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VENTILATION STRATEGY AND DESIGN OF INTERTWINING TUNNELRAMPS, OOSTERWEEL LINK ANTWERP

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ABSTRACT

The Antwerp Oosterweel Link will consist of 5 intertwined TERN-tunnels (Trans-European Road Network tunnels), which will be, together with underpasses and depressed highways, all operated, controlled and secured by an integral safety concept.

The most interesting tunnel complex of the Oosterweel Link, in terms of tunnel safety and tunnel ventilation, are the 2x2 stacked Kanaalzone tunnels. Near the Oosterweel junction intertwining ramps of the Kanaalzone tunnels create a specific geometry regarding tunnel safety and smoke control.

The paper presents analyses of the preliminary design of the ventilation system of the Kanaalzone tunnels, comprising 74 jet-fans, and the accompanying ventilation strategy.

The following steps in analyzing the smoke control can be determined:

- basic ventilation design, based on probabilistic analysis;
- quasi one-dimensional pressure balance relations;
- cold (smoke-free) CFD-simulations to analyze the system behavior in detail;
- hot-run CFD-simulations to analyze the smoke behavior and to optimize the ventilation strategy.

Relevant preliminary results are:

- Full jet-power on all fans is not always the best solution for smoke control in intertwined tunnel tubes.
- Air balances between the tubes are important for effective smoke control in interconnected ramps and are affected by many parameters.
- Interconnected tunnel tubes require a ventilation strategy on cluster level instead of tube level.

Keywords: Tunnel ventilation design, intertwined tunnels, Oosterweel Link.

1. INTRODUCTION

In order to improve the traffic flow around the city of Antwerp, the existing ring road R1 will be closed by the Oosterweel Link. The Oosterweel Link consists of 5 complexly intertwined TERN tunnels, a number of underpasses and several kilometres of depressed highways.

1.1. Oosterweel Link Antwerp

The existing ring road of Antwerp is not a full circle: it lacks a direct connection between the west and the north side of the city, including a second crossing of the Schelde river (figure 1-1). With increasing expected traffic densities this leads to more and more problems regarding traffic management, incident handling, noise and pollution.

By closing the ring road with the Oosterweel Link the traffic flow will improve, the possibilities for integral traffic management will grow and the port of Antwerp will become better accessible.

The Oosterweel Link consists of 5 tunnels: the Schelde tunnel (crossing the Schelde river), the Kanaalzone tunnels (crossing the port), the OKA tunnel (crossing the Albert channel), the Luchtbal tunnel and the Schijnpoort tunnel (both under passing urban areas). Further the link consists of the Oosterweel junction, a depressed infrastructural node that connects the Schelde tunnel, the Kanaalzone tunnels and the local road network north of Antwerp. The link is completed by several depressed highways and underpasses, connecting the tunnels and facilitating the inflow and outflow of local traffic to the link.

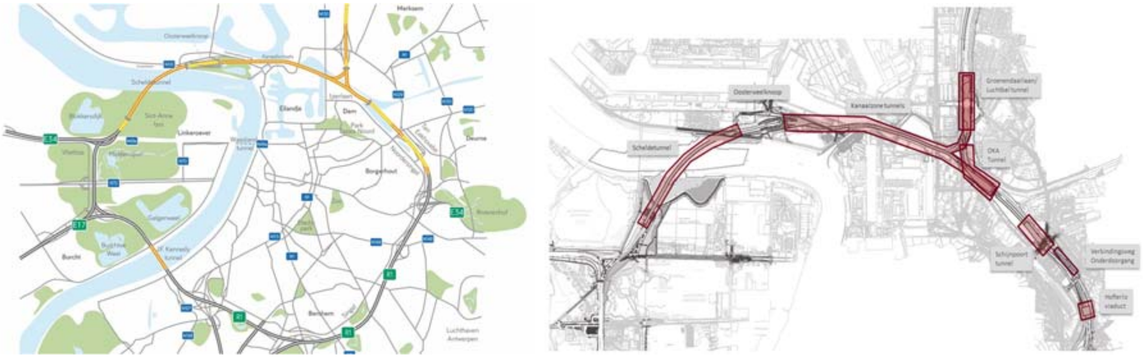


Figure 1-1 A) Oosterweel Link as closing element of the existing ring road; B) Components of the Oosterweel Link.

1.2. Tunnel safety and road safety

The safety concept of the Oosterweel Link is based on two pillars: tunnel safety and road safety. Tunnel safety starts by complying to the EU directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network (TERN) and its translation in the Belgian legislation. Next to this a quantitative risk analysis (QRA) has to be performed for every tunnel tube, in which a variety of parameters regarding the geometry, the traffic and the safety measures have to be taken into account. The calculated group risk has to be checked against the legal standard, that limits the chance of casualties at $0.1/N^2$ per kilometre of tunnel tube per year (with N the number of casualties per incident). In the final design iteration all tunnels of the Oosterweel Link comply to the legislation and the legal standard for the group risk, by applying an elaborate set of safety measures.

The second pillar of the safety concept of the Oosterweel Link is road safety. Road safety starts with a safe road design that complies to the so called “10-seconds rule” in the EU directive 2004/54/EC. This rule puts restrictions on the location of convergence and divergence points in relation to the location of the tunnel portals. Therefore the road design was subjected to a human factor analysis, that checked whether the total road system including all marks and signs is clear to the drivers and can be used safely. Finally an analysis of the dynamic traffic management in relation to tunnel safety was performed in order to guarantee that traffic flows can be guided through the tunnels safely.

1.3. Kanaalzone tunnels and Oosterweel junction

The most interesting tunnel complex of the Oosterweel Link, in terms of tunnel safety and especially tunnel ventilation, are the Kanaalzone tunnels. These are 2x2 stacked tunnels with connections to the Oosterweel junction, the Luchtbal tunnel and the OKA tunnel. Near the Oosterweel junction, multiple intertwining ramps of the Kanaalzone tunnels create a complex geometry regarding tunnel safety in general and smoke control in particular (figure 1-2 and figure 3-3).

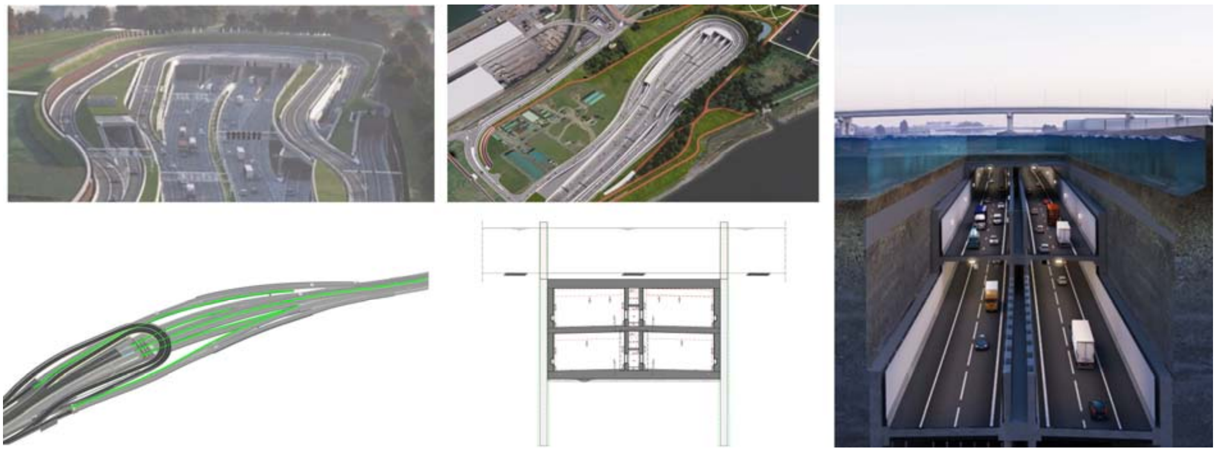


Figure 1-2 Top left: Tunnel portals of the Kanaalzone tunnels (tubes and ramps) at the Oosterweel junction; Top center: Top view of the Oosterweel junction; Bottom left: Schematic overview of Kanaalzone tubes, ramps and escape galleries; Bottom center: Cross section of stacked Kanaalzone tunnels; Right: Impression of stacked Kanaalzone tunnels.

The lower tubes of the Kanaalzone tunnels have a length of approximately 3.5 kilometers and connect the Oosterweel junction in the west to the existing ring road R1 and the new Luchtbal tunnel in the north. In the same way the upper tubes have a length of approx. 3.2 km and connect the Oosterweel junction to the R1 and the new OKA tunnel in the east. The upper and lower tubes are stacked when crossing the docklands and diverge near the Albert channel.

The east side of the Oosterweel junction is not only the entrance and exit of the upper and lower tubes of the Kanaalzone tunnels, but also the connection of the local traffic to the highway system. Therefore two additional tunnels portals are situated at the junction, which are the entrance and exit of the ramps. Although those ramps only have one tunnel portal, they split or merge just behind the portal in order to connect the traffic to both the upper and the lower main tubes. This results in a system of interconnected tubes and ramps that should be studied in detail related to smoke control conditions.

All tunnels of the Oosterweel Link will be equipped with a longitudinal ventilation system, since such a system can handle big fire sizes and can be fitted into the complex geometry of stacked tunnels.

Since Antwerp has one of the biggest ports of Europe, the amount of heavy goods vehicles at the ring road is large, just as the transport of highly flammable materials and fuels. Accidents with these trucks can result in scenarios with fire sizes up to 200MW. A transverse ventilation systems would not be able to control the smoke and heat produced by such fires. Besides, such a ventilation system would be difficult to fit into the complex geometry of the Oosterweel Link. Therefore longitudinal ventilation systems are applied.

2. METHOD

When designing the ventilation concept and corresponding ventilation strategy, a number of consecutive analyses with increasing levels of detail are necessary. In this chapter, a brief overview of the different steps is given, while the next chapter elaborates on every individual step and its results.

The probabilistic analysis can only be applied in isolated tunnel tubes however does not account for junctions, hence for design purposes the Kanaalzone tunnels are considered in two parts: the main tube, where probabilistic calculations are applicable, and the intertwining ramps near the Oosterweel junction where separate analyses are required.

The first step in designing the ventilation in the ramps is an analytical calculation, based on the pressure balance in the connected tubes. Hereafter, a detailed analyse is done by means of CFD calculations, first without and then with smoke and fire.

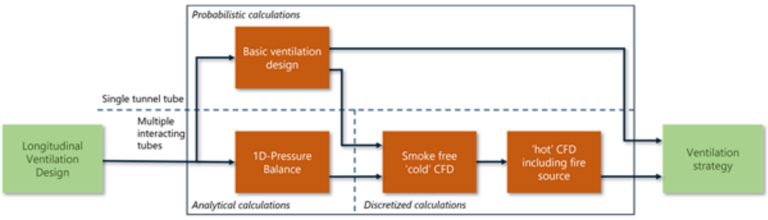


Figure 2-1 Calculation, simulation and design proces for the longitudinal ventilation of the Kanaalzone tunnels.

3. ELABORATION AND RESULTS

3.1. Probabilistic analysis

The basic design of the tunnel ventilation system is based on failure rate analyses. Probabilistic calculations determine the failure rate where the critical ventilation velocity is not achieved [1]. This is the minimum air velocity (fire size dependent) that must be achieved by the tunnel ventilation system in order to prevent backlayering of smoke.

The probabilistic calculations account for:

- External conditions: Wind conditions and terrain roughness.
- Tunnel design: Tunnel orientation related to wind, entrance and exit configuration, vertical tunnel alignment (chimney effect), tunnel roughness.
- Traffic: Traffic composition (e.g. number of trucks) and congestion.
- Fire conditions: Fire size and location. The location affects the length of the congested traffic and the chimney effect.
- Ventilation design: Ventilation power, number and locations of fans, fan efficiencies and heat resistance of fans.

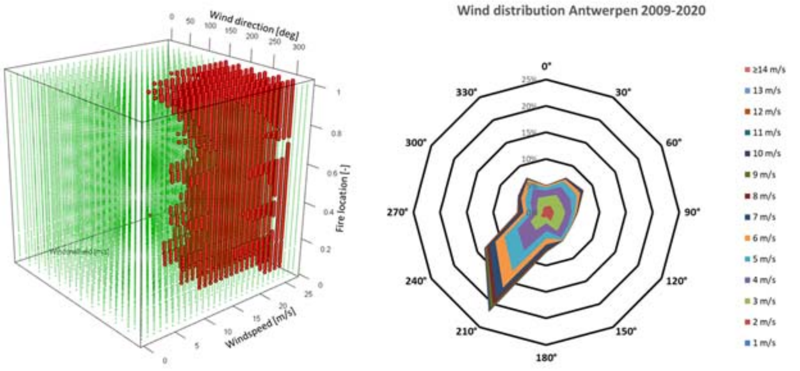


Figure 3-1 A) pointcloud of probabilistic calculations. Green indicates a pass, i.e. the ventilation speed is larger than the critical velocity, a red point indicates a failure; B) The winddistribution of Antwerp: an 11 year average of hourly measurements.

The probabilistic variables in the calculations are the non-dimensional fire location [-], the wind direction [deg] and the windspeed [m/s]. All unique combinations of the variables result in over 30.000 calculations, where a resultant ventilation speed can be compared with the critical ventilation speed.

In the figure above the results are shown for a 200MW fire in the TKZO main tunnel tube. Every green point indicates a situation where the critical velocity is reached, every red data point indicates a failure, i.e. the critical ventilation speed is not achieved. This success- and failure data is combined with the chances of occurring of a certain wind condition, resulting in the required acceptable level of failure rate, per fire size [2].

3.2. Quasi one-dimensional pressure balance relations

The airflow from the main tunnel tube will split, according to a certain distribution, at the location of the exit ramp. At the exit of both branches of the tunnel the outside pressure is assumed to be equal to atmospheric pressure, hence the pressure drop over the tunnel sections 1 and 2 (figure 2-2) must be the same.

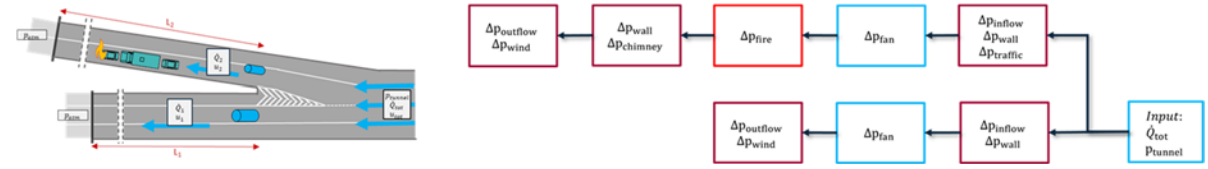


Figure 3-2 A) Simplified situational sketch of an incident at an exit ramp; B) Schematic overview of all contributions to the pressure drop in the incident tube (top row) and non-incident tube (bottom row).

Since some of the resistances faced by the air flow are velocity dependent, there is a volume flow distribution where the following relations hold:

$$\begin{aligned} \dot{Q}_{tot} &= \dot{Q}_1 + \dot{Q}_2 \\ \Delta p_1 = \Delta p_2 &= p_{tunnel} - p_{atm} \end{aligned}$$

In this the pressure drops in branches 1 and 2 are considered to be a summation of all the individual contributions according to the scheme above.

In this scheme, the fans provide a ‘negative pressure drop’ (Δp_{fan}) and can be determined such that the requested air flow distribution at the junction is reached. This method can be extended to accompany multiple junctions and has resulted in a first ventilation design for the ramps. Merging the designs of the main tubes and the ramps results in the ventilation set-up as presented below.

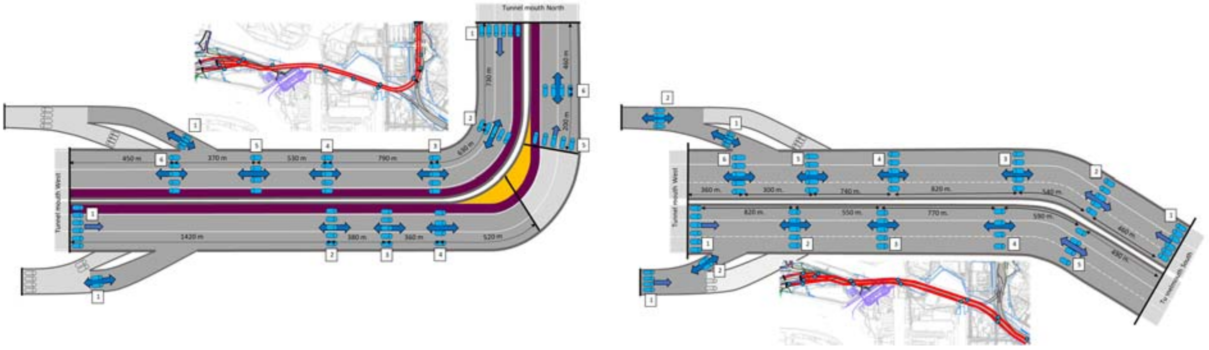


Figure 3-3 Schematic overview of the ventilation design for the Kanaalzonetunnel; A) Lower Kanaalzone tunnel. B) Upper Kanaalzone tunnel.

3.3. CFD model

In order to simulate the performance of the tunnel ventilation design in detail a CFD model of the entire Oosterweel junction has been created. The figure below shows an exploded view of the model. The full length of the exit ramps is modelled and over 600 meters of both main tubes. The total length of the geometry is roughly 800 meters. The mesh contains 5.5M cells of 0,5m x 0,5m x 0,5m, in line with [2]. The boundary conditions represent a wind pressure on all tunnel exits and a fixed inflow from the main tubes in line with earlier results (section 3.1).

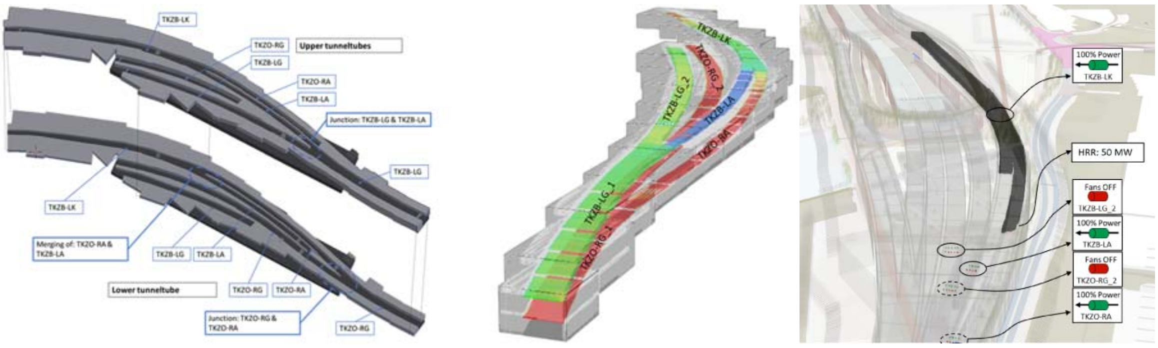


Figure 3-4 A) Exploded view of the geometry of the CFD-model; B) Impression of the airflows; C) Impression of smoke.

3.4. Smoke-free CFD-calculations

The air flows in the entire system of connected traffic tubes have been mapped systematically. The focus is on the influence of the different fan clusters (system input) on the resulting air flows in the system of tunnel tubes (system output). This determines the (degree of) controllability of the system.

For presentation purposes the resulting airflows in the tunnels are translated to schematic diagrams, see figure 3-5.

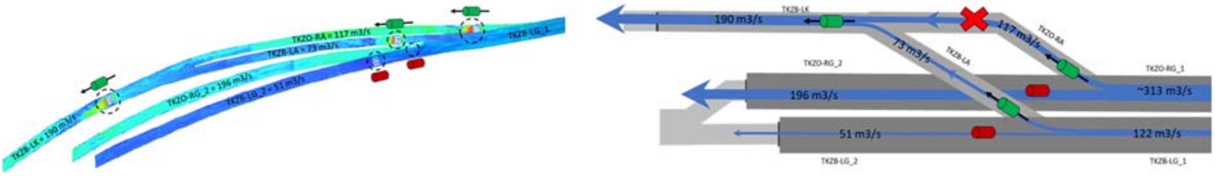


Figure 3-5 A) resulting airflows in CFD simulation; B) Schematic representation of the CFD results.

Over 10 different scenario's, with mixed conditions regarding inflow from the main tubes, ventilation settings in the junctions and traffic conditions yield the following main findings based on 'cold' smoke-free simulations:

- The volume flows in the two main tubes have a dominant influence on the system behaviour of air flows in the Oosterweel junction and are therefore also dominant in whether or not the required air flows and speeds in the various ramps are met. A correct balance is a strict requirement for the airflow in the incident ramp.
- Switching tunnel clusters on or off in a non-incident ramp can have a major (positive or negative) influence on the airflow speed in the incident ramp.
- In the event of an incident in one of the ramps, an excessive volume flow in the non-incident ramp can block the airflow in the incident ramp.
- The results of the 'cold runs' confirm the results of the previously made pressure balance analyses, where this concerns the distribution of an airflow at a split.
- Based on the airflow and system analysis (the 'cold runs'), only the basic information is acquired. This analysis only determines the system behaviour and the mutual influence of the tunnel tubes. To determine whether there is sufficient smoke control, additional CFD analyses are required, in which a fire source is also modelled ('Hot Runs').

3.5. CFD-calculations including fire and smoke simulation

The actual possibilities to control smoke are calculated using a 'hot run' CFD analysis. The 'cold run' analyses showed that the volume flows in the two main tubes (TKZO-RG & TKZB-LG) have a dominant influence on the system behaviour of air flows in the Oosterweel junction and were therefore also considered dominant in whether or not the required airflows will be met in the various ramps. The translation of the system behaviour of the air flows in the various ducts into a usable ventilation strategy is done in this step of the process. Several ventilation strategies are calculated for one fire incident scenario. The situation in which the exit TKZO-RA is the incident tube has been analysed. This situation is considered to be the characteristic case, as the 'cold run' analyses showed that realizing sufficiently large air flows in the exits could be critical. A 50 MW fire is simulated. Different ventilation strategies have been simulated. The inflow conditions from the main tunnel tubes are varied, since the cold simulation showed that these have a dominant influence on the system behaviour.

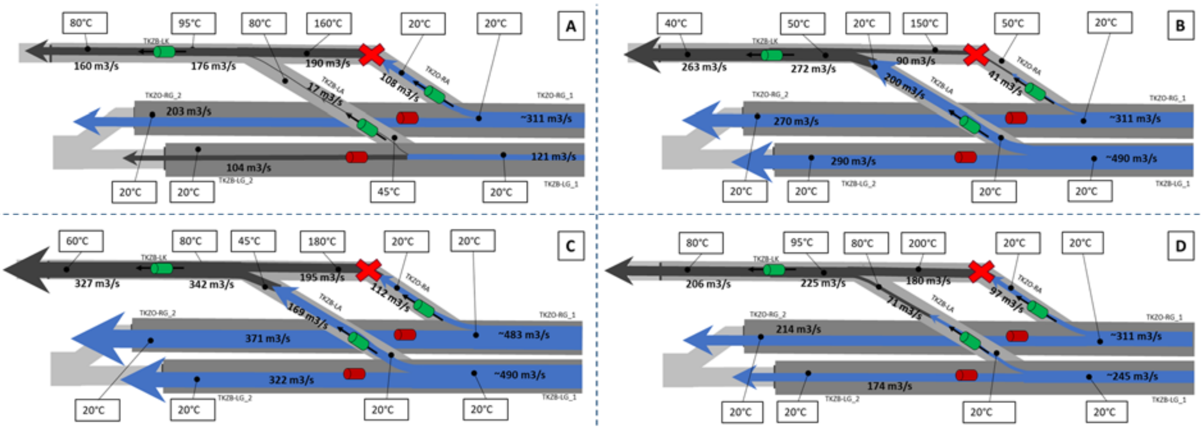


Figure 3-6 Ventilation strategies: A) Standard; B) Balanced, with congested traffic in main tube (TKZO-RG); C) Balanced, without traffic in main tube (TKZO-RG); D) Balanced and economic, without using full power.

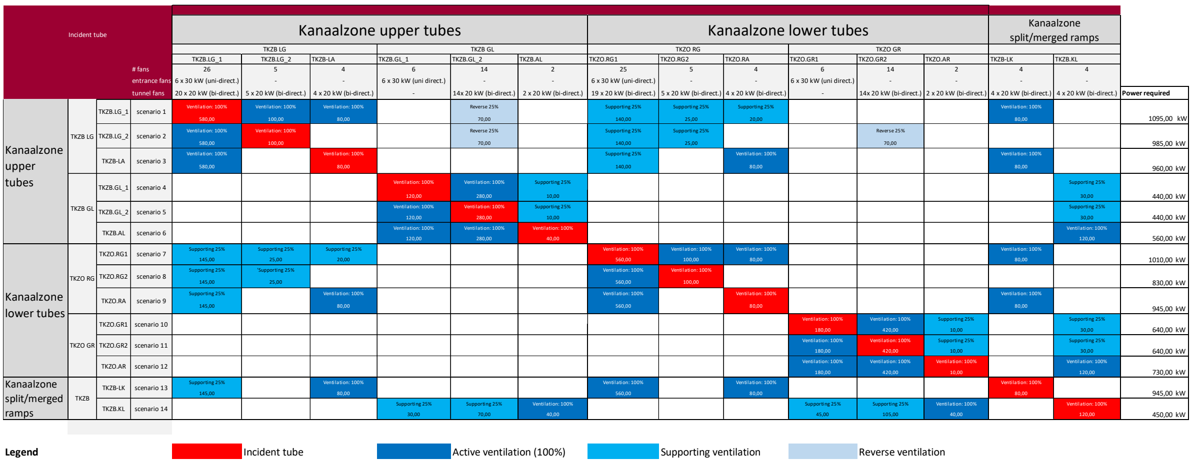
The main findings of hot-run CFD calculation of a 50 MW fire scenario in the exit lane TKZO-RA are:

- With standard ventilation strategy (Fig. 3-6 A):
  - Complete smoke control in incident ramp;
  - Smoke backlayering in adjacent ramp TKZB-LA;
  - Escalation of incident to main tube TKZB-LG_2.
- With an adapted 'balanced' ventilation strategy (Fig. 3-6 B & C):
  - No smoke in KZ main tubes;
  - No backlayering in adjacent ramp (TKZB-LA);
  - Backlayering in incident ramp for lower flow rate in TKZO-RG (Fig. 3-6 B);
  - No backlayering in the incident ramp and full smoke control with a balanced inflow in the main tubes TKZO-RG and TKZB-LG (Fig. 3-6 C).
- With a balanced energy-efficient ventilation strategy (Fig. 3-6 D):
  - No smoke in KZ main tubes;
  - Limited backlayering in adjacent ramp (TKZB-LA);
  - No backlayering in the incident ramp and full smoke control with a balanced inflow in the main tubes TKZO-RG and TKZB-LG.

4. PRACTICAL IMPLEMENTATION OF VENTILATION STRATEGY

4.1. Ventilation strategy

The calculations discussed in section 3.5 all relate to the same incident location. In order to come to a practical ventilation strategy for the Kanaalzone tunnels, the method was applied on fire locations in the other tubes and ramps. This results in the so-called "Tunnel reflex matrix": an elaborate matrix in which the fire locations are listed in the columns and the ventilation clusters in the rows (figure 4-1). The cells then indicate how the fans of each specific cluster have to be activated in the specific fire scenario. Based on this matrix the total power available in the electrical system has been analysed.



Incident tube				Kanaalzone upper tubes						Kanaalzone lower tubes						Kanaalzone split/merged ramps		
				TKZB LG			TKZB GL			TKZO RG			TKZO GR					
				TKZB.LG_1	TKZB.LG_2	TKZB-LA	TKZB.GL_1	TKZB.GL_2	TKZB.AL	TKZO.RG1	TKZO.RG2	TKZO.RA	TKZO.GR1	TKZO.GR2	TKZO.AR	TKZB-LK	TKZB.KL	
			# fans	26	5	4	6	14	2	25	5	4	6	14	2	4	4	
			entrance fans	6 x 30 kW (uni-direct.)	-	-	6 x 30 kW (uni direct.)	-	-	6 x 30 kW (uni-direct.)	-	-	6 x 30 kW (uni direct.)	-	-	-	-	
			tunnel fans	20 x 20 kW (bi-direct.)	5 x 20 kW (bi-direct.)	4 x 20 kW (bi-direct.)	-	14x 20 kW (bi-direct.)	2 x 20 kW (bi-direct.)	19 x 20 kW (bi-direct.)	5 x 20 kW (bi-direct.)	4 x 20 kW (bi-direct.)	-	14x 20 kW (bi-direct.)	2 x 20 kW (bi-direct.)	4 x 20 kW (bi-direct.)	4 x 20 kW (bi-direct.)	**Power required**
Kanaalzone upper tubes	TKZB LG	TKZB.LG_1	scenario 1	Ventilation: 100% 580,00	Ventilation: 100% 100,00	Ventilation: 100% 80,00		Reverse 25% 70,00		Supporting 25% 140,00	Supporting 25% 25,00	Supporting 25% 20,00				Ventilation: 100% 80,00		1095,00 kW
		TKZB.LG_2	scenario 2	Ventilation: 100% 580,00	Ventilation: 100% 100,00			Reverse 25% 70,00		Supporting 25% 140,00	Supporting 25% 25,00			Reverse 25% 70,00				985,00 kW
		TKZB-LA	scenario 3	Ventilation: 100% 580,00		Ventilation: 100% 80,00				Supporting 25% 140,00		Ventilation: 100% 80,00				Ventilation: 100% 80,00		960,00 kW
	TKZB GL	TKZB.GL_1	scenario 4				Ventilation: 100% 120,00	Ventilation: 100% 280,00	Supporting 25% 10,00								Supporting 25% 30,00	440,00 kW
		TKZB.GL_2	scenario 5				Ventilation: 100% 120,00	Ventilation: 100% 280,00	Supporting 25% 10,00								Supporting 25% 30,00	440,00 kW
		TKZB.AL	scenario 6				Ventilation: 100% 120,00	Ventilation: 100% 280,00	Ventilation: 100% 40,00								Ventilation: 100% 120,00	560,00 kW
Kanaalzone lower tubes	TKZO RG	TKZO.RG1	scenario 7	Supporting 25% 145,00	Supporting 25% 25,00	Supporting 25% 20,00				Ventilation: 100% 560,00	Ventilation: 100% 100,00	Ventilation: 100% 80,00				Ventilation: 100% 80,00		1010,00 kW
		TKZO.RG2	scenario 8	Supporting 25% 145,00	'Supporting 25% 25,00					Ventilation: 100% 560,00	Ventilation: 100% 100,00							830,00 kW
		TKZO.RA	scenario 9	Supporting 25% 145,00		Ventilation: 100% 80,00				Ventilation: 100% 560,00		Ventilation: 100% 80,00				Ventilation: 100% 80,00		945,00 kW
	TKZO GR	TKZO.GR1	scenario 10										Ventilation: 100% 180,00	Ventilation: 100% 420,00	Supporting 25% 10,00		Supporting 25% 30,00	640,00 kW
		TKZO.GR2	scenario 11										Ventilation: 100% 180,00	Ventilation: 100% 420,00	Supporting 25% 10,00		Supporting 25% 30,00	640,00 kW
		TKZO.AR	scenario 12										Ventilation: 100% 180,00	Ventilation: 100% 420,00	Ventilation: 100% 10,00		Ventilation: 100% 120,00	730,00 kW
Kanaalzone split/merged ramps	TKZB	TKZB-LK	scenario 13	Supporting 25% 145,00		Ventilation: 100% 80,00				Ventilation: 100% 560,00		Ventilation: 100% 80,00				Ventilation: 100% 80,00		945,00 kW
		TKZB.KL	scenario 14				Supporting 25% 30,00	Supporting 25% 70,00	Ventilation: 100% 40,00				Supporting 25% 45,00	Supporting 25% 105,00	Ventilation: 100% 40,00		Ventilation: 100% 120,00	450,00 kW

Legend 🟥 Incident tube 🟦 Active ventilation (100%) 🟦 Supporting ventilation ▨ Reverse ventilation

Figure 4-1 Tunnel reflex matrix for the Kanaalzone tunnels.

4.2. Coherence with related management- and technical systems

In the safety concept of the Kanaalzone tunnels, the tunnel ventilation system plays an important role. The concept is based on self evacuation via escape galleries next to the traffic tubes and ramps. It assumes that upstream of a fire location the traffic gets congested and people have to evacuate, while downstream the traffic is able to leave the tunnel. This concept works together with the traffic management system that takes care of the traffic handling downstream of the fire location and the tunnel ventilation that guarantees a smoke-free escape route upstream towards the escape gallery (in which over pressure is applied to prevent smoke inflow). Integrating the tunnel ventilation system with the other safety systems results in a robust safety concept for the complex Kanaalzone tunnels.

5. CONCLUSIONS

The main findings of the tunnel ventilation design process for the complex Kanaalzone tunnels can be summarized as follows:

- Full jet-power on all fans is not always the best solution for smoke control in intertwined tunnel tubes.
- Air balances between the tubes are a dominant factor for effective smoke control in interconnected ramps and are affected by a wide range of sensitive parameters.
- Interconnected tunnel tubes require a fan control strategy on cluster level instead of on tube level.

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