

The primary purpose of the normal ventilation system is to purge the diesel emissions from the tunnel, such that a complete air exchange is effected within a reasonable time frame. This is required in order to avoid potentially lethal emission concentrations due to repeated diesel train journeys through the tunnel.

The primary emissions produced by diesel locomotives are:

- Nitrogen oxides (NO_x), comprising primarily NO and some proportion of NO_2. These have been identified by Bendelius (1999) as being the most significant contaminants in diesel-operated rail tunnels.
- Carbon monoxide (CO).
- Smoke particles, as measured by an extinction coefficient K [m^{-1}].

The emission concentrations in the tunnel were derived directly from the one-dimensional aerodynamic calculations, with the emissions from the diesel locomotives and generation cars modelled in the calculations via pollution sources at train noses and ends respectively.

All passenger trains passing through the Young Dong Rail Tunnel are to be air-conditioned, with an air exchange rate of 5.25 times per hour. Assuming that the carriages enter the tunnel with a negligible internal concentration of NO_x, the build-up of toxic gases will occur only gradually within the trains. This build-up was calculated using a bulk mixing model simulating the train carriage environment. Fig. 8 shows a typical result of the simulations.

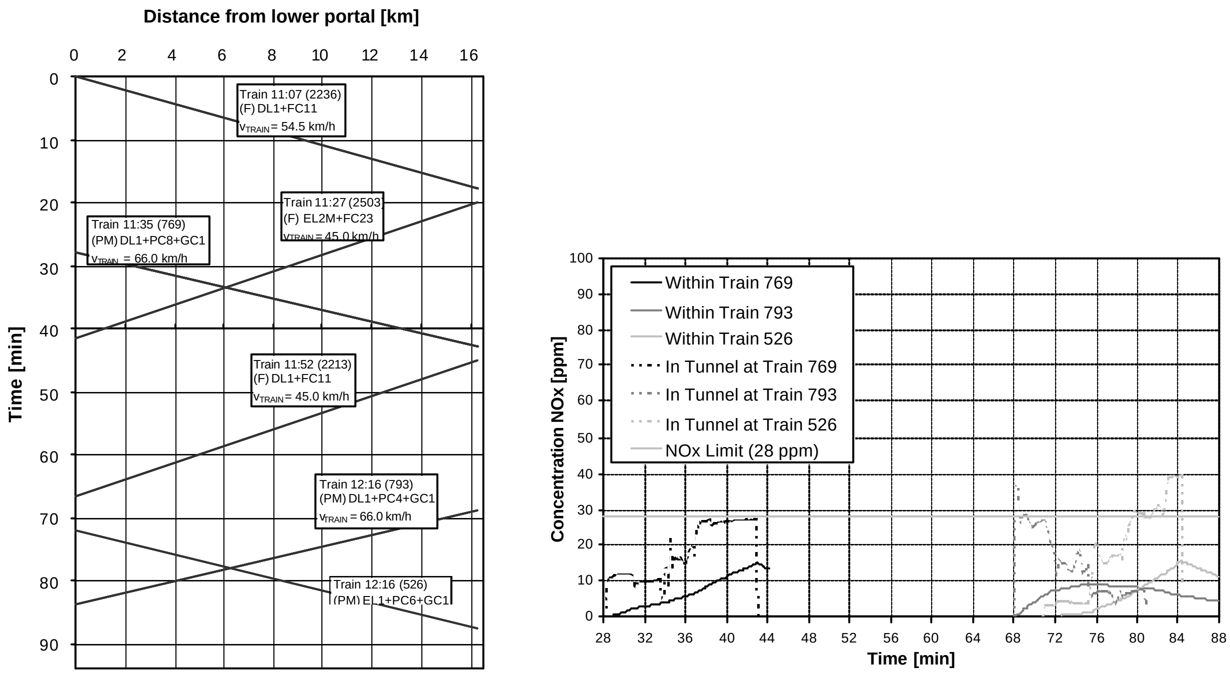

Fig. 8: Train operation schedule and calculated NO_x concentrations within the tunnel and carriages (example).

The concentrations of diesel emissions in the tunnel will be crucially dependent on the train scheduling, particularly of diesel locomotives travelling uphill, since such locomotives are particularly polluting. As a first step, we checked the worst case scenarios for emissions within passenger trains on the basis of the existing train schedule for the overground Young Dong line. Subsequently, we developed a detailed timetable which both satisfies the requirements of Korea National Railroad (integration with the rest of the rail network) and in minimising the concentrations of diesel emissions in the tunnel. The following recommendations were given to achieve the latter goal:

1. While a diesel train is moving uphill in the tunnel, no other trains (diesel or electric) should be allowed to travel uphill at the same time. This is in order that the relative flow velocity between the diesel train and the tunnel air should be kept high, and hence the concentrations of pollutants kept low.
2. No more than one diesel train (moving uphill or downhill) should be present in the tunnel at any time, in order to limit the emission concentrations.
3. It is desirable that an electric train should travel downhill as a diesel train moves uphill, in order to increase the relative velocity over the diesel train and hence reduce the emission concentrations.

In order to ensure that no diesel emissions can accumulate in the tunnel, air exchangers were designed at the base points of the two adits and at the central shaft. Fig. 9 shows the calculated purging time of the various tunnel sections for the ‘worst-case’ scenario of zero thermal buoyancy.

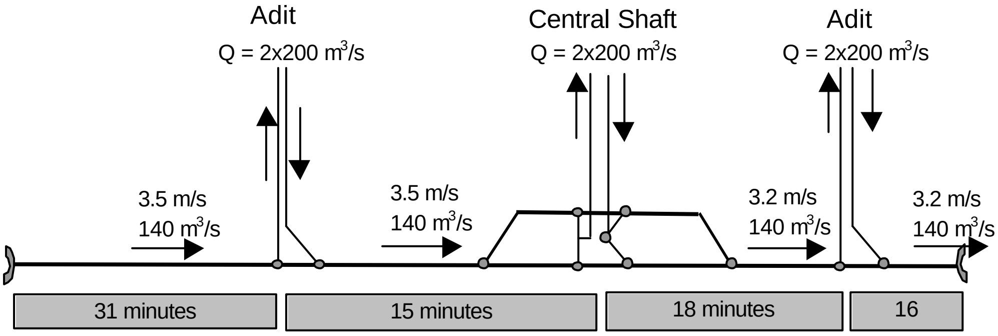

Fig. 9: Purging time for the various tunnel sections

6 CONCLUSIONS

The design of the ventilation and risk control elements for the Young Dong Rail Tunnel were key elements of the successful Daewoo tender submission to build the tunnel. This paper has reviewed the engineering design procedure for minimising the risk to tunnel passengers, and to develop robust ventilation strategies for normal and emergency operation.

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