6. VENTILATION

6.1. SCOPE OF THIS SECTION

This section focuses on ventilation aspects related to urban tunnels and tunnel networks. Urban underground traffic infrastructure differs in many cases strongly from standard road tunnels as they might have to serve multiple purposes and might be multi modal.

Characteristics that might influence the ventilation are:

- various underground interchanges and ramps to surface roads;
- connections to underground parking lots;
- connections to service tunnels;
- use by various transport systems;
- high traffic volume and density;
- high congestion probability;
- environmental aspects concerning air and noise pollution at portal area;
- low clearance tunnels.

The following will focus on the synopsis of the monograph sheets.

6.2. MAIN ISSUES RELATED TO VENTILATION FOR COMPLEX UNDERGROUND ROAD STRUCTURES

6.2.1. Issues related to ventilation system selection and design

In comparison with "*classical*" tunnels, specific design criteria that might have a significant impact on the design of the ventilation systems have to be considered in the case of urban and complex network tunnels. The design of complex tunnel ventilation systems strongly depends on the following factors:

- Changes in the tunnel cross-section: the performances of ventilation systems are generally directly linked to the cross-section of the tunnel. Consequently, particular care should be taken when changes in the cross-section occur along the tunnel. This is for example the case in tunnels including access and exit ramps, where the number of lanes may vary along the tunnel. Many tunnels analysed through the interviews contain access or exits leading to variations of the tunnel cross-section;
- Interchanges with other tunnels: the control of the air flows (distribution of the fresh air in normal operation, or smoke control in case of emergency) in tunnels including interchanges and connections with other underground infrastructure can be a key challenge. Consequently, the presence of interchanges needs to be carefully considered as a major design parameter for tunnel ventilation systems;
- Low clearance tunnels: due to the restricted space in this kind of tunnels, it is generally difficult to install ventilation equipment such as jet fans in the cross-section. In addition the low clearance minimises the benefit of smoke stratification with transverse emergency ventilation strategies. However, as in most cases traffic is restricted to light vehicles and small lorries, the design fire should be smaller than normal;
- Available space: the feasibility of installing ventilation plants or shaft exits in dense urban areas

may be an issue. Consequently, the design of the ventilation systems must be done consistently with the available space at portals or at the surface, as well as the neighbouring environmental and safety conditions. Specific ventilation solutions can be necessary due to the limited space;

- Design fire: the design fire size is dependent on the nature of the traffic. However, due to the traffic characteristics, incidents with multiple vehicles may occur more often compared to rural tunnels. Hence the fire load for single vehicles might not be that high, but the risk of having multiple vehicles on fire exists. This might result in lower heat release rates but much longer burning times. Due to higher traffic density and congestion levels, the frequency of incidents within queues might be higher. Such aspects have to be considered in the risk assessment which influences the choice of the ventilation system;
- trafic is another key parameter that can be highlighted as a significant design parameter for complex urban tunnels. The requirements for ventilation in normal operation can be increased (see also discussion related to the environmental issues) but also the safety issues leading to particular care for the design and operation of emergency ventilation systems;
- Environmental aspects clearly influence the selection of the ventilation system which is most appropriate for achieving the required goals as well as the design of the ventilation itself. In case of longitudinal ventilation systems additional equipment for portal air extraction may be needed, i.e. in addition to the longitudinal ventilation system a massive point extraction system for avoiding or reducing portal emissions may be required. In case of ventilation systems with massive smoke extraction, the change in design required due to environmental issues might not be that considerable;
- In case of having tunnel air cleaning systems it is again a question of the main ventilation system for normal operation. If this system is already a transverse ventilation system with massive point extraction, then the influence on ventilation design is given only by the additional pressure loss (head loss) resulting from the filtration system. If the main system a longitudinal ventilation system a significant change to a system with portal air extraction (see paragraph above) is required.

6.2.2. Ventilation during normal operation

Urban tunnels are characterised by a high traffic volume, a high share of light duty vehicles (passenger cars as well as commercially used light vehicles) and a high congestion level. These facts influence the operation scheme of the tunnel, and especially the operation of the ventilation system in normal operation.

In a complex tunnel network, one of the main issues regarding ventilation in normal operation is to properly control the fresh air flow inside the tunnel, and make sure that all branches can receive the required amount of air for the dilution of pollutants. Detailed design studies and adequate on-site adjustment of the system are necessary.

Due to the risk of congestion, pollution levels are generally higher than in other tunnels. Effective traffic management could reduce those risks, and consequently the in-tunnel pollution levels and the need of fresh air.

Depending on the length, cross-sectional geometry, traffic volume and pollutant emissions from the vehicles using the tunnel, a longitudinal ventilation strategy to bring fresh air in the tunnel could lead to excessively high air velocities inside the tunnel to maintain acceptable pollution levels near the exit portals. This could also lead to high energy consumption to operate the jet fans. In some cases, the use of a transverse ventilation strategy might be more economic.

6.2.3. Ventilation in emergency operation

In cases of incidents with fire and smoke propagation, complex tunnel systems represent a big challenge for smoke control in order to minimise harmful effects. A clear separation between the various tunnel sections should be achieved in order to avoid smoke movement throughout the whole tunnel network.

As the congestion level is significantly higher in urban tunnels compared to rural ones, the risk of rear-end collisions or collisions between queued vehicles is considerably higher. As such incidents come along normally with the highest number of victims (per incident) and can cause fires, special focus has to be put on ventilation control procedures.

In longitudinally ventilated tunnels, the risk of smoke movement over blocked vehicles downstream the fire is quite high (due to congested traffic). The operation of the ventilation system should therefore be consistent with traffic management measures, and the probability for having recurrent traffic jams. The risk of smoke propagation over blocked vehicles can be minimized with transverse ventilation, but under the condition that the emergency ventilation system is well managed (see bibliography *[6]*).

As the complex aerodynamic behaviour of the tunnel system complicates ventilation control in an incident case, other topics like increased number of escape routes or supporting systems like FFFS have to be taken seriously into account.

In the case of congested traffic, regardless of the chosen strategy, the regulation of the longitudinal air flow velocity is essential in preventing the fast downstream propagation of smoke and its de-stratification.
The control of the ventilation system can be based either on an open-loop or closed-loop methodology. In the investigated tunnels, both types of systems are found. The choice depends on the physical characteristics of the tunnels and their environment (notably the influence of wind), the type of traffic, and the existing structures in the case of refurbishments.

6.3. ANALYSIS OF THE QUESTIONNAIRE

6.3.1. Synthesis of information

The ventilation systems of the "tunnels complexes" of the panel are diverse. Some tunnels have even several ventilation concepts according to tube (one tube different from the other), or to section. These differences may come from numerous reasons as:

- tunnels built with different stages of construction and at different periods of time;
- vertical alignments, traffic volume, or probability of traffic jam differ from one tube to the other.

The diagrams below (*illustrations 25 & 26*) try to present an overview. Diagrams have been established for the 27 "*tunnels complexes*" of the panel. However the total number of solutions is higher according to the number of individual tunnels and the fact that some tunnels have several ventilation systems.
The *illustration 25* shows the diverse ventilation systems that are installed inside the tunnels of the panel, and the number for each of them.

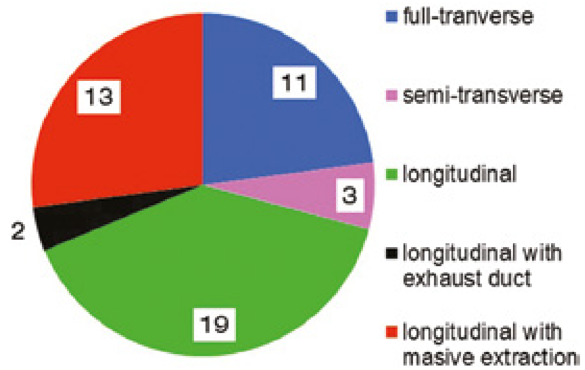

Illustration 25 – nature and number of the ventilation systems installed inside the tunnels of the panel

The *illustration 26* shows the "*tunnels complexes*" investigated and the nature of the ventilation installed inside.

As example Changsha (CHN) has two tubes:

- one tube is equipped with longitudinal ventilation system (green colour) on the diagram;
- another tube is equipped with longitudinal ventilation system and a massive smoke extraction station (red colour).

Another example is Blanka complex (CZ) that includes three tunnels. Each tunnel has two ventilation systems:

- transverse ventilation system for the sections close to the portals (blue colour) on the diagram;
- longitudinal ventilation system for the other sections of the tunnel (green colour).

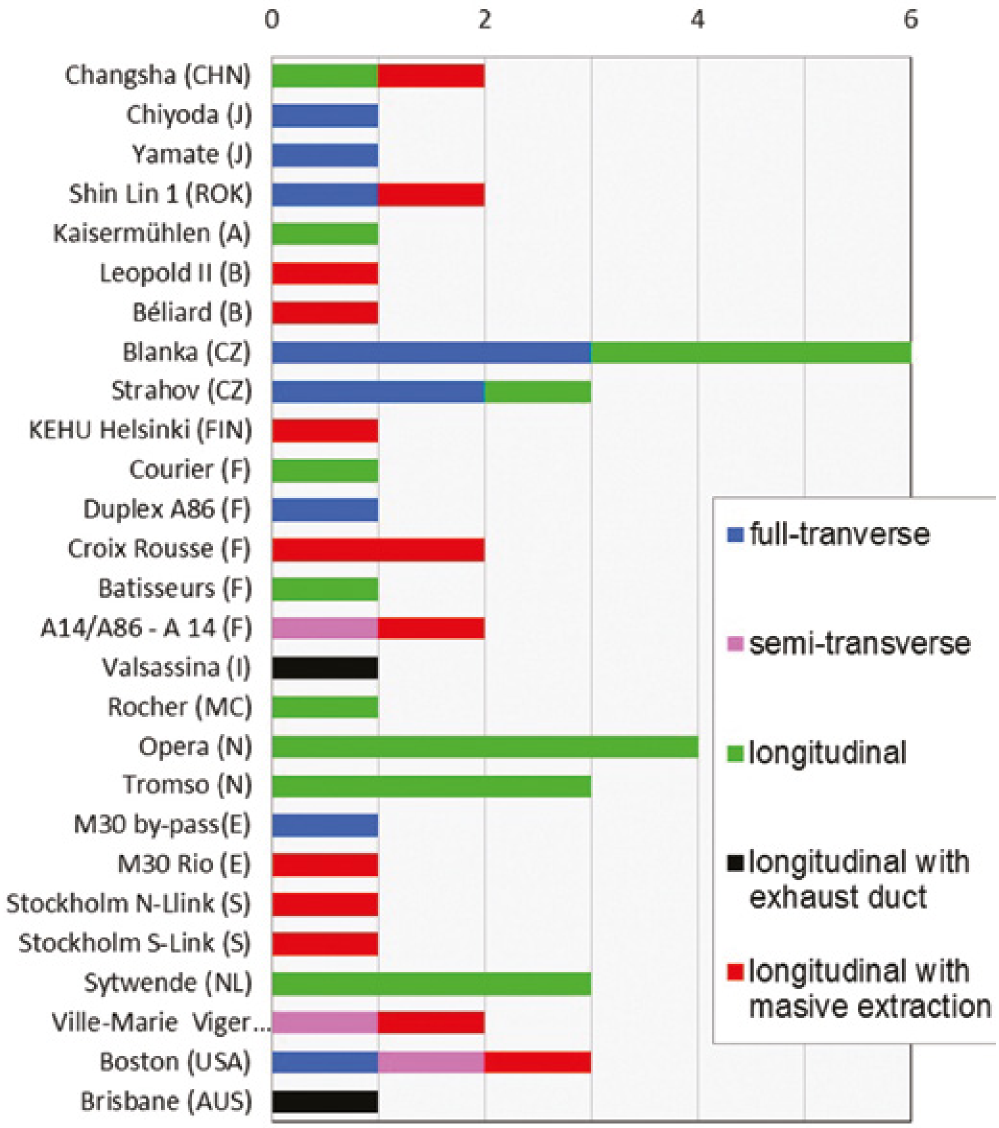

Illustration 26 – ventilation systems installed inside the "tunnels complexes" of the panel

6.3.2. Main information extracted from the investigations

A summary of the ventilation systems installed in each "*tunnel complex*" is presented in the paragraphs below. For more detailed information it is recommended to consult the monograph sheets by using the hyperlinks mentioned for each tunnel.

6.3.2.1. *Yingpan* Road Tunnel in Changsha (CHN)

- geometry and traffic: the tunnel was constructed with drill & blast. There are traffic restrictions for dangerous goods vehicles ;
- ventilation under normal conditions: the south tube has a combined ventilation system: longitudinal ventilation with jet fans associated with a ventilation shaft for air intake or exhaust. The north tube has a fully longitudinal ventilation system with jet fans;

- ventilation under emergency conditions: longitudinal ventilation and massive smoke exhaust by one ventilation station for the south tube. Longitudinal ventilation for the north tube.

6.3.2.2. *Chiyoda* Tunnel in Tokyo (J)

- geometry and traffic: it is a cut and cover tunnel with several ramps and an interchange. The tubes are partially superposed. The traffic is restricted for dangerous goods vehicles. There is no regular traffic congestion or queuing inside the tunnel ;
- ventilation under normal conditions: transverse ventilation system controlled by CO and visibility detectors. Filters are installed in the ventilation plants for air cleaning (particles);
- ventilation under emergency conditions: smoke exhaust by the galleries of the transverse ventilation system.

6.3.2.3. *Yamate* Tunnel in Tokyo (J)

- geometry and traffic: the tunnel was constructed with a TBM. It has various ramps for accesses to the surface, and the traffic is restricted for dangerous goods vehicles ;
- ventilation under normal conditions: transverse ventilation system controlled by CO and visibility detectors. Filters are installed in the ventilation plants for air cleaning (particles and NOx);
- ventilation under emergency conditions: smoke exhaust by the galleries of the transverse ventilation system. 8 sections of ventilation.

6.3.2.4. *Shinlim Bongchun* Tunnel in Seoul (ROK):

- geometry and traffic: the tunnel is under design stage. It will be restricted for HGV and buses ;
- Ventilation under normal conditions: the tunnel as a combined ventilation system: sections with longitudinal ventilation system (including bifurcations), and sections with transverse ventilation system;
- ventilation under emergency conditions: in the sections with transverse ventilation system the dampers are distributed, controlled and opened over a section of 300 m near the fire location.

6.3.2.5. *Kaisermühlen* in Vienna (A)

- geometry and traffic: Kaisermühlen tunnel is a cut and cover tunnel. A large part of the surface area is built upon and has a large economic value (international business area). The traffic volume is very high. The cross section of the tunnel is quite large. There are multiple ramps and parallel traffic collector lanes for accesses to the business area. There are no restrictions for dangerous goods transport ;
- ventilation under normal conditions: longitudinal ventilation system that is rarely used. No restrictions for portal emissions;
- ventilation under emergency conditions: longitudinal ventilation. Ramps are equipped with jet fans. Escape routes are pressurized.

6.3.2.6. *Leopold II* Tunnel in Brussels (B)

- geometry and traffic: Leopold II tunnel is a combination of driven tunnel and cut and cover, and presents various cross sections. The traffic volume is high and the tunnel is frequently congested. There are numerous ramps and traffic is restricted for vehicles > 3.5 tonnes. The transport of dangerous goods is forbidden. Some sections of the tunnel have interfaces with the metro structures ;
- ventilation under normal conditions: longitudinal ventilation system driven by injection / extraction philosophy (fans in ventilation plants) associated with jet fans. No restrictions for portal emissions. The pollution inside the tunnel is controlled by the Environmental Agency of Brussels;
- ventilation under emergency conditions: massive smoke extraction at the ventilation stations. Automatic control of air velocity. Ventilation of the ramps with jet fans.

6.3.2.7. *Belliard Tunnel* in Brussels (B)

- geometry and traffic: Belliard tunnel has several ramps for the connections to the surface. Some ramps gives also accesses to underground car park ;
- ventilation under normal conditions: the ventilation concept is similar to the one of Leopold II. The ventilation management is based on the traffic volume;
- ventilation under emergency conditions: massive smoke extraction at the ventilation stations. Automatic control of air velocity. Ventilation of the ramps with jet fans.

6.3.2.8. *Blanka* and *Mrazovka & Strahov* tunnels in Prague(CZ)

- geometry and traffic: Blanka is a complex of three tunnels. Mrazovka, Strahov tunnels are part of a complex of two tunnels. These five tunnels are combination of driven tunnels and cut & cover tunnels, and present various cross sections (horse-shoe and rectangle profiles). There are numerous ramps. The access to the tunnels is restricted for vehicles > 12 tonnes;
- ventilation under normal conditions: Blanka and Mrazovka tunnels have a combined ventilation system: longitudinally ventilation in combination with transverse ventilation at portals. There are restrictions of portal emissions at three portals (triggering parameter for portal emission management is the outside NO2 concentration). Strahov tunnel has a fully transverse ventilation system;
- ventilation under emergency conditions: Blanka and Mrazovka tunnels: smoke extraction through remotely controlled dampers. Control of the air velocity. Strahov tunnel: smoke extraction through the exhaust duct. No remotely controlled dampers and no air velocity control.

6.3.2.9. *KEHU* service tunnel in Helsinki (FIN)

- geometry and traffic: buildings and underground car parks. It is a drill and blast tunnel. The traffic is very low. HGV and dangerous goods traffic is restricted. The tunnel has four underground roundabouts and several access ramps ;
- ventilation under normal conditions: longitudinal ventilation system;
- ventilation under emergency conditions: longitudinal ventilation and massive smoke extraction stations with shafts.

6.3.2.10. *Courier* Tunnel in Annecy (F)

- geometry and traffic: courier is a cut and cover tunnel, whose construction has been fully integrated with a new building area (recreational and commercial centres, residences). The tunnel provides access to underground car parks. It is a low clearance tunnel with some traffic congestion. The traffic is restricted for dangerous goods and heavy goods vehicles ;
- ventilation under normal conditions: longitudinal ventilation system operated on the basis of the air quality inside the tunnel. The ventilation system is reversible in order to push the air (even against the traffic flow) to the portal where the air pollution level outside is less sensitive;
- ventilation under emergency conditions: longitudinal ventilation with specific scenarios taking into account the tunnel and the car parks. The smoke-proof remote-controlled doors giving access to the car parks are closed in case of fire inside the tunnel or inside the car parks. Escape routes and pedestrian accesses to the car park have their own ventilation. The ventilation systems for tunnel, car park and pedestrian access are independent.

6.3.2.11. *A86 duplex* tunnel in Paris area (F)

- geometry and traffic: duplex A 86 is a double deck tunnel with a single tube, with low clearance. It was built with a large TBM. The access is restricted for HGV >3.5 tonnes, LPG and LNG. Duplex is operated with tolling system ;
- ventilation under normal conditions: transverse ventilation system managed according to the NO_2, CO and visibility measures;
- ventilation under emergency conditions: smoke exhaust galleries of the transverse ventilation system. The dampers are distributed and controlled. The movement of the smoke is controlled with jet fans and air curtains for the ramps.

6.3.2.12. *Croix-Rousse* Tunnel in Lyon (F)

- geometry and traffic: the tunnel has been constructed by drill and blast. The road tunnel has traffic restriction for vehicles > 3.5 tonnes. The parallel tunnel, also used as escape route, is a multimodal tunnel for public transport, pedestrians and bicycles ;
- Ventilation under normal conditions: longitudinal ventilation system. The management of the polluted air extraction (according to the traffic and air quality conditions inside the tunnel) is based on an environmental policy at the portals: using either longitudinal ventilation, or the extraction shafts, or a combination of both in order to limit the pollution discharge near the housing areas;
- ventilation under emergency conditions: the cross passages joining the road tunnel and the multimodal tunnel are pressurised. Massive smoke extraction for the road tunnel through five shafts. Control of the longitudinal air flow and containment of the smoke inside the road tunnel with jet fans. Smoke exhaust for the multimodal tunnel: longitudinal ventilation system and massive extraction by two galleries connected to the extraction shafts of the road tunnel.

6.3.2.13. *A14 A 86* Tunnel in Paris (F)

- geometry and traffic: it is a cut and cover tunnel under the La Défense Business District. The tunnel has interchanges and many ramps for the accesses to buildings, shopping malls, and underground car park. The dangerous goods traffic is restricted ;
- ventilation under normal conditions: combined ventilation system with all type of ventilation

systems due to the construction stages, the long period of time between construction of the stages and the evolution of the ventilation and safety requirements. No particular precautions for environmental issues. Management of the ventilation based on NO2, CO and visibility measures;
- ventilation under emergency conditions: multiple ventilation plants with massive smoke extraction. Predefined fire scenarios without real-time air flow control. Interaction with neighbouring structures (commercial centres, metro, train etc.).

6.3.2.14. *Voie des Bâtisseurs* in La Défense Business District (F)

- geometry and traffic: it is a one-way traffic tunnel giving access to numerous office buildings, commercial centres and car park of the La Défense Business District. It is a service tunnel, with a low traffic, a high percentage of trucks and access restriction for the hazardous goods ;
- ventilation under normal conditions: longitudinal ventilation system.
- ventilation under emergency conditions: longitudinal ventilation and fire proof doors to make the main branches independent. These doors are closed in case of fire.

6.3.2.15. *Valsassina* Tunnel (I)

- geometry and traffic: Valsassina Tunnel is a tunnel of 3.3 km length with a long access ramp of 2 km linked to the tunnel by an underground interchange. The tunnel has another underground connection with short ramps. The tunnel has a ventilation gallery inside the cross section above the traffic space. For one part of the tunnel it is a single reversible gallery. For the other part of the tunnel the gallery has two ducts, one for supplying fresh air and the other for smoke extraction. 85 motorized and remote-controlled dampers equip the ventilation gallery. Two underground ventilation stations (Bione and Lecco) are connected to the surface by shafts ;
- ventilation under normal conditions: longitudinal ventilation by 20 sections each equipped with 3 or 4 jet fans. The air is extracted by the Bione underground ventilation station. In case of dense traffic additional fresh air volume is supplied from Lecco station by the ventilation gallery;
- ventilation under emergency conditions: the smoke is exhausted by the ventilation gallery to the ventilation stations Bione and Lecco according to the place of the fire. The jet fans are used to manage the air velocity inside the tunnel and contain the smoke in the fire location.

6.3.2.16. Tunnel *sous le Rocher* in Monaco (MC)

- geometry and traffic: tunnel sous le Rocher was built by drill & blast. A branch of the tunnel reuses a former railway tunnel of 19th century. The tunnel has a shape of a double “Y form”. One branch is restricted for the transit of dangerous goods vehicles. One branch has a low clearance of 3.2 m. The HGV traffic of more than 3.5 tonnes is forbidden during the three daily peak hours;
- ventilation under normal conditions: longitudinal ventilation system;
- ventilation under emergency conditions: longitudinal ventilation with 8 predefined scenarios of ventilation. Tunnel Sous le Rocher has 8 branches with interconnections. Four water curtains are installed at the main connections and are activated in case of fire. A deluge system is installed in a section of the tunnel in order to protect the tunnel structure and the buildings on the surface.

6.3.2.17. *Opera* Tunnel in Oslo (N)

- geometry and traffic: Opera tunnel in Oslo is a complex of 4 tunnels: one is an immersed tunnel; one was built with cut & cover method and two with drill & blast method. These tunnels have several ramps ;
- ventilation under normal conditions: longitudinal ventilation system;
- ventilation under emergency conditions: the design fire power is 100 MW, with the exception of the immersed tunnel with design fire power of 300 MW.

6.3.2.18. Tunnels Complex in *Tromsø* (N)

- geometry and traffic: Tromsø complex includes 3 tunnels that are connected together with roundabouts. The tunnels were built with a drill & blast method. Each tunnel has a single tube and is operated with bidirectional traffic. Tromsø complex tunnel gives also access to underground car park, that also have 3 direct accesses to the outside ;
- ventilation under normal conditions: longitudinal ventilation system. The ventilation systems of the car parks and the tunnels are independent;
- ventilation under emergency conditions: longitudinal ventilation. Doors giving access to the car park from the tunnel are closed and fire-proof.

6.3.2.19. *Calle 30 – By-pass* in Madrid (E)

- geometry and traffic: the tunnel has been excavated with a large TBM. The tunnel has many access ramps, with a heavy traffic volume. The HGV traffic is forbidden inside the tunnel ;
- Ventilation under normal conditions: transverse ventilation system with 4 ventilation stations managed on the basis of CO, NO and visibility detectors. The ventilation stations are equipped with air cleaning plants for particles and NOx;

ventilation under emergency conditions: smoke extraction by the ducts of the transverse ventilation system. The dampers are neither distributed nor controlled.

6.3.2.20. *Calle 30 – Rio* section in Madrid (E)

- geometry and traffic: Rio Tunnel is a cut & cover tunnel with many access ramps, and a heavy traffic volume. HGV traffic > 7.5 tonnes is forbidden inside the tunnel ;
- Ventilation under normal conditions: longitudinal ventilation system with massive extraction and injection stations. The short ramps and branches are longitudinally ventilated. Shafts with axial fans are designed for branches whenever the length is greater than 300m. The ventilation stations are equipped with air cleaning plants for particles and NOx;
- ventilation under emergency conditions: massive smoke extraction by shafts and ventilation stations. The jet fans are switched off in case of fire.

6.3.2.21. *Northern Link* and *Southern Link* in Stockholm (S)

- geometry and traffic: the Northern and Southern link tunnels have been constructed by drill & blast methods. Tunnels have various ramps and no traffic restrictions;
- ventilation under normal conditions: longitudinal ventilation system with exhaust shafts at the ends of the main tunnels in order to limit the pollution discharge at portals. The NOx emissions are also taken into account for the management of the ventilation;

- ventilation under emergency conditions: smoke extraction of the main tunnel by the ventilation stations near the portals. Longitudinal ventilation for the ramps.

6.3.2.22. *Sytwende* Tunnels complex in The Hague (NL)

- geometry and traffic: this tunnel complex includes 3 tunnels, one of them (Vliettunnel) being multi-modal (road and rail) within separated tubes. Tunnels have been constructed with cut & cover method. The dangerous goods traffic is partly allowed: flammable liquids are authorised, while toxic liquefied gases are forbidden ;
- ventilation under normal conditions: longitudinal ventilation system;
- ventilation under emergency conditions: longitudinal ventilation system.

6.3.2.23. *Ville-Marie and Viger* tunnels in Montreal (CND / QC)

- geometry and traffic: Ville-Marie tunnel has an underground interchange with a main branch from the East, and several ramps giving access to the urban surface roads networks. The tunnel has 6 ventilation shafts that include the technical M&E substations and the ventilation stations. The number of lanes varies from three to five lanes in each traffic direction. The tubes are stacked up on about the half of the Ville-Marie tunnel length. Viger tunnel has 2 ventilation shafts and only one ramp giving access to the outside;
- ventilation under normal conditions: Ville-Marie has a semi-transverse ventilation system with 6 ventilation stations located in the shafts: 42 fans for air supply and 31 fans for polluted air exhaust. Vigier tunnel has a longitudinal ventilation system with four jet fans in each traffic direction.
- ventilation under emergency conditions: in the Ville-Marie tunnel, smoke is exhausted by the ventilation stations. Viger tunnel has two ventilation shafts and the smoke is exhausted with three fans in each ventilation shaft.

6.3.2.24. Boston *Central Artery* (USA)

- geometry and traffic: Boston Central Artery is a complex tunnel with numerous that was constructed with cut & cover method. The tunnel crosses two metro lines, one above and the other underneath ;
- ventilation under normal conditions: the ventilation system incorporates a combination of ventilation systems including fully-transverse or semi-transverse ventilation system, as well as longitudinal ventilation system using jet fans or Saccardo nozzles;
- ventilation under emergency conditions: smoke exhaust either by the smoke channels of the transverse or semi-transverse ventilation system, or by massive extraction stations for the sections with longitudinal ventilation system.

6.3.2.25. *M7 Clem Jones* Tunnel in Brisbane (AUS)

- geometry and traffic: the tunnel was built partially with TBM (37% of the length) and partly with a road-header. The tunnel has 7 entry and exit ramps;
- ventilation under normal conditions: longitudinal ventilation system with jet fans. Polluted air is exhausted by ventilation stations and shafts located prior the exit portals;
- ventilation under emergency conditions: smoke extraction by extraction ducts located above the traffic spaces and dampers.

6.3.3. Main findings from the questionnaire analyses

6.3.3.1. Traffic and design fire

Most of the tunnels investigated do not allow dangerous good vehicles (DGVs). The design fire size is consequently limited at 30 MW, or even less for tunnels with only low clearance and light vehicles. Only four tunnels (Kaisermülhen tunnel (A), Southern and Northern links (S), Opera (N), Sijtwendetrace (NL) allow access to DGVs.

For Opera tunnel (N) the design fire power is 100 MW for the tunnels built with cut & cover and drill & blast methods. The design fire power is 300 MW for the immersed tunnel, essentially for structural reasons.

6.3.3.2. Selected ventilation system

Almost all the tunnels investigated are operated with unidirectional traffic. Longitudinal ventilation strategies in normal and emergency operation are therefore often suitable (if no traffic jam is present).

However, the emergency ventilation is rarely based on purely longitudinal ventilation (only six tunnels – Opera (N), Tromsø (N), Courier (F), Sijtwendetunnel (NL), Southern and Northern links (S), have a pure longitudinal ventilation system). In most of the cases, the emergency longitudinal ventilation system also includes massive smoke extraction points in order to reduce as much as possible the propagation of the smoke in the tunnel and to limit the consequences to passengers that could be blocked by a traffic jam. The spacing between two massive extraction points generally varies between 400 m and 600 m.

The operation of emergency longitudinal ventilation system includes in some cases two phases:

- first phase where the longitudinal velocity is controlled at low speed in order to improve the smoke stratification during the self-evacuation;
- second phase where the longitudinal flow velocity is increased to push the smoke in one direction for the intervention of the fire brigade.

In some cases (Ville-Marie (CDN/QC), Shinlim (ROK), A14-A86 (F), Chiyoda and Yamate (J), Strahov (CZ)), the emergency ventilation is fully or partially based on a transverse ventilation.

In a few cases (A14-A86 (F), Ville Marie (CDN/QC)), space constraints in combination with permanent extensions of underground road networks resulted in various combinations of different ventilation systems.

In some tunnels with particular issues with the connected ramps, specific ventilation equipment is installed to isolate the different branches of the network:

- for instance, air curtains are used in the A86-Duplex (F) to maintain the pressurization of the safe tube and to avoid smoke propagation through the interchange tubes;
- the "*Sous le Rocher*" tunnel in Monaco (MC) also includes a water curtain in the merging area of tunnel branches in order to cool the smoke before propagating in upstream tunnel sections;

- in some other tunnels the isolation between branches is obtained by management of the ventilation system, in order to get no air flow (zero velocity), at the connection zone between to tunnel branches.