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LARGE UNDERGROUND INTERCONNECTED INFRASTRUCTURE

TECHNICAL COMMITTEE D.5 ROAD *TUNNEL OPERATIONS*

WORLD ROAD ASSOCIATION
MONDIALE DE LA ROUTE
AIPCR PIARC

STATEMENTS

The World Road Association (PIARC) is a non-profit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2016– 2019 and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organisations or agencies.

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LARGE UNDERGROUND INTERCONNECTED INFRASTRUCTURE

TECHNICAL COMMITTEE D.5 *ROAD TUNNEL OPERATIONS*

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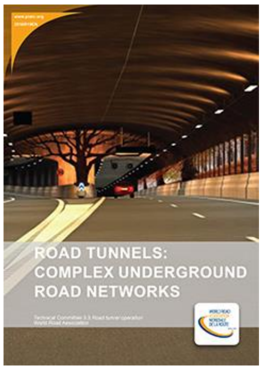
EXECUTIVE SUMMARY

2019R24EN

LARGE UNDERGROUND INTERCONNECTED INFRASTRUCTURE

The PIARC "Road tunnel operation" technical committee" published in 2016 a report with the following title and reference:

Road tunnels: complex underground road networks



- **Author(s) :** Comité technique 3.3 Exploitation des tunnels routiers / Technical Committee 3.3 Road Tunnel Operation
- **PIARC Ref. :** 2016R19EN - **ISBN :** 978-2-84060-404-4

Complex underground road networks are under development in the world given the growing concentration of the population in large urban cities and the high occupancy of the urban surface. The objective of the above-mentioned report is to make as comprehensive as possible a point of the current situation around the world.

This first analysis highlights the particular problems faced by this nature of networks. It has also helped to point out the need for thorough reflection. Today's networks have often been designed by transposing in the underground, the concepts of infrastructure in the open air and of current tunnels, omitting the particularities of the underground networks.

The report published in 2016 presents numerous summary information, statistical elements, as well as lessons and preliminary recommendations concerning the design and operation of these networks. In this analysis, which was carried out with extensive surveys and interviews with operators, owners and designers, twenty-seven "complex underground networks" (or set of tunnels), comprising a total of forty-one tunnels, have been investigated. The report contains in appendices monograph sheets for most of the tunnels analysed.

The objective of this report, which is the continuation of the previous one, is twofold:

- extend the panel of networks investigated, both geographically and in terms of their complexity and diversity,
- analyse in a much more thorough manner the particularities of this network nature, including
    - the geometry and impact of all the constraints related to the interchange points and connections,
    - ventilation facilities: aspects related to traffic assumptions – surface impacts – specific concepts and design – implementation, equipment and facility acceptance tests, and verification of the performances of the overall system,
    - signalling: location of an incident and addressing – signalling devices – evacuation aid,
    - the operation and management of interfaces between the many operators (with very rare exceptions of a single operator) involved in a network – organisation – the multiplicity and complexity of interfaces – safety – traffic management – special care and maintenance provisions.

Six other networks were assessed during this cycle, and additional monographs were published. However, the statistical data from the 2016 report has not been updated, as the number of new networks analysed is insufficient.

The analysis presented in this report is particularly relevant to the major aspects of a network of large interconnected underground infrastructures:

- geographic and functional complexity,
- the extend of interlinks and interactions between the different infrastructures,
- the multiple interfaces between operators and the organisational structures,
- the need to create a "Coordinating Entity" between the various operators, its obligation of overall effectiveness in respect of particularities and responsibilities of each individual operator.

The consequences of complex interconnected underground networks may often be underestimated, particularly when it results from adding new infrastructure to existing infrastructure that has not been designed for this purpose. The new network thus set up must be the subject of a detailed global analysis, covering in particular:

- societal cost-benefit aspects,
- all questions relating to design, safety, interfaces, compatibility between the initial network and the addition of new infrastructures,
- operation and maintenance, as well as the organisations to be set up for the management of the numerous interfaces,
- the new provisions concerning the intervention of the emergency services.

The feasibility and relevance of this new network can only be validated after this in-depth analysis.

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1. GENERAL OVERVIEW

1.1. INTRODUCTION

The 2012-2015 PIARC's Strategic Plan initiated a reflection concerning underground road network infrastructure, their features and the management of interfaces which are often divided between several operators.

The mission was then entrusted to the Working Group No. 5 of the Technical Committee 3.3 Road Tunnel Operation, under the designation of "Complex Underground Road Networks". At the end of this cycle, a report was published under the reference *[1] PIARC 2016R19 – Technical Committee on Road Tunnels – "Road Tunnels Complex Underground Road Networks"*

The "Strategic Plan" launched for the 2016-2019 Cycle confirmed continuing the reflection on this topic under the definition of "Large Underground Interconnected Infrastructures".

The mission was entrusted to the Working Group No. 5 of the Technical Committee D.5 Road Tunnel Operation.

1.2. OBJECTIVES

1.2.1. "Overall" objectives

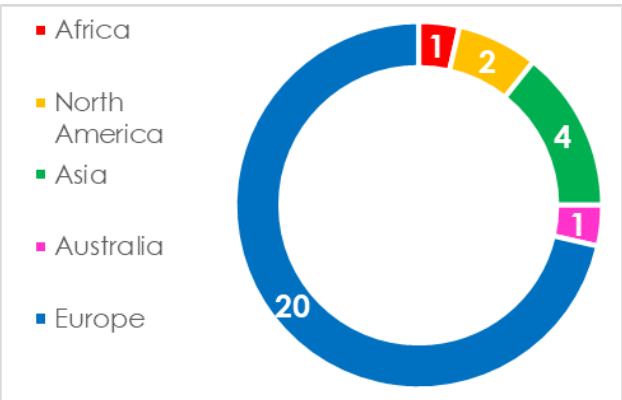
The objectives of this report are:

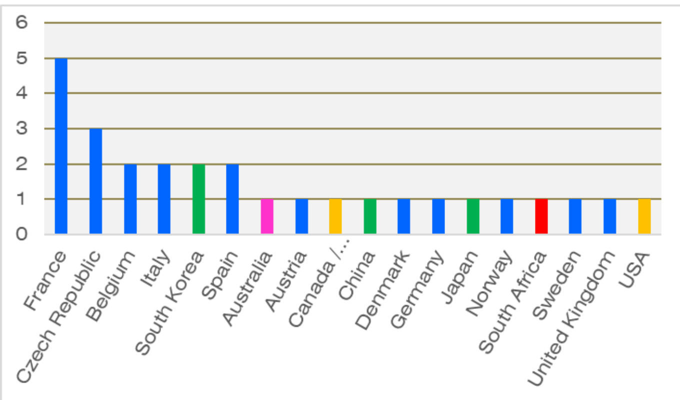
- To identify and analyse existing and planned urban underground and interconnected complex road networks with interchanges and multimodal elements from an operational and safety point of view, and,
- To establish recommendations contributing to the improvement of the traffic conditions, efficiency, safety and comfort of road users (ventilation, signalling, operation, safety).
- Promote knowledge and enhanced understanding about the relevance of ventilation design, signalling, and operations in the context of large underground and interconnected infrastructure.

1.2.2. Authors and target groups

This working group includes 28 members from 18 countries (Figure 1). It includes representatives from public authorities, owners, engineers, designers and operators of tunnels.

This report is addressed to tunnel owners, engineers, designers and operators to assist them in their strategic thinking when they are dealing with complex underground road networks.





The working group has outlined the concept of "Large Underground Interconnected Infrastructure" which was during the previous PIARC cycle, known as "Complex Underground Road Networks" the following infrastructure which is essentially located in urban areas:

- Road tunnels with interchanges or underground connections, a set of interactions and interfaces between the underground space and the open-air space, as well as between the underground and the surface networks;
- A series of road tunnels located close to each other and interactions between them, especially from the point of view of traffic and safety conditions;
- Road tunnels giving access to underground car parks or to commercial and business centres (example access for supplying of shopping malls). In particular, the interfaces are considered during normal operation and in case of fire;
- Multimodal Road tunnels or tunnels including facilities shared with other underground infrastructure;
- Tunnels with reduced vertical clearance, where access is reserved for passenger cars (short urban underpasses are not included).

Standards urban road tunnels are not part of this present analysis, nor are underground facilities having no traffic function or interface with a road.

The activities of the Working Group focused on issues and specific characteristics of such complex infrastructure. It pays particularly attention to interactions and interfaces between the infrastructure and its operating and safety conditions. These reflections and recommendations of the working group are aimed not only to basic conceptual designs, nor the main tunnel equipment which has been the subject previous publications of PIARC. They have been completed to provide specific characteristics and special operating conditions.

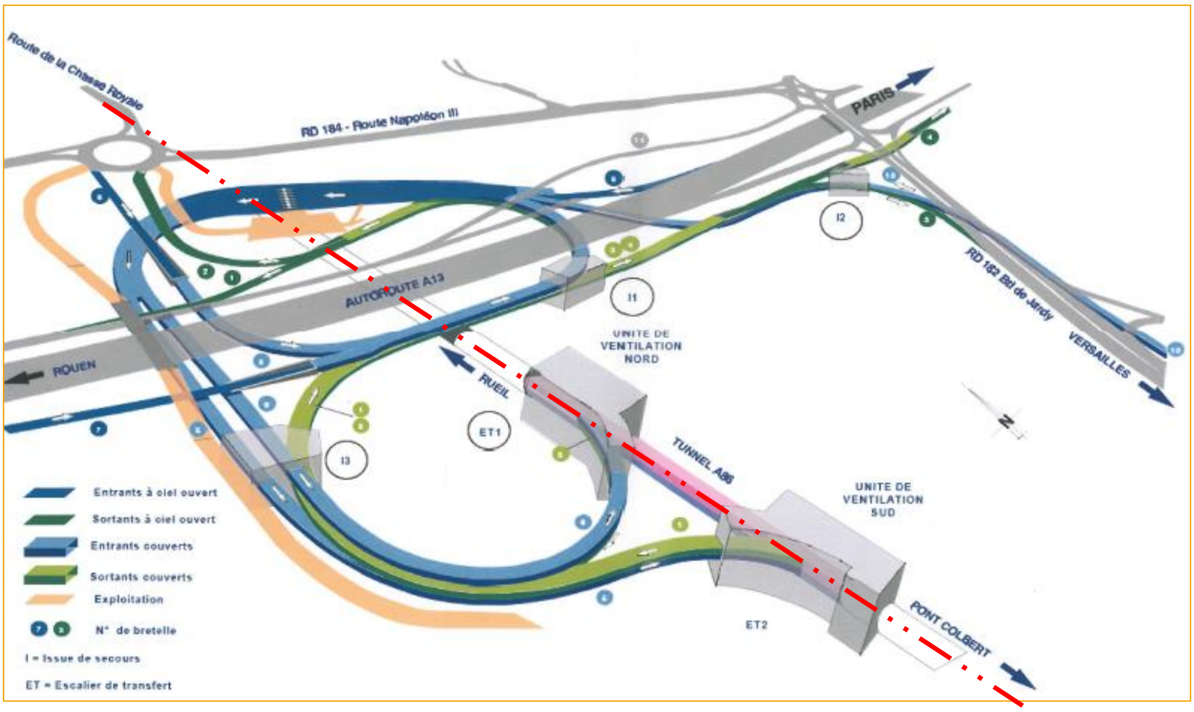


Figure 2 - Example of a complex underground infrastructure -underground interchange between Duplex A 86 and motorway A13 in the Region Ile-de-France. (See monograph 2-8)

1.2.4. Organisation of the present report

Additional interconnected infrastructures have been investigated in Europe, the USA and China during this cycle. These have included the following:

Country	City	Name of the tunnel
Germany	*Düsseldorf*	*Kö-Bogen Complex*
Spain	*Madrid* *Madrid*	*AZCA Tunnel* *Cuatro Torres Tunnel*
China	*Chongqing*	*Underground Ring Road in Jiefangbei C.B.D.*
USA	*Seattle* *Seattle*	*Interstate 90 Mt. Baker Tunnel* *SR 99 Alaskan Way Viaduct Tunnel through Seattle*

Table 1 - New complex tunnels investigated during the cycle

Additional complex tunnels related to other countries were originally planned for investigations. However, this was not possible and as a result, the limited number of complex tunnels that were added proved to be insufficient to trigger the updating of statistical analysis that was done in previous PIARC Cycles.

Monograph sheets have been drafted for all the new tunnels investigated, as well as for tunnels identified in the previous cycle. Additional information has now been collected, making it possible to fully edit the required monograph sheets. All new monograph sheets as well as the previously completed are listed in the Table 8 in chapter 9.1 below. The hyperlinks of the table give direct access to the monograph sheet which the reader may wish to access.

2. GEOMETRY

2.1. Foreword

A tunnel is a complex system resulting from a wide range of parameters which are variable and interactive. The relative weight between them and their decisive nature vary according to the nature of each tunnel. Readers are encouraged to consult the page "A Complex System" of the chapter "Strategic Considerations" of the "Road Tunnel Manual" *(see reference* **[37]***)*, which presents this problem in more detail and how to approach it.

This complexity is amplified for "large interconnected underground infrastructures" due to the multiplicity of infrastructures, branches, underground or surface interfaces, as well as the multiplicity of operators.

The evolution of tunnels throughout their life cycle is very important. This evolution is rarely anticipated and often leads to the implementation of successive but separate solutions, which are rarely the most suitable for the tunnel. The evolution is even more prominent for an underground network, often located in an urban area, which has its own complexity and the scaleability of functions and needs in the urban space.

This is why it is essential to proceed from the beginning of the project with a clear and exhaustive reflection of the needs and potential future evolutions. This reflection will make it possible to integrate flexibility and concepts into the project that will facilitate these future developments. This often-complicated process is certainly a challenge, but it is essential to choose and implement solutions that are relevant from both a technical and an economic point of view.

2.2. Alignment

Readers are encouraged to consult the "General Studies of New Tunnels" Session of the "Strategic Considerations" chapter of the "Road Tunnel Manual" *(see reference [37])*, which presents the problematic nature of the horizontal and vertical alignments in detail.

The constraints are much greater for an interconnected network of underground infrastructures, particularly due to:

- The multiplicity of infrastructures and the constraints specific to each of them,
- Numerous interfaces with the surface (road entrances and exits, ventilation structures, emergency exit routes) that require finding surface rights-of-way for their locations,
- The need, in the event of poor soils below the groundwater level, to be able to build temporary shafts several tens of metres apart to the right of the convergence zones due to diverging ramps,
- Constraints related to the occupation of the underground areas which are denser in urban areas, and more restrictive regarding the insertion of an infrastructure network compared to those related to a simple linear structure,
- The need to consider the geometric definition of the network specific constraints associated with the construction method.

All these constraints can lead to a more sinuous layout with steeper longitudinal profiles. It is therefore essential to be very vigilant in this regard. The analysis of accidents in correlation with the horizontal and vertical alignments, the traffic conditions, the number and geometry of interchanges and access ramps, as well as with signalling and lighting quality, shows that most accidents occur due to:

- The tight radius of the curves, especially if they are associated with steep slopes,
- At exit areas when visibility on the exit is too low, or in the event of a traffic jam (collision at the end of the plug),
- In the insertion areas of the entrance ramps.

To this end, the following recommendations are made during the general studies of a new underground network:

- It is essential to analyse the geometry (plan layout, design of entrances and exits), lighting and signalling provisions for the upcoming phases of the project at the same time, in order to achieve a satisfactory balance between the constraints resulting from urban occupation, technical constraints and safety objectives, in relation to the characteristics of the horizontal and vertical alignments,
- The design of the exits is essential in order to: (1) have good visibility - (2) ensure that the sizing is appropriate to the traffic volume and traffic conditions - (3) provide parallel exit lanes (the length of which must be defined according to the traffic volume and the probable recurrence of traffic jams), to prevent the jams on the exit ramps from blocking traffic inside the tunnel,
- Particular attention should be paid when designing (location and geometry) the connections of the exit ramps to the surface road network. The capacity of the roads to which the exit ramps will lead must be consistent with the expected traffic volume. Otherwise, it is very likely that traffic jams will occur on the relevant exit ramp with an impact on traffic and safety in the main tunnel,
- It is also essential to consider the behaviour of the daily user of a car park compared to that of a user in transit. The two behaviours can be very different and cause accidents.

2.3. CROSS SECTION

2.3.1. Foreword

Surveys carried out during the previous PIARC Cycle shows that 80% of the tunnels analysed are prohibited for vehicles over 3.5 tonnes *(see reference* **[1]***)*. However, this access restriction was not considered during the design of the structures, particularly the width of the traffic lanes and the vertical clearances.

Recent studies by members of the working group for a project involving a succession of three urban tunnels with interchanges, and a total length of 8 km, show that it is possible to significantly optimise costs by adapting the width of the traffic lanes and the vertical clearance to the nature of the authorised vehicles.

These studies were carried out for:

- twin-tube tunnels with two lanes of traffic in each direction, built by means of the tunnel boring machine (TBM) circular cross-section,
- tunnels with limited access to light vehicles, minivans and vans.

The table and the diagram below show the construction cost savings based on the vertical clearance. Savings would have been similar for tunnels with a "horseshoe" section built with drill and blast construction methods.

vertical clearance	construction costs	cost savings
5,0 m	*100*	*0%*
4,5 m	*95*	*5%*
3,2 m	*79*	*21%*
2,7 m	*73*	*27%*

Table 2 - Construction costs versus vertical clearance

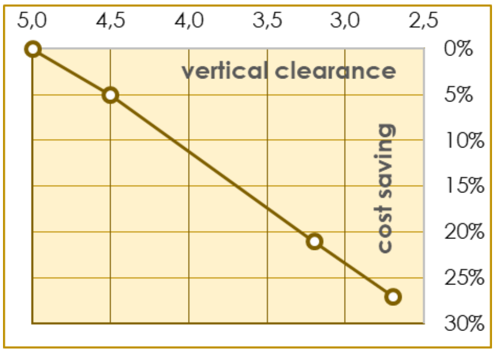
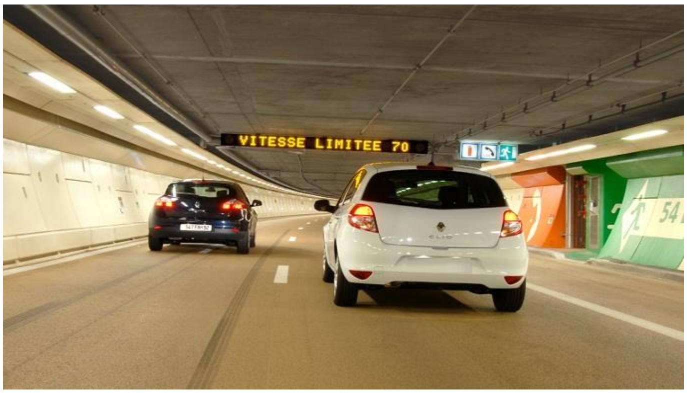


Figure 3 - Construction costs saving versus vertical clearance

The cross section profile for the 3.2 m and 2.7 m vertical clearance described in Table 2 above have been designed according to the standards defined by the RECTUR, French “Recommendations for the design of low clearance urban tunnels *(see reference* **[27]***)*



Picture 1 - France - Duplex A86 - vertical clearance 2 m

2.3.2. Recommendations

From the beginning of the project, it is necessary to carry out detailed studies on the function of the tunnel, traffic conditions (volume and nature of vehicles), as well as financial capacities and financing methods, in order to analyse the potential optimisations of the project, without reducing the level of service and safety conditions.

The investment costs of complex urban infrastructure are generally very high, and their financing is difficult to raise. As mentioned above, 80% of the tunnels analysed were designed with standard vertical clearance, even though they are prohibited for heavy goods vehicle traffic.

Preliminary analyses of the tunnel's function and use could lead to financial optimisation and, due to cost reduction, could make projects feasible, whereas they cannot otherwise be financed.

3. VENTILATION

3.1. INTRODUCTION

The construction of any new infrastructure within an urban area is a real challenge due to the great impact that this construction will cause on the existing developed area. This challenge is relatively greater when a complex underground infrastructure is being designed, because it will normally require additional special needs.

PIARC has published numerous recommendations concerning the ventilation of standard road tunnels, including urban tunnels. However, the complexity of a large underground infrastructure facility does not make it possible to outline simple solutions for the ventilation systems.

The existence of many interchanges, entrances and exit ramps, results in a connected aerodynamic system with substantial impacts on the ventilation design. These concerns are not only applicable to the normal operation, but they are also relevant to the emergency operations where the smoke management is more complicated. Furthermore, the control of the smoke spreading to the different tunnel sections may represent a great challenge for the operator.

Another issue on complex underground urban infrastructure is the high probability of congestion and the creation of traffic jams, which have a great impact on the selection of the ventilation system. As an example, when using a longitudinal ventilation system, the risk of smoke movement over blocked vehicles downstream the fire is higher, and a pure simple solution of traffic management is insufficient to solve the issue.

The control of the ventilation system is also more difficult and essential compared to conventional road tunnels. Not only because there is more equipment to be controlled (fans, dampers, fire compartmentation doors, and others) but also because the ventilation strategies are different and depend on the location of the fire. Control can be based on an open-loop (predefined ventilation scenarios) or closed-loop methodologies (based on real measurements inside the tunnel during the fire). The ventilation scenarios and the operating modes must be defined during the design.

The impact on the surface due to this more complex ventilation system requires particular attention, especially the ventilation buildings at the portals, the intermediate shafts or massive extraction grilles, towers, etc. All the possible impacts on the surface should be identified and assessed at the preliminary evaluation stage as they may influence the feasibility of the project. This is aimed to minimise the risk of developing an unsuitable design for the defined environment. The integration of these facilities into the urban area may be influenced by the available space, and the associated shortcomings. A consultation with the local, regional authorities and the stakeholders is essential at a very early stage of the project to find the most appropriate solution.

The complexity of the ventilation system and the multiplicity of equipment make these facilities very sensitive to the type and quality of the components being used, including their performance, implementation, robustness and lifetime. Particular attention to performance and testing procedures must be incorporated from the start of the tendering process and during the selection process of contractors and suppliers. Furthermore, special attention must be given throughout the manufacturing process at the factory, the installation of the equipment on-site, testing procedures and during the process of intermediate and the final tests and commissioning of the infrastructure.

This section contains the following four chapters:

- Traffic assumptions
- Impacts at the surface.
- Ventilation strategy-concept-design
- Procurement, implementation, testing and acceptance, preparation for operation

3.2. TRAFFIC ASSUMPTIONS CONCERNING VENTILATION

3.2.1. Issues associated with the complexity

A complex network of underground infrastructure generally includes numerous road branches, junction points (interchanges or connections) and facilities connected to the main infrastructure (such as underground car parks - commercial centres – office or residential towers). It can also include many interactions with other multimodal infrastructure.

A network has many entrances and exits, which constitute many interfaces with the outside especially in terms of traffic. A good appreciation of the traffic entering and leaving the network, of the traffic mix and the traffic evolution is essential in terms of:

- capacity of the network and the design of the infrastructure,
- comfort of the users,
- sizing of the ventilation facilities,
- definition of the safety conditions, of the organisation and the effectiveness for the emergency intervention in case of an incident, particularly in case of fire.

The analysis of the existing networks shows that traffic assumptions are often insufficient with rather hasty or risky considerations regarding the consequences that may result.

This chapter essentially presents the traffic assumptions in relation to the design of the ventilation and the safety conditions.

3.2.2. Current situation

Complex networks are mainly located in urban areas and are subject to significant traffic with morning and evening peak hours, as well as intense traffic during the day. The traffic diagram during the working days is often an "M-curve" (see Figure 4): example of a tunnel traffic diagram in a major French city.

The traffic is mainly made up of passenger cars, light vehicles, public transport vehicles and deliveries.

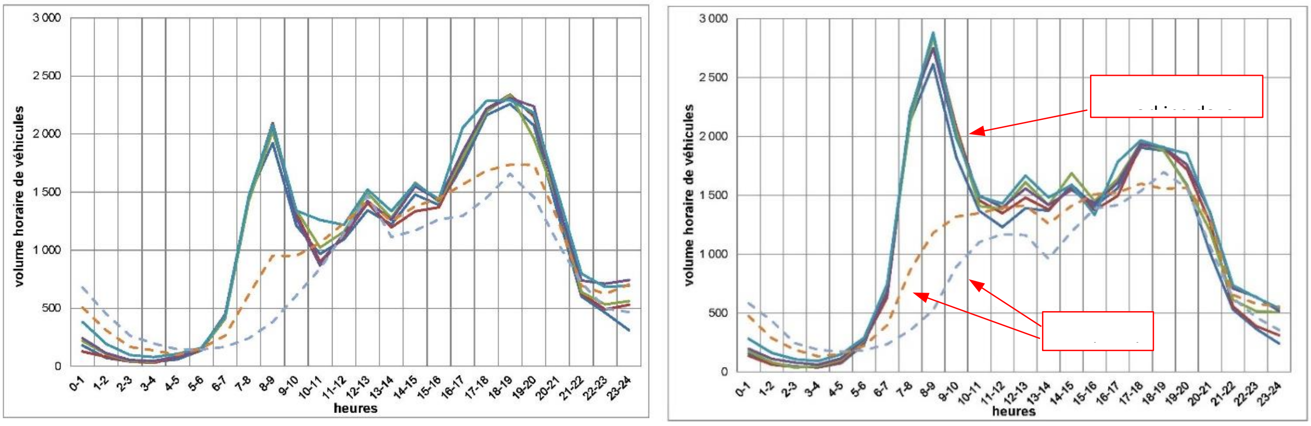


Figure 4 – Daily traffic diagram as «M curve » - traffic directions 1 and 2

There are numerous interfaces:

- at the entrances and exits of the main tunnel with connections to an infrastructure of the same nature (expressway – urban motorway – etc.) in the open-air space,
- with the surface urban street network to which the entrance and exit ramps are connected to,
- with other underground infrastructures such as car parks.

Analysis of the 27 tunnel complex underground networks that have been investigated *([1]PIARC 2016R19 – Technical Committee on Road Tunnels – "Road Tunnels Complex Underground Road Networks)* shows that:

- the congestion and the traffic jams are frequent at peak hours in front of the exit ramps and less frequent at the entrance ramps. These congestions and traffic jams have immediate repercussions on the main tunnel, in terms of the formation of a traffic jam on the lane upstream of the exit, with a repercussion on the other lanes that can thus be blocked,
- most of them are rarely concerned by recurring congestion or traffic jams for the go through traffic. Go through traffic is, however, concerned by the impact of the congestion or blockages on the exit ramps,
- the tails of the traffic jam, or late lane changing before exit ramps to avoid queuing, are the cause of many collisions and areas of concentration for the accidents,
- the concept of the existing ventilation facilities and their sizing does not always consider these specific conditions, particularly in case of fire.

3.2.3. Traffic forecast - congestion & traffic jams

3.2.3.1. Traffic forecast

The traffic forecast estimates are like "difficult art", especially in urban areas, even though many methods and models of reliable computations representing a network are available.

The assumptions of traffic growth and the evaluation of traffic newly induced for a new infrastructure are also a very subjective exercise, and a set of scenarios should be analysed with low, medium and high traffic volume assumptions.

These observations concern the main tunnel, which is generally part of the primary network of the road system, and for which continuity is ensured with infrastructure of the same nature on the surface.

The situation is much more complex for the secondary branches of the underground network, especially for the entrance and exit ramps. The traffic conditions on these branches are strongly impacted by the interfaces connecting with the surface road network, and by the traffic conditions on the surface road network itself. Potential traffic demands may, however, be assessed with more uncertainty than those of the main network, but it is difficult to assess the current capacity of traffic on these branches during peak traffic hours. This capacity depends mainly on the conditions of connections to the surface network, the traffic management at the connection, and the time for absorption of the outgoing traffic by the surface network when it is saturated. A saturated surface network near the connection of an exit branch has a very high probability for creating congestion and jams on the secondary branches of the underground network, as well as by creating congestion and traffic jams on the main tunnel.

3.2.3.2. Congestion and traffic jams

In cities where the surface road network is saturated and is impacted by recurring traffic jams at peak hours, it is illusory to imagine that the traffic jams in the interconnected underground network can be eliminated by pure simple provisions of traffic management and regulation.

Some management provisions may certainly improve the conditions, but only marginally *(see chapter 5.2 Traffic management)*. A strong lowering of the probability of traffic jam in the underground network requires strong actions to reduce traffic entering the underground network. Actions are often enforced that garner the following type of comments:

- difficulty of their physical implementation in urban areas,
- significant impact on surface traffic near entrances on the underground network,
- political difficulty to have them accepted,
- inability to maximise the benefits of the infrastructure translating into non-fulfilment of the function to which it was originally designed for,
- in cases where the funding of the infrastructure, its construction, operation and maintenance are governed by toll collection, the drastic reduction in incoming traffic is likely to impact the economic model and thus the feasibility of the infrastructure.

3.2.4. Recommendations

3.2.4.1. Basic aspects

The ventilation system's size and the safety requirements are the two fundamental aspects that need to be examined carefully, because they have an essential impact on the concept of the ventilation system, as a whole, and also on the safety conditions in the underground network:

- The traffic volume in normal conditions and during peak traffic hours. These traffic evaluations are mainly concerned with the size of the ventilation for pollution control,
- The likelihood of the formation of recurrent traffic jams in the main tunnel (go-through traffic), in the secondary tunnel branches (local service traffic), with or without repercussions in the main tunnel. The likelihood of recurring traffic jams has an essential impact on the ventilation concept, the smoke exhaust provisions and the sizing of the entire facility.

3.2.4.2. Ventilation for pollution control

- ***Traffic forecast***

Traffic forecasts are to be performed under the conditions mentioned above, considering different scenarios with assumptions of traffic evolution and newly induced traffic, low, medium and high-volume assumptions. In urban areas with recurring congestion conditions, a scenario of generalised traffic congestion should also be assessed.

It is recommended:

- to perform a preliminary sizing of the ventilation system for each of the main traffic scenarios,
- to analyse whether the architecture of these installations easily allows a reinforcement during the tunnel's life cycle, from the installation corresponding to the low or medium traffic scenarios to the facilities corresponding to higher traffic scenario,
- to assess the costs of each facility to be able to determine and improve the balancing of the stakes and risks.

- ***Pollutant emission assessment***

The evolution of the nature and composition of the vehicle fleet is an important factor. The regulations are evolving quickly, imposing objectives for a significant reduction in pollutant emissions. Special provisions are being made in many countries and many major cities around the world to banish the oldest (very polluting) vehicles, to make restrictions on diesel-fuelled vehicles, and to promote hybrid and electric vehicles.

The evolution is likely continuing to promote health in large urban agglomerations with an increase in the proportion of hybrid and electric vehicles. The impact is very important for the sizing of the ventilation systems. The evolution of the fleet must be considered by considering scenarios adapted to the policy specific to the country concerned, and to its realism of implementation over time.

The emission values of pollutants are presented in a new PIARC report reference: *[2] PIARC 2019R02 - Technical Committee on Road Tunnels – "Vehicle Emissions and Air Demand for Ventilation.*

3.2.4.3. Ventilation in case of fire

The concept of the ventilation systems, their sizing and their control are tightly related to

- the nature of the vehicle fleet in the area, which will determine the design fire heat release rate to be considered. This is in most cases a fire of one or several light vehicles. The fire heat release rates to be considered are presented in the PIARC report reference: *[3] PIARC 2017R01 - Technical Committee on Road Tunnels – "Design fire characteristics for road tunnels".*
- the presence or absence of traffic jams located or generalised in the underground network concerned. These jams, moreover, increase the risk and frequency of incidents (especially the collisions in the tails of the queue), as well as the fire hazards resulting from it,
- the possibility to discharge the smokes and toxic gases at the tunnel portals, at mass extraction points or at the smoke exhaust shafts. An analysis must be done in relation to

the environmental constraints and the safety conditions for the population living adjacent to these discharge points.

The likelihood of the formation of recurrent traffic jams must be carefully analysed. It cannot be evaded by the frequent assertion of "the implementation of traffic management provisions to prevent the creation of traffic jams".

In the urban areas subjected to recurrent traffic jams, all the interfaces of the underground network with the surface network in congested areas would lead to congestion and jams for the relevant branches of the underground network, with usually extension to the main tunnel. Failure to take this into account is a major design error, which also leads to unmodifiable, often unmanageable irreversible design concepts that will expose users to significant risks.

In case of doubt about the frequency of the jams, it may be advisable to quickly sketch and evaluate a ventilation system considering the jams, and one not taking them into account, to be able to compare and to make a transparent and documented choice between the aspects of financial over costing (not always as high as one imagines), and the consequences in terms of risks and use of the infrastructure.

3.2.4.4. Selection and sizing of the ventilation system

The traffic volume, the composition of the fleet of vehicles and the traffic conditions are important factors in the selection of a ventilation system, its sizing and other relevant components which may include:

- the safety of the users,
- the environmental conditions, the health and safety of populations near tunnel portals or polluted air discharged points,
- the contribution of the ventilation system to facilitate the intervention of emergency services during a fire,
- its contribution to reducing damage to the structures or minimise the risk of their destruction during a fire.

The purpose of this section is not to present the advantages and disadvantages of the different ventilation systems or sizing methods. This will refer to the numerous reports published by PIARC over the years (see especially references: *[2], [3], [4], [38] and [39]*).

An underground network is, due to its many interfaces, subject to conditions that are quite difficult to predict and subject to many variations and evolutions during the tunnel life. Decisions on the concept of the ventilation system and its sizing should not be the result of risky and poor-considered postulates.

Therefore, it is essential:

- to analyse the different potential ventilation concepts that can meet the different traffic assumptions,
- to proceed with their preliminary sizing and financial estimate, to have a rational overview of the potential additional costs between the different solutions,
- to examine the possibility of evolution and adaptation of each alternative of the ventilation system. How is the installation considering low traffic scenarios, likely to evolve for complying to high traffic assumptions?

- to make a rational decision considering: (i) uncertainties regarding the evolution of traffic and potential jams – (ii) the differences in construction and operating costs between the different alternatives – (iii) the evolutionary capacities and adaptation of the final solution.

3.3. IMPACT ON THE SURFACE

3.3.1. Key issues

The objective of this chapter is to identify the major impacts on surface resulting from the ventilation that should be taken into consideration when designing a “complex underground structure” within an urban area.

The ventilation system of a complex underground network generally requires the construction on the surface of ventilation buildings and intermediate shafts along the tunnel for the management of the air in the underground structures.

The location of these constructions in open air is more complicated for projects in urban areas according to the occupation of the underground (other infrastructure, networks, etc.) and the limited availability of space on the ground surface (buildings, roads, miscellaneous facilities). The choice of the location for the tunnel portals and the buildings requires an in-depth analysis following an environmental assessment study. The management of emergency (discharge of smokes, polluted air and toxic gases in case of fire) must also be analysed. These discharges may often have an essential impact for the health and safety of the residents and neighbouring communities.

The identification and analysis of all environmental impacts should be done from the start of the feasibility studies in order to promote initial discussions with the stakeholders for the location of the various surface buildings associated with the ventilation. These discussions may sometimes lead to adjustment of the initial concept. It may often be necessary to modify the alignment, the design (layout, longitudinal and vertical alignments and ventilation) once the consultation process with the stakeholders has been considered. All these elements are indeed interrelated and must be developed simultaneously from the beginning of the project. The modifications of a part of the project may significantly affect other parts of the project in the iterative process.

Picture 3 - Shaft of the Stockholm Southern Link Tunnel

Picture 2 - Ville Marie Tunnel shaft in Montréal downtown

The process of land acquisition, the enquiries and administrative authorisations, the building permit should also be identified at an early stage of the project development. These processes may be extensive, complex, time consuming and considerable consequences on the whole project schedule.

3.3.2. Previous reports published by PIARC

The previous reports published by PIARC concerning the surface impacts of road tunnels relate only to construction issues and environmental aspects of the air pollution [9] *PIARC 2008R04 - Technical Committee on Road Tunnels – "A guide to optimising the air quality impact upon the environment for road tunnels"* .

The other topics mentioned in the present report have not been analysed.

3.3.3. Main consideration

3.3.3.1. General Context

A preliminary design and sizing of the ventilation system must be done to identify the equipment and structures required on the surface along the alignment of the underground complex infrastructure.

These facilities situated in open air might have a serious impact. Therefore, the earlier the problem is known, the faster the solution can be formulated and discussed. For this reason, it is essential to start such analysis at the initial stages of the project.

It is also important to evaluate the investment and operation costs, by doing cost-effectiveness assessments for any of the various alternatives to justify the economic feasibility of the infrastructure.

The main ventilation facilities that may have an impact on the surface are situated at tunnel portals, at the ventilation buildings and the shafts. The main difficulty for the location of these facilities is to find the appropriate site. The decision process for finding the proper location shall be based on urban constraints, as well as on the key issues described section 3.3.4 below.

3.3.3.2. Urban Constraints

A detailed analysis of existing constraints in the neighbourhood of the ventilation plants is essential. This analysis must be carried out in the earliest stage of the design to avoid unforeseen issues which could then have an impact on the general deadline.

A priority is a detailed survey of all the information and constraints in the area under consideration:

- as-built drawings must be collected to have a good knowledge of the existing buildings and their foundations,
- the situation of the Services Utilities or of other underground infrastructure (as sewage or other tunnels).

This investigation, which requires to involve the Utility Service companies upstream, allows either to confirm the location of the ventilation structures, or to define the modifications to apply to these structures, or to remove the existing underground networks. In case this is not possible a change of the alignment or of parts of it might be required.

A tight coordination between the project teams in charge of the alignment, the ventilation and the urban infrastructure, is required to achieve the best solution through an iterative process.

Land acquisitions and demolitions of existing constructions may be necessary. Hence it is importance to have close consultations with communities and stakeholders to achieve consensus for the project, as in most cases administrative procedures and lengthy deadlines are needed.

3.3.4. Environmental, health & safety issues

The environmental impact, as well health and safety issues, are main factors to be considered when choosing the location of the ventilation shafts.

The designer must consider the appropriate solution for the polluted air being released to avoid unacceptable negative impacts to local air quality, the health of the neighbouring communities. He also must consider toxic gas releases in case of fire inside the tunnel and their impact for safety of inhabitants. An Environmental Impact Assessment (EIA) with the participation of all stakeholders is required.

A cost / benefit analysis including energy consumption should also be carefully considered.

3.3.4.1. Air Quality

Different strategies might be considered for reducing the impact on the air quality:

- ***Tunnel air dispersion techniques***

The aim of the dispersion techniques is to enhance pollution dispersion and, in the process, to reduce its concentration in the air.

One application of the dispersion technique is to design a stack and to discharge the polluted air at the top of the stack. The stack height is defined by the height of the surrounding buildings to avoid negative downwash effects of pollutants due to the constructions and the terrain relief.

Another option is to design grilles placed at a certain height. Some regulations outline the need of having the grilles some meters above the ground to avoid annoyance for the people walking on the streets from receiving the forced and contaminated air. In this case, the strategy to increase the dispersion would be to achieve a quite high vertical extraction velocity of approximately 8 to 10 m/s by using the positive effect of the momentum of the tunnel air jet.

The dispersion strategy is the one that presents the highest impacts over the surface. For that reason, it is worthwhile to explore the other air dispersion strategies as described below.

- ***Dilution of contaminants***

This strategy must be considered during the ventilation design phase. An increased flow of the incoming air provides a better dilution of the pollutants and subsequently reducing the concentration level within the tunnel as well as at the portals and/or stacks. Capacity of the fans must be increased to obtain an adequate dilution of the contaminants under an acceptable level at the location of the portals and/or the ventilation shafts.

- ***Contaminant removal technology (tunnel air cleaning).***

Currently, the existing technologies cover the treatment of small particles and NO_2. Those technologies are already described in the report *[9] PIARC 2008R04 - Technical Committee on Road Tunnels – "A guide to optimising the air quality impact upon the environment for road tunnels".*

Such systems allow for the removal of pollutants from tunnel air. Hence, they might optimise the sizing of the ventilation system. However, such systems have a high electrical power consumption, and their maintenance and operation costs are very high.

3.3.4.2. Noise impact

The EIA (Environmental Impact Assessment) must also discuss the noise component. The land-use plan fixes the limit for acceptable noise levels conforming to the existing legislation in the country aligned to the facility in use: schools, hospitals, residential and industrial areas, or others.

Special attention should be paid during the design phase to ventilation systems and buildings to comply with these norms. Sound attenuators should be installed to limit the noise levels from fans within the urban area.

3.3.4.3. Architectural integration

The ventilation buildings often have a significant visual impact on the urban landscape. It is therefore advisable to appoint a team of architects to develop the most appropriate solution from an architectural point of view. This aspect of visual integration in urban space is generally fundamental during the consultation with communities and stakeholders. It must be presented in the form of sketches using numerical models

3.4. VENTILATION STRATEGY - CONCEPT – DESIGN

3.4.1. Key issues

The chapter highlights the special aspects and considerations which must be considered in the design of the ventilation system for complex tunnels. They are characterised by various issues that in most cases do not simplify the design and the operation of ventilation systems. Entrance and exit ramps, intersections or connections to other subsurface structures like car parks often result in a complex aerodynamic system.

Complex tunnels are in most cases a subsurface network of connected tubes. This results in a connected aerodynamic system with strong implications on ventilation design and operation.

Limitations in space (in the open air and in the underground) within urban areas very often require special solutions for ventilation systems. Combinations of various ventilation systems are often used or even mandatory to fulfil the requirements for tunnel ventilation.

Often the network has been built over the years with successive additions of connections and extension of the existing underground infrastructure. The ventilation systems are then often juxtaposed or multiform of different ages and designs and comply to different standards or technologies. Their homogeneity and their compliance often raise many questions.

3.4.2. Previous reports published by PIARC

Ventilation issues of urban tunnels have been published in various reports of previous PIARC working groups. Most of the information in these documents are given rather on a descriptive and qualitative way. It concerns:

- for fire and smoke control:
  - [4] *PIARC 1999 - Technical Committee on Road Tunnels – "Fire and Smoke Control in road tunnels (Report 05.05.B)"*

  - [5]. *PIARC 2007 - Technical Committee on Road Tunnels – "Systems and equipment for fire and smoke control in road tunnels (Report 05.16.B)"*
- operation strategies for emergency ventilation:
  - [6] *PIARC 2011R02 - Technical Committee on Road Tunnels – "Operation Strategies for Emergency Ventilation"*

3.4.3. ventilation strategy & design for complex networks

3.4.3.1. Reminder of ventilation principles

The following ventilation principles are generally used for road tunnels:

- Longitudinal ventilation systems are generally appropriate for unidirectional traffic with few or no congestion. It may also be acceptable when the fire risk is relatively low, e.g. when heavy vehicles are not allowed in the tunnel.
- Massive smoke extractions are a valuable additional system to longitudinal systems when traffic congestion is frequent. They effectively subdivide the tunnels into shorter, aeraulically disconnected sections. The spacing between massive extractions are generally in the range of 500 m to 800 m. A 500 m tunnel section is emptied in 3 minutes if the average speed of the traffic is 10 km/h, and fires do not generally reach a significant size in that time. However, massive extractions can be very costly for deep tunnels or if the real estate is dense at the surface. Furthermore, they may not be sufficient if the traffic is completely blocked inside the tunnel.
- Transverse ventilation system is the most adaptable concept. It can be used for smoke extraction and to keep the smoke stratification in the case of blocked traffic. It may also be operated in a simpler and more robust way to create a longitudinal airflow when traffic is free flowing. However, it is the most complex and expensive system to build and to operate.

3.4.3.2. Specificities for complex tunnels

In complex networks, the usual ventilation concepts must often be adapted or combined. The interactions between the various components of the network should be analysed extensively.

The design process is most of the time iterative for a complex network. This process starts with the general definition of a ventilation concept which must be consistent with the expected traffic conditions. As already discussed, an appropriate safety margin should be used for facing possible traffic congestion or traffic blockage.

The ventilation strategy for emergency operation requires to be closely analysed with the fire department to optimise the access route for fire engines as well as the conditions for evacuation and fire fighting in all sections of the tunnel complex.

In complex tunnel networks, a particular attention must be paid on the fact that smoke control may be less effective at junctions (and roundabouts) and in large open areas. In addition, it may not be feasible or cost-effective to provide a ventilation system that achieves tenable conditions indefinitely. Rather, it may be necessary to estimate the available safe egress times provided by the ventilation system in comparison with the required safe egress times for evacuees, in order to demonstrate that there is an acceptable margin of safety.

❖ ***Normal operation***

The normal operation mode is driven by the targets of internal air quality and environmental issues. Special precautions must be taken to minimise traffic congestion and to subsequently reduce the risk of accidents and in-tunnel pollution levels.

A further aspect of normal operation concerns pollution management at portals (see chapter "Impact on the surface").

Due to the complexity of the network, there are often different ways of achieving objectives of the ventilation in normal operation (e.g. required velocity of longitudinal airflow can be achieved by different jet fans in different sections at minimum operation costs, etc.). This may require the installation of expert systems to effectively monitor the operation and meet all the environmental requirements. *[6] PIARC 2011R02 - Technical Committee on Road Tunnels – "Operation Strategies for Emergency Ventilation".*

❖ *Emergency Operation*

The control of smoke propagation in the case of fire and the mitigation of the negative consequences represent a big challenge in a complex underground network. A clear consideration of the various tunnel sections must be accomplished to avoid or to control smoke movement throughout the whole tunnel network. The presence of multiple connected tunnels brings more complexity in the smoke management process. Theoretically, physical separation between different branches of the network would be the simplest solution to revert to a standard, one-tunnel problem. However, this is often unfeasible or unreliable, since blocked vehicles could prevent the setting up of the separation device, and by the way the emergency services may need to use one of the branches to get into the tunnel. Most of the time, one must therefore control the airflow in the whole network.

Smoke management in tunnels mainly relies on controlling longitudinal air velocities, and in the case of several branches, the aerodynamics (velocity and direction) in these must also be considered. Usually controlling the air velocity is required when certain parts of the tunnel need to remain smoke-free or when the smoke stratification must be preserved.

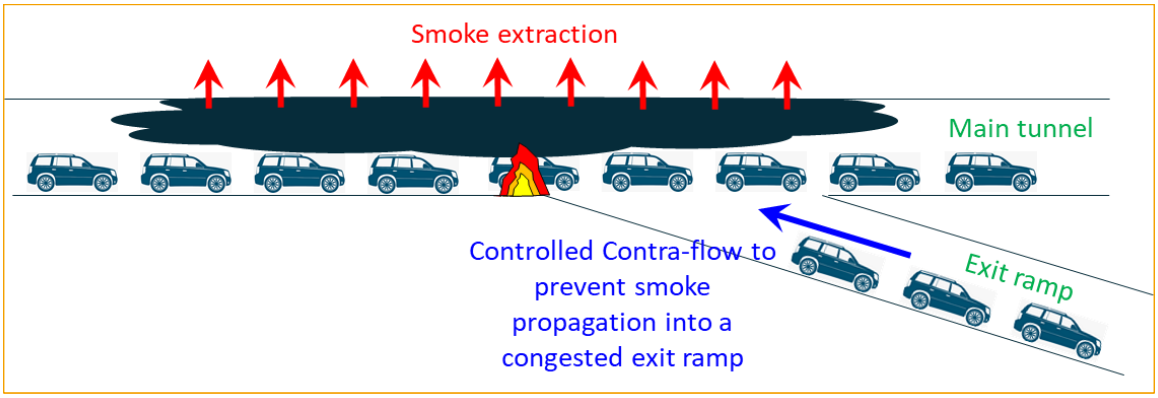


Figure 5 – Example of ventilation strategy in case of fire in a tunnel with a congested exit ramp downstream the fire

Additionally, possible exceptions to general strategies must also be defined. For instance, in case of a fire inside a unidirectional tunnel near the entrance portal, it would make under certain conditions sense to direct the smoke towards this entrance portal.

❖ *Interaction with neighbouring structures*

The structures which are directly connected to the tunnel, such as underground car parks, service tunnels or unloading bays, must be considered when designing the ventilation system. Such facilities are often under the responsibility of a different operator than the tunnel and must comply with other regulations. Therefore, physical separation (e.g. doors, air curtains, etc.) and independent ventilation systems, at least for emergency situations, are preferable to avoid legal and technical issues. If this is not feasible, the neighbouring structures must be considered as parts of the tunnel network, and vice versa.

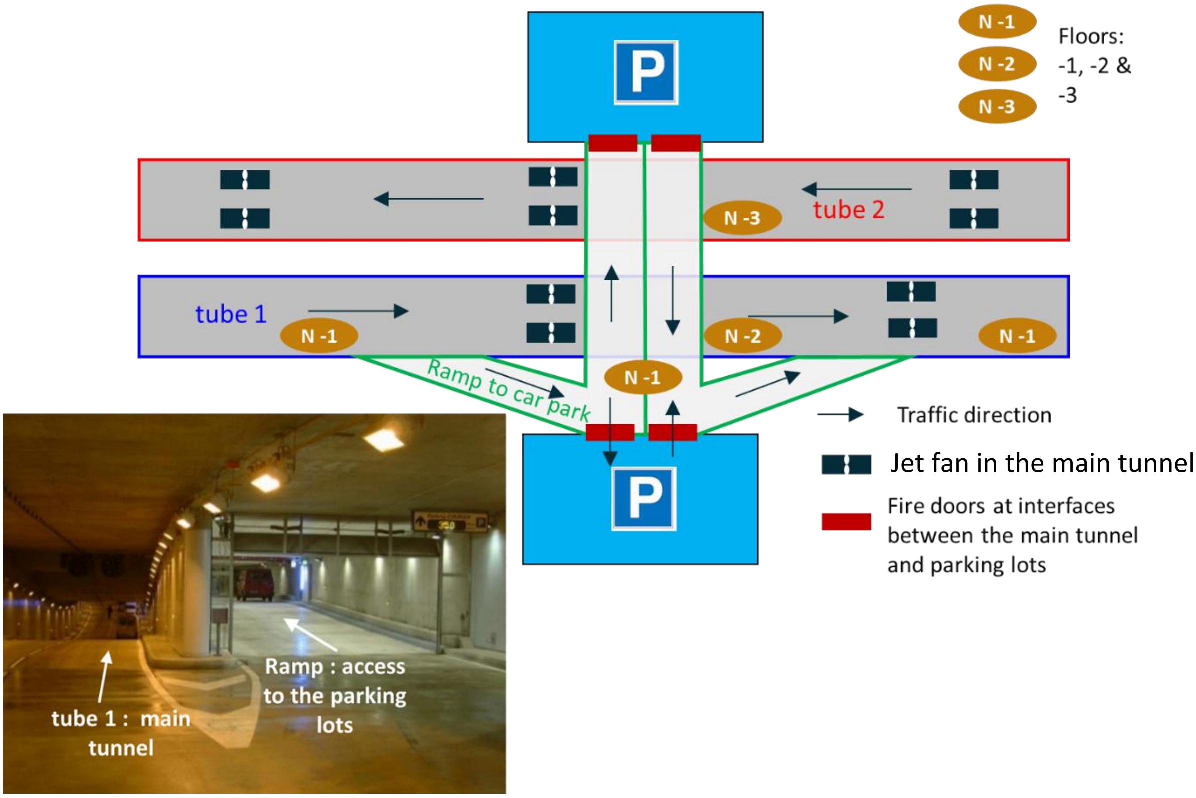


Figure 6 - Example of Courier Tunnel in Annecy (F) including interfaces with parking lots equipped with fire rated doors

❖ *Limiting factors*

Achieving acceptable “Reliability, Availability, Maintainability and Safety” (RAMS) including the complexity of the system should also be considered in the design process.

Degraded modes need to be analysed (loss of selected fans, etc.). It requires to refer during the design stage to Minimum Operating Requirements without waiting on starting of the operation period. The level of redundancy required is usually higher for an interconnected network. However, the RAMS requirements and procedures are not different from any other tunnel.

3.4.4. Ventilation control philosophy

The complexity of these tunnel networks leads to more stringent requirements for the ventilation control and management. Special attention concerning the ventilation control should be given at the stages of design, testing, commissioning and operation.

When considering complex interconnected infrastructures, the use of simulation tools (for example, tunnel simulator) should be considered. Through simulations it is possible to analyse different strategies for ventilation's control system for facing a variety of fire conditions. In addition, it could provide to the tunnel operators (in a reasonable amount of time) the opportunity to observe the effects it has on the conditions in the tunnel. Furthermore, possible flows in the implementation of the control procedure can be detected early and corrected. Simulations may also reduce the time of the testing and commissioning stages, since it is possible to perform sample tests. Furthermore, upgrades or retrofitting of the tunnel equipment over its lifetime can be simulated and refined before their final deployment.

More complex algorithms need to be implemented in the control system (programming issues), probably requires pre-defined modes (combinations of fans/dampers/etc.). An automated management of the ventilation system through pre-defined ventilation modes for emergency ventilation is particularly recommended. Nevertheless, for the firefighting stage, specific ventilation modes could be required by the fire brigade according to their own firefighting strategy. All switching options, including the option to deactivate the ventilation, must be clearly defined and as simple as possible to select. Furthermore, the smoke management strategy must consider not only tunnel branches but also any possible connected underground infrastructure in which people may be present (for example, car park), to prevent their endangerment through smoke spreading.

More difficulties may arise during testing and commissioning – it needs to cover separate sections and combinations of sections and the tunnel system as a whole. The correct execution of all necessary tests can be very time consuming.

The ventilation control can be based on different strategies *[6] PIARC 2011R02 - Technical Committee on Road Tunnels – "Operation Strategies for Emergency Ventilation".*

The closed-loop control of the longitudinal velocity in a network requires air velocity monitoring and active equipment, such as jet fans, in almost all the branches.

The open-loop control may be a choice for simple situations. However, it must be considered that any changes in air and smoke propagation velocity which might result e.g. from cars leaving the tunnel, changing buoyancy forced or external wind pressure, cannot be considered properly.

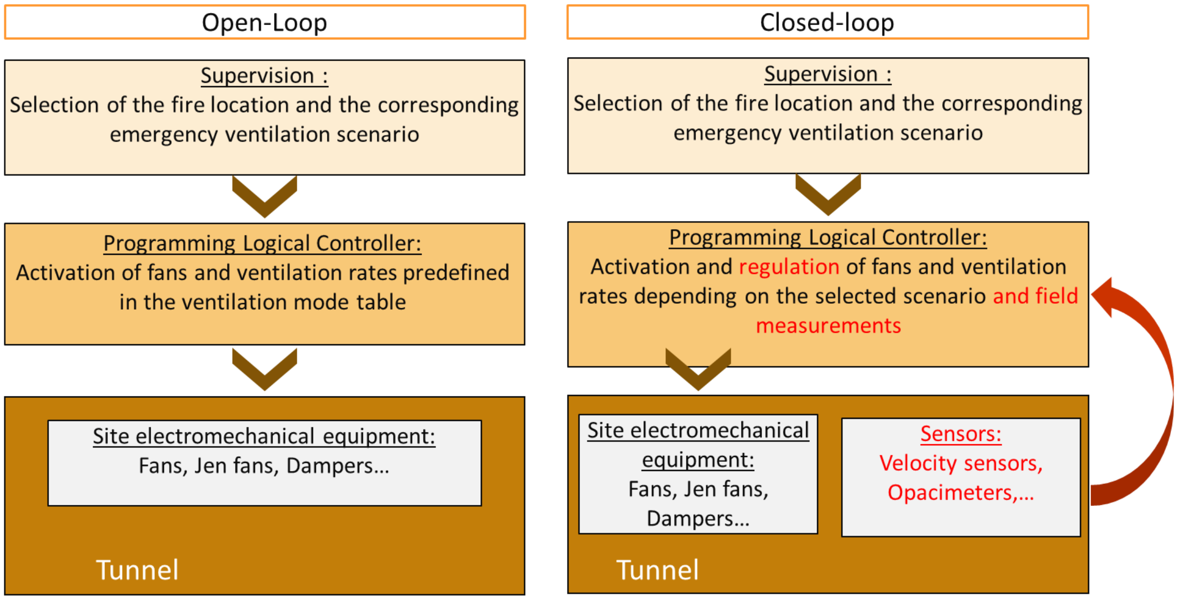


Figure 7 - Illustration of open-loop versus closed-loop control of the ventilation system

The sensors' specifications, which are used for ventilation regulation are more advanced and their incorporation in the tunnel monitoring system can be complex. For instance, in case of flow velocity regulation, plausibility check of the anemometers' reported values must be performed.

The conditions inside the tunnel associated with the ventilation regulation must be synthesised and clearly displayed. They are essential for the implementation of the ventilation monitoring. For example, the current operating mode of ventilation, the status of each fan, the airflow direction and its velocity, the traffic condition, the position of a possible fire, etc. must be clearly displayed. The options available to the operators must also be unambiguously presented.

3.4.5. Design tools

The design tools are numerical models and it is generally indeed not possible to analyse the aeraulic behaviour of interconnected tunnels using algebraic formulas.

The one-dimensional models are very useful to analyse the general behaviour of the network, considering all branches and ventilation devices. They run very quickly even for large systems, and therefore they enable detailed sensitivity analyses. The robustness of the ventilation concept can be assessed for various boundary conditions, the fire power, etc. A one-dimensional analysis of the global aeraulic behaviour of a tunnel network should always be performed.

Three-dimensional models are necessary for investigating some phenomena. The topics for which a 3D analysis can be valuable include:

- the detailed assessment of the local conditions in case of fire, especially the smoke stratification,
- the evaluation of the local pressure losses at tunnel junctions and other singular points,
- the evaluation of the boundary conditions at the tunnel portals (pressure due to external winds).

The three-dimensional models are powerful but complex tools which require a good understanding of the physics and the various modelling approaches used in the software. When 3D calculations are performed, the minimum requirements for quality insurance for such applications – like the independence of the result of the calculation according to the mesh definition - must be proven. In most cases a full 3D CFD (Computational Fluid Dynamics) calculation of a tunnel network is not useful, as most of the sections within a tunnel network have a one-dimensional flow behaviour.

Sometimes a combination of 1D - 3D approaches might be helpful, using the results of a 3D calculation of some critical tunnel sections as boundary conditions within the 1D model and vice versa. The use of appropriate boundary conditions is crucial to perform a physically valid analysis. The difficulty is that the “right” values are often difficult to evaluate precisely. The influence of the wind at the tunnel portals is a good example of that. For this reason, it is generally appropriate to run sensitivity analyses for the most important and uncertain parameters (portal pressures, fire power, etc.). These analyses may lead to a complete redefinition of the ventilation concept if the initial one does not achieve a sufficient level of robustness.

3.4.6. Recommendations

To sum up, the following topics should be considered:

- The ventilation concept must be based on realistic assumptions especially regarding the traffic congestion and traffic pollutant emissions. The uncertainty of these assumptions should be kept in mind. Moreover, the design of the ventilation system should be considered with the available assumptions at the design stage and then as it might evolve over time.
- In a complex tunnel network, the ventilation concept can differ from those of other tunnels. They sometimes could be a mix between different solutions including specific technologies. Appropriate design tools must be used.
- The process should be iterative during the whole design stage to consider all the constraints
- Due to the complexity of the ventilation system, the testing and commissioning before opening for operation require more time.

As the complex aerodynamic behaviour of the tunnel system makes the ventilation control in case of fire more complicated, additional provisions must be seriously considered, like increasing the number of escape routes or supporting systems like FFFS (Fixed Fire Fighting System). *[10] PIARC 2016R03 - Technical Committee on Road Tunnels – “Fixed Fire Fighting Systems (FFFS) in road tunnels: Current practices and recommendations”.*

The design and development of a ventilation control system for a complex underground network presents many technical and organisational challenges. Although the main steps for designing the ventilation control system are the same as for a standard tunnel (namely the object description, determining the ventilation goals and actions towards them), in practice the increased complexity of the system can make the process very demanding. Besides the technical issues, organisational aspects must be considered in the case where underground structures such as a car park, subway stations, etc. are connected.

The use of simulation tools is recommended with regard to the increased effort required to establish a satisfying smoke management process and the demanding requirements on the tunnel operators. The current tools and methods allow modelling of complex underground systems, which can be proved to be indispensable to quickly optimise performance, to discover and correct weaknesses within the system, and to assist in the education and the training of the operators.

3.5. Procurement and Implementation

The procurement and the implementation of the equipment are not specific to the complex underground networks. However, their impact is more sensitive due to the complexity of the systems, the number of the equipment, the interfaces and interactivities.

Furthermore, there is no PIARC recommendation published concerning these issues that become particularly important concerning the reliability, the availability and the time live of the equipment and the systems.

3.5.1. Preamble

The ventilation system of an interconnected underground road network is generally quite complex due to:

- the complexity of the network itself, with its many branches and interfaces,
- the network often being built over the years with successive additions of connections and extension of the underground sections. The ventilation systems are then often juxtaposed, multiform, of different ages and designs. They often comply to different standards or technologies, and their compliance often raises many questions.

This complexity and the multiplicity of the subsystems require that each piece of equipment or subsystem constituting the ventilation installation be reliable and has the required performance, consequence being that the overall operation will be unbalanced, inefficient and unreliable.

3.5.2. Recommendations

In order for the implementation and operation of the ventilation system to be a success, several precautions and fundamental requirements need to be meticulously reviewed during the following stages:

- Tender procedure - Choice – Drafting of the contract,
- Manufacturing of the equipment and materials,
- Implementation on site,
- Preparation of operating procedures,
- Education and training.

3.5.2.1. Tender stage

Over the years, a decline in the quality and the life span of the ventilation systems and components can unfortunately be seen. The life expectancy of the ventilation facilities, which could reach more than thirty years (subject to normal regular maintenance), was reduced by half if not more under:

- the pressure of the recurring race to " Low Cost" during the tenders,
- the continuous pressure of the main contractors on the suppliers of the equipment,
- the owner's lack of consideration towards the life span of the equipment, its maintenance costs and constraints, the consequences on the users and the expenses related to any heavy maintenance or replacement of equipment under traffic. A saving of about 25% on the supply price of the equipment is absorbed after a ten-year operational period which subsequently grows to a cumulative cost of more than four times the initial saving for the owner at the end of a cycle of thirty years of operation. These figures do not consider the expenses imposed and supported by the users.

Although this is not specific to the ventilation system of a complex network, it is emphasised by the complexity of the systems, by the multiplicity of the equipment and by the fact that the failure of a single component affects the reliability of the whole installation.

The main recommendations during the tender stage of the ventilation systems are:

- A very accurate definition of the objectives, specifications, performances, life expectancy and guarantees required must be defined,
- The tender’s offer must include (under penalty enforcement for non-compliance) very accurate details and irreversible commitments about the suppliers of equipment: (i) their names and references - (ii) their quality standards and specific quality control procedures – (iii) the justification of the lifetime of the components and commitment concerning the availability of their spare parts more than 10 years after the commissioning.
  Note: the competitors are often reluctant to take this commitment. They prefer to remain vague and provide a list of potential suppliers in order to be able to better negotiate with them at a later stage. This cannot be accepted because the quality, the performance and the lifetime of the installation are essential and depends on the quality of the supply,
- It may be advisable to undertake very detailed technical visits to the main suppliers (fans, engines and other technical utilities) to audit their control procedures, test benches, aeraulic equipment like fans, engines and other technical utilities. Then, if necessary, to contractually impose modifications in the manufacturing and control procedures. Check carefully the test benches for all the aeraulic equipment, particularly for the fans,
- Project owners are required to acquaint themselves from possible important discrepancies made during the tendering Process. This may include heavy repair costs, maintenance and life cycle costs which will impact the overall cost of the project.
- The contract must make provisions to cater for all additional commitments made in writing by all Parties during the negotiations, tender clarifications, technical visits, additional commitments and others to minimise the risk of unnecessary open discussions after the award.
- Ensure that all the provisions of the agreement are fully enforced during the implementation phase of the contract. Define precisely the contractual rules in the event that the performance would not be achieved: refusal of the material, possible reduction of the price, etc.

3.5.2.2. Manufacture of the equipment – Factory Acceptance Tests

The main recommendations are as follows at this stage:

- Visa by the owner of the "Technical procurement Specifications" that is prepared by the contractor mandatory before being sent to the equipment supplier. The review of these documents often reveals deficiencies or inconsistencies in relation to the technical specifications of the main contract,
- Require the transmission of the detailed manufacturing programme, the monthly production progress and the updates,
- In order to prepare the performance tests at the factory, and the procedures for the acceptance of the equipment, require and review all the test procedures and their methodology in due time,

- Attend the essential factory tests and the reception of the equipment in the factory before the material is sent to the implementation site. That includes all tests relating to the control of the aeraulic characteristics. Tests of this nature can only be carried out at the factory on the manufacturer's "Test benches". Control and sign the factory acceptance tests of the equipment, decide on the nonconformity if any and the follow-up to be given from the contractual point of view. *Note: These tests quite often show underperformance of the equipment whose compliance can only be carried out at the factory*.

3.5.2.3. Implementation on site - Site Acceptance Tests

The main recommendations at this stage focus on the functioning of the installation and its overall performance.

The ventilation system was essentially sized based on the numerical model results, and the simulation calculations. It is thus essential to carry out extensive and detailed tests to be able to check the overall performance of the installation in relation to its theoretical sizing. These tests must cover all aeraulic aspects, as well as smoke management tests in relation to low-power reference fires.

These tests require time after the complete installation of the equipment and its settings. They must include many aeraulic measures in all branches of the network. The global construction schedule and the deadline must incorporate the necessary duration to carry out these tests in a rigorous and complete way. These tests may not be botched or superficially performed. They are indispensable for checking all the assumptions of sizing, for measuring the actual performances of the installation, and for a better understanding of the system and its reactions from the future operators.

3.5.2.4. Operating Procedures

The ventilation system of an underground network is complex, and there are numerous scenarios likely to be used during its operation, especially in case of traffic congestion and fire. The choice of the right scenario requires skills and an aeraulic understanding of the system often more advanced than those of operators or firefighting teams especially when they are placed in a stressful position during a fire.

It is therefore essential that the designer of the ventilation system analyses multiple conditions that may occur in the network and prepare as many scenarios for the activation of the ventilation in response to these conditions. These scenarios must consider the actual performances of the installation measured after the on-site tests. Given the large number of conditions, it is essential that the ventilation system be equipped with an expert system suggesting the right scenario the operator should activate. This expert system can be supplemented with a simulator, allowing the operator to model and visualise the forecast evolution of smoke conditions simultaneously.

The choice of the right scenario and its activation can be left to the operator's decision or not, in order to give him more time to manage the tasks he must achieve in the event of a fire. It is an organisational decision which is the responsibility of the owner, depending particularly on the complexity of the system and the competence and skills of the operators.

The evolution of systems based on “Artificial Intelligence”, and the associated analytical capacity should lead to an increasingly automatic consideration of the scenarios to be activated for the ventilation in the event of a fire. It should be borne in mind, however, that the operator must be trained to be able to handle operations in the event of a failure of an even redundant automatic system.

3.5.2.5. *Education and Training*

The ventilation system of a complex underground network, all the possible interfaces with other associated infrastructure, and the potential multiplicity of operators, requires:

- A perfect knowledge of the site, the equipment and the ventilation by all the teams involved,
- A good knowledge of the performances of the systems,
- For the operators, a perfect knowledge of the procedures, scenarios and tools at their disposal to drive the ventilation system under normal operating conditions, as well as under «minimum operating conditions" in case the system is temporarily degraded.
- The operators and the emergency teams (firefighters) must be educated and trained in a programme specific to each team's nature, mission, and particularities of the network. Tools must be developed to allow this basic education and then the continuous training, including:
  - A BIM (Building Information Modelling) virtual model describing in 3D the geometry of the network and its equipment,
  - A ventilation simulator allowing operators and firefighters to better understand the ventilation system and simulate fire and smoke scenarios.

Picture 5 - Fire tests

Picture 4 - training of the firefighters and the emergency services

4. SIGNALLING

4.1. LOCALISATION OF AN INCIDENT

4.1.1. Issues associated with the complexity

A complex network of underground infrastructures contains generally numerous branches of the road section, junction points (ramps or interchanges), connected infrastructure, buildings or facilities served by the road network (like underground car parks - shopping malls – towers for offices or habitation). It can also include numerous interactions with other multimodal infrastructures (bus station - tram or rail tunnel and station).

The interactions are numerous between these various infrastructures in particular in case of an incident, of accident or in case of fire. These infrastructures, often built at different times, are managed under the responsibility of several operators. These operators, with varied human resources or heterogeneous systems and tools, can be classified in three families:

- The operators of public road or railroad infrastructures of transport, with full-time or part-time service,
- The operators of networks (traffic management – public transportation), who are only present during the period of operation of their network,
- The operators of underground car parks or of the other partly underground infrastructures (like parking lots or logistic services of shopping malls, apartment buildings or office towers), served by the road network, whose presence is generally limited to the business hours.

Three actions are essential to manage an incident:

- a - detection and definition of the location of the incident with a high accuracy,
- b – addressing system and transmission of the information concerning the location and the particular conditions,
- c – choice of the process for intervention - coordination of the actions – monitoring of the intervention.

The sections 4.1.2 and 4.1.3 concern bullets (a) and (b). Additional information concerning the bullet (b) as well as the bullet (c) are developed in the section 5.1 “Organisation”.

4.1.2. Detection & accuracy location

4.1.2.1. Detection and location

The detection modes depend on the nature of the infrastructure, and the nature of the event as synthesised for the following three infrastructures:

Road infrastructure	video	AID	Patroller of the operator (1)	Alert of the users by emergency phone	Alert of the users by GSM (2)	Heat detection cable	Sensors of smoke detection	SOS system inboard of the vehicles (3)
breakdowns	X	X	X	X	X			
collisions	X	X	X	X	X			X
fire	X	X	X	X	X	X	X	X

Table 3 – Road - detection system related to the nature of the incident

Note:

- *AID: automatically incident detection*
- *GSM: Global System for Mobile communication*
- *GPS: Global Positioning System*

Car park accesses	video	Alert to operator by park users	Fire detection system	Sensors of smoke detection
breakdowns	X	X		
collisions	X	X		
fire	X	X	X	X

Table 4 – Car park - detection system related to the nature of the incident

Rail infrastructure (light train – underground)	video	Driver – system inboard of the vehicles	Heat detection cable	Sensors of smoke detection
breakdowns	X	X		
collisions	X	X		
fire	X	X	X	X

Table 5 - Rail - detection system related to the nature of the incident

Operators of public transportation systems, which vehicles are using a third-party infrastructure, receive information mainly from drivers as well as the inboard vehicles system.

Note: the following comments could be added for some detection methods identified in the tables above:

- *(1) - it is essential to implement a tracking and marking system enabling the patroler to locate the incident reliably. The location can also be provided by GPS inside the structures equipped with a system ensuring a continuity of the positioning by GPS in the underground (technology under development and testing).*
- *(2) the information given by a user makes possible to identify and, if any, to characterise an event. However, it does not locate it with certainty, failing for the user to be able to establish his position certainty and precisely inside the network, despite the signalling.*

- *(3) - more and more vehicles are equipped with "call of distress" systems, allowing automatic triggering transmission in case of accident, or a manual call by the user. These calls are sent to rescue centres. The GPS location of the vehicle is broadcast automatically. This requires that the GPS positioning can be identified (see note 1 above)*

4.1.2.2. Technology for detection and location

The operating and safety equipment installed in the infrastructure allow for a more precise location of the incident. Some equipment may give general preliminary information, which requires to be refined by the operator using other facilities available to him.

The most commonly installed detection equipments are described in various reports or technical recommendations of PIARC. See the PIARC virtual library:

https://www.piarc.org/en/publications/search/

In a complex network, in order to determine the exact location of the incident, the detection equipments have to be denser particularly in areas of interfaces (divergence or convergence of ramps - entrances and exits of car parks - underground stations) and then to make it possible to implement the actions associated with this position as well as with the nature and the gravity of the incident.

4.1.2.3. Address of an incident

After detecting an incident, it is essential to locate and assign a "precise address" identifiable unambiguously by all the services (operator, emergency teams, police, fire brigade, towing trucks).

Generally, for a linear infrastructure, the "address" is defined:

- by the name of the tunnel tube and a distance from one of the two portals. Many tunnels have a hectometre marking on the wall, for the use of the operator, teams of intervention and the users,
- by giving the position between two emergency recesses. The recesses are identified by a number painted on the tunnel wall.

In underground car parks the “address” is in general the number of the floor, the name of the aisle and the number of the parking place. These are marked on the floor or on the walls. The different areas are often associated with a colour or pictograms. These allow for easy location by the user.

In a complex network, the referencing may be reasonably complicated by nature. It is essential to make it understandable, legible and unambiguous for users and stakeholders.

❖ GPS address

It is unquestionably the most accurate addressing mode. However, it requires that:

- the continuity of GPS positioning is ensured in the underground network. This is currently not the case, but this technology will be available in the short term,
- all emergency teams (vehicles and personal) are frequently equipped with a GPS system.

The advantage of this addressing mode is to facilitate the transmission of information to all operators as well as assistance to emergency teams. It also facilitates the preparation of interventions followed by their actual effectiveness on the site.

❖ «Conventional » addressing mode

The most common addressing mode mentioned as “current positions” above can be used for a complex network by applying the following principles:

➔ ***A - The road network infrastructure is broken down in three subcomponents,***

namely branches or sections, the direction of the flow and areas of merging or diversions. Details of these are:

- **A-a - in branches or sections.** This refers to the structure of the network arborescence. The position within each branch (or section) is defined by the distance from the origin of the branch concerned in the normal direction of flow. The signage on the tunnel walls is essential for providing guidance to tunnel users, operators and other emergency teams. For example, the marking could be made by any of the following methods (*see Figure 8):*
  - a letter designating the branch (or section),
  - a colour that may be associated with a traffic direction, or a branch,
  - a graphic form (a blue line in the diagram below),
  - a number corresponding to the distance within the branch (kilometre. hectometre),
  - emergency exit signage associated with the marking.

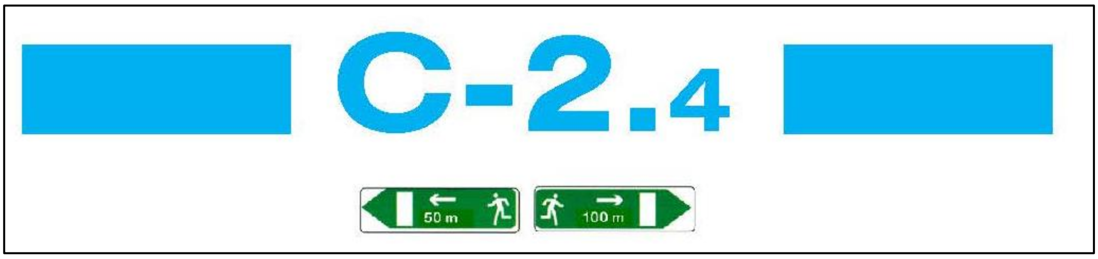


Figure 8 - example of marking within a branch

- **A-b - by direction of the traffic flow.** The branch of the direction 1 is designated by a letter (“C” in the above example). The branch is designated by another letter for the opposite traffic direction ("D" in the example proposed Figure 9).
- **A-c - in areas of merging or divergence.** Each of the areas must be identified, and the corresponding marking materialised on the tunnel walls. For example *(see Figure 9):*
  - ”e.A-E” refers to the exit area from the "A" branch to the "E" branch,
  - “i.F-B” refers to the convergence area and merging of the “F” branch to the branch "B".

➔ ***B - Connected infrastructures***

The infrastructures connected to the tunnel may be defined by:

- their nature and a name (example: "parking 2" or "parking rail station").
- by a specific address (example for parking: floor, aisles, place numbers). The floors may be identified by different colours, while aisles may be defined by pictograms instead of alphanumeric (*see example Picture 6).*

Picture 6 – examples of marking for a car park: Praha – Geneva Cointrin airport

❖ *Example of addressing system inside an underground network*

The diagram of Figure 9 below is just an example of addressing system intended to illustrate some recommendations of the chapters above. Other systems could also be developed.

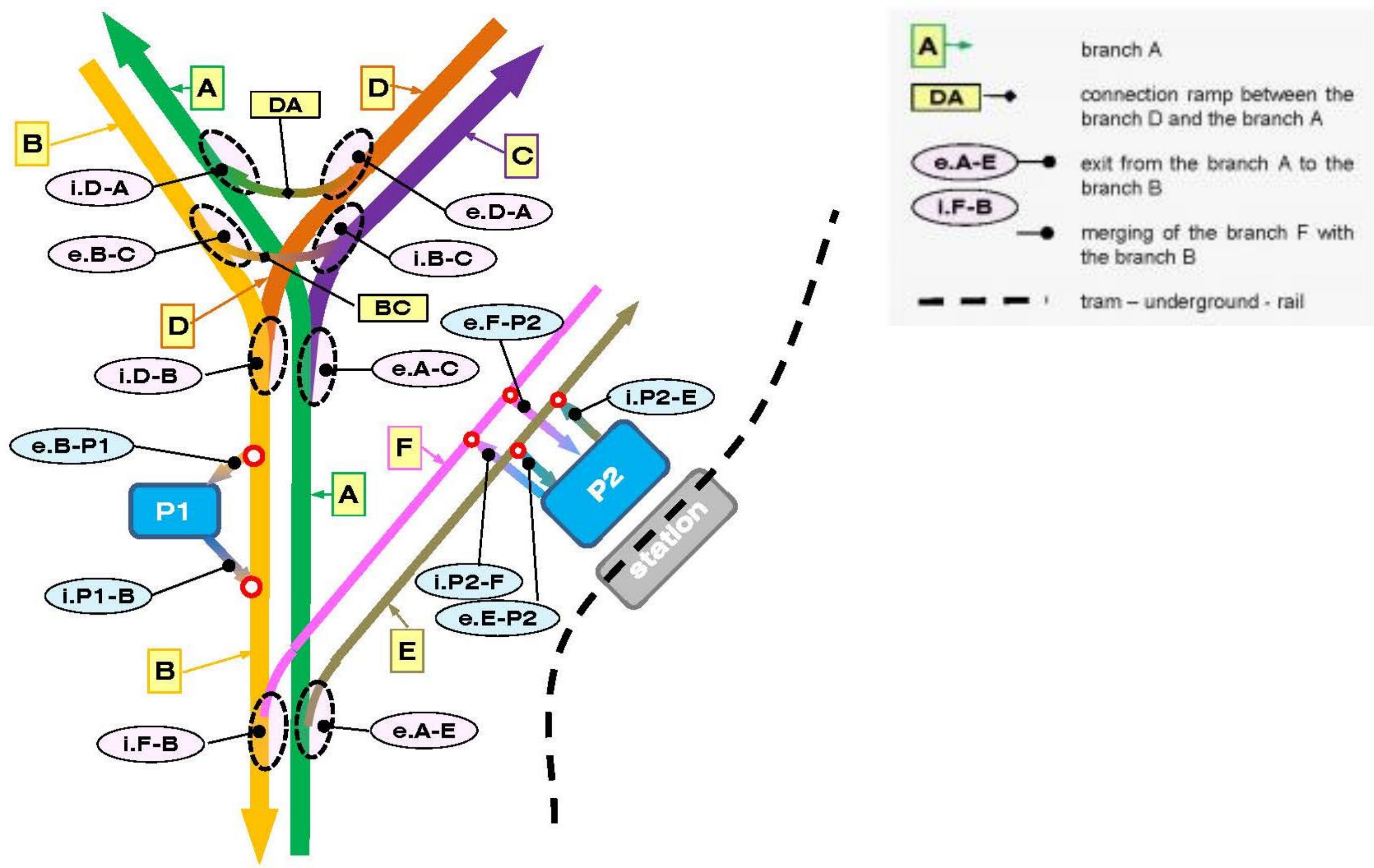


Figure 9 - principle of address for a network

4.1.3. Quality of the information – Transmission & sharing

The contents of this chapter are further discussed in *Chapter 5.1 "Organisation".* In the interim the following recommendations are drawn to outline the flow and transmission of information:

- The dissemination of information must be selective. It must result of a coordinated analysis among all operators, and be established as a flowchart of selective dissemination in accordance with the location and nature of the event, its impact on each operator or stakeholder,

- The information must be concise, complete, accurate and updated on an ongoing basis,
- The transmission mode of the information must be fast, reliable, traceable, and must allow immediate and efficient actions of the different operation and response teams.

4.2. ROUTE SIGNS – VARIABLE MESSAGE SIGNS (VMS)

4.2.1. Key issues

Complex underground road networks must be equipped with an appropriate traffic management system, with the objective of maximising the operationality of these networks, both in extent and in time.

This traffic management system should be designed for the specific traffic conditions inside the network and on both the sides of the tunnel. Apart from general conditions of standard road tunnels, such as closures due to maintenance and incidents, these also include traffic congestion, since these networks are situated mostly in cities.

This more sophisticated VMS system should be able to alert the motorists and tunnel users in advance of the imminent danger/situation, to stop incoming traffic, redirect the traffic accordingly and to divide the tunnel complex in independently operated sections.

The typical issues encountered due to the complexity of the underground structure are, on the one hand, related to the perception and comprehension capabilities of the motorists and, on the other hand, related to the design of the signs, VMS, traffic lights, barriers and the other tunnel equipment. The distance between the signs and the position of the different signs relative to the tunnel geometry and the other tunnel equipment are important factors to assure the legibility of the information.

4.2.2. Previous reports published by PIARC

Several previous PIARC reports mentioned the topic of the VMS and signals in tunnels.

The report *[7] PIARC 2005 - Technical Committee on Road Tunnels – "Traffic incident management systems used in road tunnels" (report05.15.B)* mentions the VMS as an important part of the incident response scenarios to systematically close lanes or redirect traffic to prevent secondary accidents, and in the event of a fire, implement safe and efficient evacuation of motorists. However, the detailed recommendations, which are included in this report, are not given in the above-mentioned report.

Another report *[8] PIARC 2016R06 - Technical Committee on Road Tunnels – "Improving safety in road tunnels through real-time communication with users"* mentions Variable Traffic messages as important devices for alerting the users in case of emergency (in combination with other information sources).

Last report *[1] PIARC 2016R19 – Technical Committee on Road Tunnels – "Road Tunnels Complex Underground Road Networks"* describes traffic conditions in city tunnel networks and discuss origins of traffic congestions.

4.2.3. Some key points about signs & signals in a complex tunnel

4.2.3.1. Human Factors

The difficulties regarding VMS that motorists of complex underground structures are confronted with are the same as in standard tunnels, however, due to the complexity, they are more distinct.

❖ ***User's perception capabilities of the traffic signs and signals***

High traffic density causes an increase in the driver's cognitive tasks. This leads to a reduced driver's perception capability of the traffic signs and signals, which determines the acceptable level of density of the VMS network (the number of and the distance between the signs).

❖ ***User's comprehension capabilities of the messages***

As these complex underground structures are situated mostly in urban areas (cities), a very high proportion of the users will be local, everyday users. For those users, language comprehension will not be a limiting factor.

Nevertheless, it is good practice to use graphic symbols, which are understood independently from language, or to use internationally recognised expressions.

If it is considered necessary to make the announcements in different languages, it is important to consider the number of languages to be used, depending on the type and position of the road communication system.

❖ ***User's reaction time***

In case of a sudden implementation of a traffic restriction (i.e. lane closure, closure of the next section or a closure of an exit ramp) the average driver needs 4 – 6 seconds to change their driving mindset completely.

The variable traffic system, which is implemented to inform the user and to lead them through the incident in the safest way, should be designed in accordance with the needed reaction time.

❖ ***Awareness of everyday users***

Drivers using the complex underground structure on a regular basis, learn the standard operational conditions of the network (during no incident or traffic restriction). This may lead to a situational "blindness", meaning that their reaction time increases significantly or that they do not react to changes anymore. To prevent this from happening, more distinct alerts might be necessary.

4.2.3.2. Interaction with the geometry and the tunnel equipment

❖ ***Positioning of devices***

The location of the VMS devices should be determined depending of their purpose, whether it is to alert the tunnel users of imminent danger, stop incoming traffic, redirect the traffic or divide the tunnel complex in independently operated sections. Placing them in coordinated position with emergency exits may help users to find exits, for example in case of a fire. They should be installed in places, offering the possibility of redirecting the route as well as ahead of these "choosing locations".

Picture 7 - Traffic signs and signals before the intersection (exit ramp)

The horizontal alignment, sighting distances and the presence of other technical installations affect the visibility of the VMS. For example:

- Impact of signs on the ventilation effectiveness (including smoke stratification). In return and vice versa, the reduced ventilation effectiveness may diminish the visibility in case of an incident with smoke development.

Picture 9 - VMS vs. ventilation effectiveness

- Physical conflicts between tunnel equipment such as ventilation fans, tunnel lighting, variable message signs, etc. which can reduce the visibility of the VMS.
- Congestion, traffic jams, disconnection and merging zones of the exit and entry ramps may be dangerous, especially when hidden by bends. They require increased signage, particularly variable signage.

Picture 8 – Ventilation vs. VMS visibility

❖ *Standardisation of the signs*

The graphical and textual messages and the symbols:

- They should at least be standardised across the country (sometimes it differs depending on the road site managers) .
- The meaning should be part of the driver education system.

❖ *Accuracy of the incident detection system and automatic reaction*

If the incident detection system reacts swiftly on an incident, it is appropriate to install an automatic response of the VMS on the base of the detection systems. However, this entails the risk of displaying inaccurate information to the user in case of a false alarm, which could lead to the perception of the VMS as being unreliable.

With the development of events over time, it is possible for a user to receive a hazard report on the route, regarding the position of the reported danger, instead of the cause of the danger.

In case of an automatic reaction on detected incidents, the speed of the information is transmitted and displayed on the VMS is an important factor. The tunnel equipment should be designed and implemented in the way that shortens the total transmission time.

❖ ***Vehicles that queue back into the main tube and their handling by the traffic system***

On tunnel exit ramps or parking entrances, vehicles could queue back into the main tube due to capacity problems on the receiving road in the outside, or inside the parking. The arriving tunnel users should be warned, and the appropriate information should be communicated. It is better to handle this congestion problem and implement temporary detours before vehicles enter the tunnel than to allow traffic jams to increase in front of the saturated exits.

❖ ***Priority and type of traffic information***

Two types of information should be spread:

- Global information from the wider area (the whole city road network)
- Local info from the tunnel network itself.

The displayed information depends on the location of the VMS and of the drivers, which determines the priorities of the messages. General information about the global city road network will have lower priority than local info about incidents in the tunnel just ahead.

The displayed information in the tunnel might also be different from those on the approach road. The priorities should consider not only safety policy, but also sustainable development issues and mobility demands. It is appropriate to ensure continuity with a superior citywide system with appropriate prioritised scenarios.

4.2.3.3. Technical systems, sustaining the spread of information by the VMS

Other technical solutions could be complementary to the VMS to spread the appropriate information in time.

Radio rebroadcast of all frequencies should be generally recommended. One frequency is not enough (in the urban environment with relatively short routes, only a few drivers will switch to the correct frequency; the switching itself could lead to a potentially dangerous incident, since it is a distraction from the driver’s primary cognitive task of observing the road).

Satnav/GPS-based systems – the continuity of GPS could in the near future help to navigate users through the underground network in case of immediate traffic restriction.

Augmented reality – in-car information and navigation systems help to replace or adjust the information of the VMS positioned along the route.

Supplementation of vertical VMS with horizontal light signals is another way of improving the information transfer between the VMS and the user. In the case where number of traffic lanes change or in the case of a closure of the next tunnel section, the traffic stream could be redirected, by changing the way of the horizontal lights function (stable or in sequence).

4.2.4. Conclusions & recommendations: signs & design process

The tunnel networks put increased demands on both the tunnel users and the traffic management. It is necessary to equip the network with information displaying devices that alert the user in advance of the imminent danger/incident and change the transport regime along the route. It is important to have a VMS system that is interconnected across all tunnel network sections. Traffic signs and signals should be placed at sufficient distances; the average driver needs 4–6 seconds to change their driving mindset completely.

Recommendations:

- Perform a human factors evaluation on the effectiveness of the complete system of signing and signalling to check that combination of signs and signals is effective as a whole
- Set clear safety policies and sustainable development demands to be implemented into the traffic regulations (automatic).
- Enhance the driver education systems – i.e. important behaviour during incidents, but also the interpretation of VMS during standard operation.
- Minimise the conflicts between VMS and another technical installation.
- The construction of devices and their features must comply with national and international standards for the devices - considering the light, sight distances, etc.
- Install a clear system for redirection of traffic on the edges (route vs. exit ramps).
- Use additional technical solutions to VMS (re-broadcasting etc.)
- Shorten the time between incident detection and automatic reaction.
- Use warnings only for the users clearly affected by the incident (the users do not need to know about the incident in the parallel tube, etc.).
- Use unified language and symbols.
- Use additional horizontal VMS.

Picture 10 – pre-signalling of an exit (first place) - signalling of an escape with blue underlining (second place) - VMS with the information of a traffic jam (third place.)

4.3. Evacuation aids

4.3.1. KEY ISSUES

This chapter considers key points for the design of evacuation aids for a complex underground road network. These can be critical to support self-rescue by tunnel users in the event of a tunnel emergency.

In most modern road tunnels, the evacuation strategy involves evacuating through cross-connections to a parallel non-incident traffic tube. In some cases, access/egress routes are constructed directly to the surface or connected to the surface through an escape gallery.

In comparison, complex underground networks may include 'non-standard' tunnel configurations that require extra attention. For example, tubes may be spaced further apart at interchanges or there may be single tube branches, and therefore it may not be possible to provide connections between tubes. Wayfinding may be more complicated if there are non-standard or multiple choices of evacuation routes depending on the incident location, ventilation regime and traffic situation. Moreover, due to the multiplicity of infrastructures and operators, coordination is absolutely required to have consistency in evacuation routes and consequently appropriate evacuation aids.

4.3.2. Previous reports published by PIARC

Previous PIARC reports have addressed the topic of evacuation aids in tunnels. The report *[11] PIARC 2008R17 - Technical Committee on Road Tunnels – "Human factors and road tunnel safety regarding users"* considered what measures should be considered in a road tunnel design from a perspective of human factors and human behaviour. Concerning evacuation, the report provided guidance on measures for alerting tunnel users in case of emergencies, escape routes and emergency exits, and measures beyond emergency exits to a final place of safety. The more recent report *[8] PIARC 2016R06 - Technical Committee on Road Tunnels – "Improving safety in road tunnels through real-time communication with users",* deals specifically with dynamic equipment (such as signs, sirens, warning lights, etc.) that can be used to inform and warn users and encourage them to adopt appropriate behaviour in the event of tunnel incidents.

All these recommendations described in those reports have usually been implemented in each individual branches of tunnel networks, but it should be noted that some recommendations might be adapted for the global consistency of the evacuation process.

4.3.3. Evacuation strategy

To guide the selection of evacuation aids for a complex network, an evacuation strategy should be developed to address how all tunnel occupants can readily find their way from their vehicles to reach the emergency exits distributed along the tunnel network, and then to proceed through protected escape routes to final places of safety at the surface. The interaction with the external network at these safety places has to be carefully considered.

The requirements for evacuation aids will depend on the locations of emergency exits. The maximum spacing between emergency exits along road tunnels is dictated by national and international regulations. These requirements can be basically followed in general even for complex underground networks. However, the spacing may have to be reduced according to the results of the risk analysis and the preliminary simulations for escaping.

Particular attention may be needed to coordinate the locations of exits in more complex areas such as at junctions and interchanges, taking account of the number of people that may try to use the exits.

The requirements for evacuation aids will also depend on how evacuation is to be managed. The most common approach is to indicate all emergency exits by means of evacuation aids and to allow tunnel users to make their own decisions on which exits to use. An alternative approach that could be adopted is to direct tunnel users towards specific exits. For example, it may make an incident easier for the tunnel operator and emergency services to manage if all evacuees join in a small number of escape routes rather than exiting the tunnel at numerous locations. This approach may require accurate detection of the incident location (*refer to chapter 4.1 for further details*) and specific evacuation means.

Fire and evacuation simulations are recommended in complex underground infrastructures to assess the adequacy of the evacuation strategy and therefore the design of appropriate evacuation aids. A comprehensive set of possible incident scenarios and locations should be considered. The evacuation requirements need to be considered in conjunction with the emergency ventilation strategy (*refer to chapter 3.4 for further details*).

4.3.4. Recommendations for appropriate evacuation aids

A variety of evacuation aids have already been developed, tested and installed in many road tunnels worldwide including signs, lighting and sound systems, handrails, etc.

Nevertheless, for underground networks, specific issues might be carefully addressed that would require the development of specific aids. Indeed, users need more information than in standard configurations to indicate which way they should head:

- Controllable, illuminated signs may be used, enabling the sign to be illuminated for one direction only. For instance, in UK, specific signs have been implemented as illustrated in Figure 10. These may be useful in more complex situations, perhaps in the vicinity of junctions. An important point to note is that such signs could be thought as active safety critical systems and therefore could add extra requirements for their design, control during operations and maintenance.

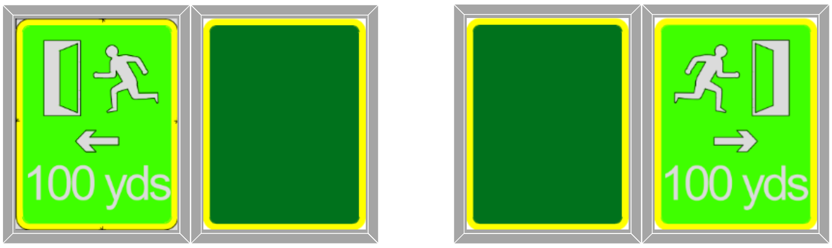


Figure 10 - example of controllable signs with left- or right-pointing side illuminated.

- The standard evacuation signs could also be supplemented when relevant at specific points by information signs to help orientate road users.
- Evacuation routes along non-incident branches of the network may require additional measures, such as 'special' lighting solutions, to assist way finding to distant portals or any other safe area. Th … ces involved and junctio …
- Directional sound evacuation systems (sound beacons) are proven to be effective in dense smoke. They provide audible guidance to direct evacuees towards the exits in a smoke-filled environment. In the complex network, particular attention should be paid to the consistency of various sound messages given to the users in the overall network. Audibility is also a key challenge especially in junction areas where different sound messages may interfere.

Last but not least, it has to be emphasised that the evacuation strategy and the associated requirements for evacuation aids should be determined at the outset of the concept design in conjunction with the development of the traffic management, ventilation and emergency response strategies.

5. OPERATION

5.1. ORGANISATION

5.1.1. General introduction

5.1.1.1. Introduction

This document concerns large complex and interconnected underground road infrastructure networks. It also presents the peculiarities of these large infrastructure networks, but not the specific peculiarities of each element of the network. The objective is not to present in detail all possible peculiarities which, out of the nature of the infrastructure, are numerous. The assessment must be adapted to each individual case in line with particulars of the network, its complexity and the regulations of the country concerned. The intention is to give some existing examples and to sketch an outline for reflection.

This kind of infrastructure is characterised by:

- the large number of operators,
- the multitude of regulations to which each of the infrastructure components has to comply,
- the large number of role players and interfaces, as well as and the need for information exchange between the operators,
- the need to define a number of common rules, procedures and provisions for managing the interfaces.

Each operator remains fully responsible for the operation and the management of his own infrastructure sector, as well as its own safety conditions. This concerns particularly the application of each specific regulation mandatory for each infrastructure. He has the obligation to contribute, at his level, to the operation and overall security and safety of the network to which his infrastructure is connected, in accordance with the common rules and procedures that have been agreed.

Some global organisations have been successful in co-ordinating their actions and efforts towards promoting tunnel safety. However, it is also apparent that many of the existing organisations have not managed to do the same, due in particular to the lack of a comprehensive and transversal analysis, and in the absence of a clear definition of the interfaces, the common rules and procedures. Quite often, each operator is unfortunately only concerned about his own infrastructure without any information on other connected infrastructures. This situation can lead to malfunctions and results in an increase in the level of risk for the users.

5.1.1.2. Previous PIARC recommendation

In previous works, PIARC has already paid a great attention to organisational issues for road tunnel operation for classical infrastructure. Before moving on to the specificities of the complex underground infrastructure, it is recommended that the reader should get a preliminary insight into the key issues related to the organisation of the operator referring to previous PIARC technical reports.

Among them the reader should in particular refer to the following reports:

- *[12] PIARC 2004 - Technical Committee on Road Tunnels – "Good practice for the operation and maintenance of road tunnels (report 05.13)",* which points out the need for a quality plan for the organisation of the operator

- *[13] PIARC 2007R04 - Technical Committee on Road Tunnels – "Guide for organizing, recruiting, and training road tunnel operating staff",* which gives guidelines to help the operator to better face his responsibilities and the tasks he has to ensure on a daily basis starting from the needed skills and the related process to get trained and prepared
- *[14] PIARC 2008R03 - Technical Committee on Road Tunnels – "Management of the operator – emergency teams' interface in road tunnels",* where special attention is paid to improve the organisation of the operator related to accidents and fire event management in collaboration with all the safety actors.
- *[15] PIARC 2008R15 - Technical Committee on Road Tunnels – "Urban Road tunnels: recommendations to managers and operating bodies for design, management, operation and maintenance",* that emphasises the specificities of urban tunnels and points out the need to consider the complexity of these tunnels in the very early stages of the design phases.

5.1.2. Complexity

5.1.2.1. Complexity and Key factors/components

The complexity of the large interconnected underground road infrastructure stems mainly from their geometric structure, the interfaces between different infrastructures (access and exit ramps), from the multitude of operators, of interfaces between them, of the variety of legal and regulatory frameworks applicable to the various infrastructure in line with their operational objective.

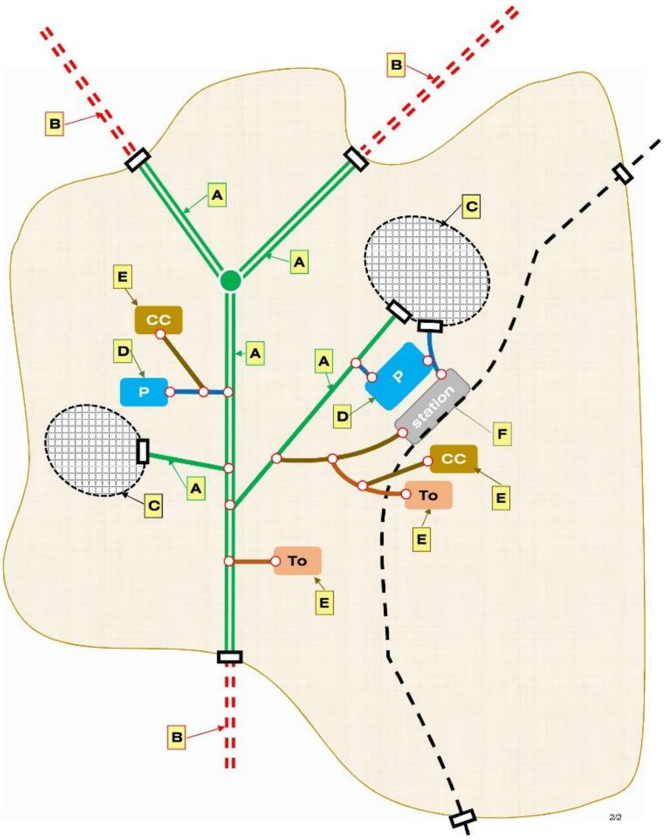
- ***Complexity***

The diagram below illustrates the complexity of interconnected networks, as well as their numerous interfaces. In counterpoint to this network nature, a non-complex tunnel infrastructure would be characterised by the absence of interfaces and connections with other infrastructures, thus making the operational management process simpler.

Many complex networks were built over many years through successive additions of new infrastructures; of new features or equipment to existing tunnel facilities. These developments happened over time and added to complexities of the ongoing evolution of the regulations. The evolution over the years has to cater for technological developments including equipment. This stratification of regulations and technologies often makes it very difficult to create interfaces and integration.

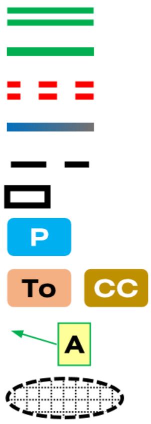
The schematic below shows a complex network, which includes various types of underground and open-air interconnected infrastructure:

- primary underground or surface infrastructure,
- access or exit ramps,
- urban surface road network,
- underground road infrastructure, such as underground public car parks - underground private parking lots combined with shopping malls, with office towers or residential buildings - underground service or unloading platforms - etc.
- underground service roads to service ramps these public or private infrastructures.



Note: networks are rarely as complex as the ones shown, but it is common for a network to comprise at least four or five operators.

Figure 11 – Schematic representation of an interconnected underground network



- Main underground infrastructure (operated by A)
- Access or exit ramp to or from the main infrastructure (operated by A)
- Main surface infrastructure (operated by B)
- Connection road to the various underground infrastructure
- Train or subway (operated by F)
- Tunnel portal
- Underground car park (operated by D and E)
- Various underground Infrastructure: shopping malls – office towers – residential buildings (operated by D and E)
- Operators : A, B, C, D, E, F
- surface urban roads network (operated by C)

❖ *Key role players*

These various components were often built over many years by different owners, in most cases the oldest ones lack global analysis and partial integration of several essential functions including the overall safety and security.

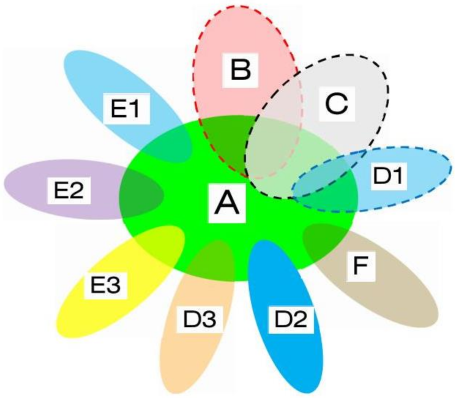
These various components are operated by different operators whose missions and priorities are very diverse. The analysis of many existing networks reveals very different modes of collective organisation. Some examples are provided in the paragraph 0.

This analysis also highlights the lack of coordination and organisation of the various operators in common fields, in particular traffic management, information and safety of the users. This deficiency is all the more critical in that the number of operators is high, that they are essentially focused on their own objectives and that they are not all aware of the collective tasks to be assumed by each of them. This is particularly true when there is no ' major operator ' able to act as a coordinator and pilot for all the common essential tasks. This mission requires, furthermore, having common rules and procedures to which all operators have subscribed and also a statutory coordinating body. It is therefore essential to have in complex tunnels a coordinated working environment with all role players, to minimise the risk of counterproductive outcomes.

The diagram below shows several operators of the schematic network represented in the Figure 11 above. It shows the main interfaces and in particular:

- The major role of operator A, who has interfaces with all operators,
- The multiple interfaces of operators B, C and D1 in this scenario,
- The limited number of interfaces (only with operator A) for other operators in this scenario.

The existing organisations sometimes show another partner in this global organisation, the Traffic Management (T) body, which is relatively independent, single or double (primary network traffic – traffic from the urban road network of the surface). This will be reported in more detail below.



- A : operator of the main underground infrastructure
- B : operator of the main surface infrastructure
- C : operator of the surface urban roads network
- D : operator of public underground car park
- E : operator of private underground car park: : shopping malls – office towers – residential buildings – facilities for cultural, sports or recreational activities
- F : operator of the rail or subway line

Figure 12 - schematic representation of interfaces between operators in an interconnected network

Notice: *During the surveys carried out under the report* [1] PIARC 2016R19 – Technical Committee on Road Tunnels – "Road Tunnels Complex Underground Road Networks", *it has been identified that "service tunnels" linking several dozens of underground infrastructures and bringing together many different operators.*

❖ *Missions of the key role players*

The mission and vision of various operators, their objectives, their organisation, their human and material resources available are diverse. It is therefore essential to evaluate each of them correctly before carrying out an analysis of a global organisation, of the interfaces, of the human resources and materials, as well as the drafting of "rules of procedures" for all shared missions.

➔ *Operator A – operator of the main underground infrastructure*

It is the operator of the main underground road infrastructure. His network includes two multi-channel independent roadways operated in unidirectional traffic, underground interchanges, underground connections and ramps giving access to the urban surface road network.

He manages the network that hosts the most important traffic volume and usually has the duty of managing the traffic in the underground.

His main responsibilities are:

- The operation, the upkeep and maintenance of his network,
- The safety of users and the communication with them through emergency telephone calls, VMS (variable message signs), safety information, video surveillance, management of the accesses, etc.
- Information being transmitted for emergency services, safety and rescue services, firefighting services and assistance to them during their onsite intervention,
- In general, the mission of coordinating and assisting all other operators of the underground network for the interfaces and the missions shared among all, for ensuring the comfort and safety of the users.

To carry out his obligations this operator has:

- A supervisory and control room with high performance equipment.
- A 24h a day and 7 days a week supervisory team,
- Intervention and troubleshooting teams on standby.

Note: In some organisations, operator A may be in charge of the management, the maintenance and the technical review/overview of the infrastructure and all equipment. He may not be in charge of traffic management, monitoring and safety. In this case another entity would be expected to fulfil these functions (see below paragraph 5.1.4.1 the example of Prague).

➔ ***Operator B – operator of the main surface infrastructure***

It is the operator of the main surface road infrastructure. His network ensures continuity of transit traffic flow to and from the tunnel.

His network includes one-way urban highways or multi-lane expressways operated in unidirectional traffic. His missions are like those of operator A. They are, however, lightened because of the shortage of all the operating and safety equipment that are specific to a road tunnel. His organisation and operational approach are similar, but less exhaustive when compared to operator A. (supervision and control room – intervention teams).

➔ ***Operator C – operator of the urban surface roads network***

It is the operator of the urban surface road network to which the entrance and exit ramps are connected, allowing the public and road traffic commuters to move between the tunnel and the urban environment.

His network includes mainly medium-scale urban roads, a mix of users (cars, buses, trucks, bikes, cycles, pedestrians), numerous intersections and level crossings whose traffic is often managed by traffic lights. The interface between the tunnel ramps and the urban surface network may not always be equipped in all instances with facilities for remote traffic management.

The C operator generally supports the monitoring and management of traffic with the support of a road maintenance service. Depending on the size of the city and the traffic density, this operator may be equipped with a safety and traffic management supervisory room. It usually has video information from the surveillance cameras located in the strategic areas to enhance traffic management and safety. It is quite often possible to act remotely and control the traffic lights that manage the major crossroads.

➔ ***Operator D – operator of a public underground car park***

It is the operator of the public underground car parks connected to the main infrastructure, through its ramps for access and exit, to underground service roads (serving several infrastructures or facilities) connected to the main underground infrastructure. These underground parking lots often have direct accesses to the urban surface road network.

These parking lots are generally open to the public only part of the day. Access control is more likely to be done by means of control beam or toll gates during the day, while during the night they would remain closed.

Operator D is responsible for the management of the toll installations, the comfort and safety for the parking users, the maintenance and the management of all the operating and safety equipment. He alerts intervention and emergency services in the event of an incident inside the parking lot to which he is responsible for.

Operator D uses simple equipment for monitoring, management and control of his installations. These facilities can be shared between several car parks located in the same urban area. Operator D is only operational for part of the day during the period of public opening of its facilities.

➔ ***Operator E – operator of a private car park associated with buildings, commercial centres***

It is the operator of private underground car parks connected to the main infrastructure, to its entrance and exit ramps, or to underground service roads (serving several infrastructures and facilities) connected to the main underground infrastructure. These underground car parks may also have direct access to the urban surface road network.

These car parks are associated with private facilities or buildings for which they provide accesses and services: office towers – residential buildings – shopping or leisure centres – logistic platforms – etc. Their accesses can be public (shopping and leisure centres) or restricted to users (residential and office towers) or to their visitors.

Operator E supports the same duties as those performed by operator D. His responsibility may also include the access control when the parking use is restricted.

Operator E supports equally the management, the maintenance of the main equipment of the facilities served by these car parks: lifts – all the common facilities of the buildings (boiler room, air conditioning, energy, security and safety, alarms) – guarding - alert of the emergency and rescue services - etc.

Operator E has a monitoring system to control and manage all the equipment of the infrastructure for which he operates.

Operator E is generally fully operational during the peak periods of frequentation on facilities he is responsible for. He has staff to guard and/or to be on duty during the night or the close times.

➔ ***Operator F – operator of the rail or subway network***

Is the operator of the rail or urban transport network. He may be concerned by interfaces with the main underground road infrastructure:

- Either as his underground parking lots connected to the main infrastructure and associated with a station, or,
- as users of facilities that may be shared between the road network and the rail network, such as emergency exits.

Similar to operator A, operator F has a control room, for the monitoring of services, the control and the management of all his equipment and system. This control room is expected to operate full time. It is standby during periods of inactivity but remains operational to ensure and secure maintenance operations.

➔ ***Operator T – traffic management***

Traffic management operates in a different set up and it is governed by the prevailing legal framework of each individual country or organisation. Examples of this may include the following:

- Operators A, B and C provide traffic management for their own network with coordination arrangements between them,
- The traffic management of the A and B infrastructures is grouped and managed by a specific T-operator who may have a regional coordination responsibility for similar or other types of the infrastructures,
- The traffic management of the A, B and the C-primary level is carried out by the same T-operator, which also provides traffic safety, monitoring of the users, as well as the call for breakdown service, safety and emergency services and firefighting services.

5.1.2.2. Legal framework

Generally, all the existing legislative and regulatory documents in the different countries are dedicated to safety issues related to standard tunnel operation. However, the regulations of some countries pointed out the specific conditions for a tunnel network. Some non-exhaustive examples are given below.

❖ ***European countries***

The European Directive *[18] EUROPEAN UNION - Directive 2004/54 / EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network" (EC Tunnel Directive),* is mandatory in all the EU countries. However, each country has the possibility to fix a higher level of safety requirements. This is generally the case for the countries having a very large number of tunnels, or who have suffered dramatic tunnel fires.

The European Directive does not define specific requirements for "large tunnel networks". It is the case also in the majority of the European countries. However, some countries have defined specific requirements as presented in the non-exhaustive review below.

❖ ***Czech Republic***

Following the "Directive 2004/54 / EC of the European Parliament and of the Council of 29 April 2004 on Minimum Safety Requirements for Tunnels on the Trans-European Road Network" (EU Tunnel

Directive) the Czech Government created the necessary law, governmental decree, directives, standards and technical requirements for the design, construction, equipment and operation of the road tunnels.

The Czech Government Law No. 80/2006 on Road Infrastructure *[19]*, which became effective in July 2006, applies to all road tunnels of over 500 metres - not only the TERN tunnels. On the basis of this law, Governmental Decree No. 264/2009 *[20]*, which came into effect in January 2009, determines minimum safety requirements, emergency report forms, the Safety Officer's duties, education, knowledge and experience in addition to the contents and purpose of safety documentation.

The Ministry of Transport in the ČR developed and issued "Methodical Instruction of the Tunnel Inspection Performance" *[21]* in September 2009 which determined:

- requirements of main and extraordinary inspections according to TP 154 "Operation, administration and maintenance of road tunnels " *[22]*,
- requirements for the award „Authorisation of main and extraordinary road tunnel inspections",
- requirements of education, in addition to the professional experience and knowledge of the inspector (ČSN, TP, etc.), including further gains of knowledge.

The basic standards and guides for design and construction of road tunnels are stated in ČSN 73 7507 Design of Road Tunnels *[23]* which was revised according to the Directive in 2005 and issued in 2006 (actual version is 2013). The technical requirements of TP 98 Road Tunnel Equipment *[24],* with its Amendment Z1 updated by the Ministry of Transport in 2010, meets the Directive requirements as well. There are not any requirements in these documents for complex tunnels. Regarding all solutions which are not able to be proposed according to the standards, it is necessary to create a design based on the risk analysis consistent with the Directive and TP 229 Safety in Road Tunnels Legal Force 12. 2010 *[25]* (safety policy, tunnel category according to length and traffic volume, RA methods, qualitative, quantitative and the deterministic methods of CAPITA risk analysis (self-rescue in the case of a fire). The recommended procedure is qualitative RA, QRA – 20 MW fire + DG – Fn curve, CAPITA)

The last technical requirements, as stated in TP 154 Operation, Administration and Maintenance of Road Tunnels *[22]* and issued by the Ministry of Transport in 2009, give specific details of the administrator's necessary duties and activities for the complete lifespan of the tunnel and its equipment.

There are not any special standards or technical requirements for complex underground infrastructures, such as city tunnels, in the Czech tunnel standards and technical guides. The investor and designer, based on the engineer's views, use risk analysis to reach an agreement on the final approved design.

- ***France***

In France the key document for road tunnel safety is the *[26] France – Ministry of Transport – "Technical instruction relating to safety measures in new road tunnels (design and operation)" published as appendix 2 to "inter-ministry circular No. 2000-63 of 25 August 2000 ",*concerning safety in the tunnels of the national highways network. This instruction has been extended to all road, motorway and urban tunnels, regardless of their status. This document gives essential safety requirements for standard tunnels and points out that the operating conditions must be adapted to the tunnel characteristics, its equipment, the traffic level and the global surface road network with which it interfaces.

Special attention is paid to urban tunnels with risks of congestion, high traffic volumes and with interchanges or specific facilities for cyclists, pedestrians, etc.

Another document is dedicated to low clearance tunnels *[27] France – Ministry of Transport – "RECTUR 1995 - Recommendations for the design of low clearance urban tunnels",* which focuses on geometry and safety equipment for these specific tunnels. This document also includes recommendations for urban tunnels and in particular underground interchanges.

It must be noted that the key safety principles for the design of standard tunnels have been considered in these documents and that some provisions concern the design of underground networks. However, the specific and fundamental issues of interfaces between the operators are not addressed.

These interfaces between the multiple operators, the shared global safety concept, the common safety procedures (each operator being responsible for their own safety procedures inside the perimeter of their infrastructure), the common shared emergency intervention plan, and the interactions between the operators, should normally be analysed in detail and discussed during the submission of the safety files to the CNESOR (National Commission for the safety in the road tunnels) and then with the Préfet (Local representative of the State) which gives the authorisation to open the tunnel to traffic. Each network and organisation are specific and require a specific attention.

- ***Germany***

When transposing the European Directive at national level, the "Richtlinien für die Ausstattung und den Bereich von Straßentunneln" *[28]* have been revised and amended, essentially with regard to the bodies required by the EC Tunnel Directive (Managing Authority, Tunnel Manager, Security Officer and Investigation Body), the traffic regulations (traffic signs and information signs), the reporting system, the security documentation, the risk analysis as well as the structural and operational measures.

The RABT edition of 2006 was introduced by the Federal Ministry of Transport, Building and Urban Development (BMVBS). It was revised by the responsible Road and Transport Research Association (FGSV) working committee, but due to not complying with the legal requirements, the BMVI decided not to introduce the updated RABT draught of 2016 for the federal trunk road sector. Instead, in agreement between the FGSV and BMVI, it was converted into a "recommendation for the equipment and operation of road tunnels at a design speed of 80 km/h or 100 km/h (EABT-80/100)"*[29]* .

The number of tunnels' tubes and entrances or exits in the tunnel are to be treated as safety-influencing factors in the overall safety concept. The presence of entrances / exits in the tunnel should be considered by a higher luminance. In the case of entrances and exits in the area of the tunnel or its area of influence (in front of and behind the tunnel as far as relevant for traffic), supplementary traffic measures or equipment must be considered.

- ***Italy***

On the 5th of October 2016, the "Directive 2004/54 / EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network" (EU Tunnel Directive) was adopted by the Italian Government with the Law Decree n. 264. The Law Decree adopted all the requirements from the EU Tunnel Directive and establish the "Commissione

Permanente Gallerie” as the Administrative Authority with power of approbation on projects in terms of safety for all road tunnels along the Trans-European Road Network (TERN) in Italy.

Only the tunnels belonging to the TERN have to fulfil the Law Decree n. 264 [30]. All the other tunnels along the Italian Road Network (inter-regional roads, regional roads, local roads) haven’t any particular standard to strictly respect, but usually they adopt as a design and operational reference a guideline issued by ANAS SpA that is the Italian government-owned company deputed to the management, the construction and the maintenance of Italian roads and motorways network (ANAS SpA is under the control of the Ministry of Infrastructure and Transport).

In addition to the Law Decree n. 264, all the Italian tunnels must fulfil the requirements of Ministerial Decree issued on the 3rd of August 2015, that defines and emits the new “Codice di prevenzione incendi” (Fire Prevention Code) [31].

❖ *Spain*

The Spanish Regulation applicable to road tunnels are different depending on the type of the road networks these tunnels form part of:

- The National Road Network: The Spanish legal framework establishes that all road tunnels belonging to the National Roads Network must comply with the Royal Decree-Law RD635/2006 [32] for minimum safety requirements. This law reflects the European Directive 2004/54/EC which makes additional provisions for all tunnels longer than 500 m as well as all urban tunnels, even those not forming part of the Trans-European Network.
- The Regional or Local Road network: Most of the tunnels owned by the 17 Regional Administrations such as Town Halls, across decided to follow the Royal Decree-Law for National Tunnels. If this is not the case, then specific regional or local regulations might be applicable.

At the same time, the Royal Decree-Law RD 393/3007 [33] enforces the application of the Basic Standard of Self-protection for centres, establishments and dependencies whose activities may potentially lead to any emergency situation.

This Basic Standard of Self-protection establishes the obligation of these centres establishments and dependencies, to expand, implement and keep the Safety Plan, which must contain actions for any risk or emergency that could happen in the facility. The plan should be clear with a detailed index of all the information that should be compiled.

It is relevant to point out that in the case of complex underground infrastructures, where the road tunnel is connected to other facilities such as parking areas or transport stations that these facilities also comply with the Basic Standard of Self-protection RD 393/2007. The relevant authority is responsible for ensuring that these facility owners do submit an “integrated Self-Protection Plan”. Following this principle, owners of the adjacent infrastructures have the obligation of detailing any activity that could potentially happen inside the tunnel into their Safety Plans. Similarly, the tunnel owner is required to give due consideration to risks that may be induced by those adjacent activities or properties.

The relevant authority also has the responsibility to ensure that the integrated Safety Plan is updated and coordinated. They could also propose any appropriate modification to ensure the appropriate protection for people.

The “Safety and Operation Plan” must be reviewed every three years. It must update in between if there are major modifications concerning the structure, the facilities or the operational conditions.

5.1.3. Main organisational issues

5.1.3.1. General framework

Figure 12 above depicts the various operators as well as the interfaces between them. Each operator is fully responsible for the operation, the care, the maintenance and management of its infrastructure and the security within the boundaries as indicated, including the safety of the users.

The infrastructures of a network are not independent due to their interconnections and the interfaces between operators. The management of these interfaces requires coordination and operating rules between the operators to manage the entire network under optimal conditions of service for users and for ensuring the safety of all.

The operation of one infrastructure of the network may impact one or more other infrastructures of the networks, their operators and their users in many cases, for example:

❖ ***Normal operation conditions***

- During peak daily traffic times,
- During the heavy weekend traffic, start of the holiday, during an important sporting event, cultural events (saturation of the parking associated with the event and congestion in the main tunnel), opening hours of shopping malls or sales (queue in front of the parking lot), etc.
- In case of police control,
- When activating traffic restrictions related to environmental provisions or air pollution peaks
- Restrictions on traffic to carry out routine maintenance work.

❖ ***Particular operation conditions***

- An accident or fire, in one of the infrastructures that may require the interruption of traffic in other infrastructures, rerouting provisions and user information,
- During important maintenance work with restriction of the use of one of the infrastructures. It may be advisable to coordinate these interventions,
- Using emergency exits shared with another infrastructure.

5.1.3.2. Principles of organisation

The operation of a network requires two types of actions:

- individual actions of each operator within the perimeter of the infrastructure they operate in,
- collective and coordinated actions for all interfaces.

Figure 13 was prepared on the basis of Figure 12. It shows, in the form of ellipses, the field of individual actions by each operator.

The Red Ring covers all the interfaces between the different infrastructures. It corresponds to the collective and coordinated actions to be assumed by the operators.

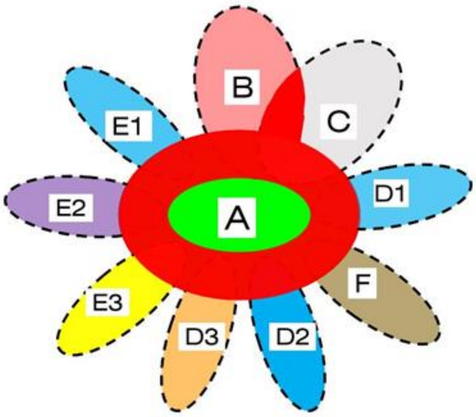


Figure 13 – Schematic representation of individual actions and collective actions for the operation of an interconnected underground network

❖ *Perimeter of individual actions for each operator*

Each operator must develop all documents, procedures and hazard analyses, for the infrastructure they are responsible for. They manage and maintain their infrastructure and all of its own equipment. They manage, control and train all their staff.

In accordance with the common procedures, they transmit information concerning their infrastructure, equipment, operating status and all shared operating and security information. They activate the equipment of their infrastructure according to the common procedures and under the control of the operator in charge of the coordination

❖ *Perimeter of collective actions*

The field of collective action is that which is represented by the red-coloured surface of Figure 13 above. It covers all the interfaces between operators.

Where things go wrong between operators usually originates from the interfaces between them. It is therefore essential to define the common strategic procedures, modus operandi, modes of exchange of information between all operators. It is also essential to create a permanent coordination structure, in order to achieve coherence between the different contingency plans and an overall efficiency to ensure an excellent level of safety and a very good level of service for users.

The creation of a "coordination structure" implies that there will be common operating rules adopted among operators. This "coordination structure" can have multiple forms depending on the nature of the network, the number of operators and the potential acuity of the problems to be addressed.

This structure must be managed by one of the operators, designated as the Coordinator. It is desirable that this Coordinator be the main operator of the network (the one with the most interfaces with the others), who usually has the necessary human resources and the means to fulfil this role, and who is operational 24 hours a day, 7 days a week. This coordinator has multiple roles:

- Organisation: development of common operational documents – consistency with the procedures of each operator – updating of documents – organisation of joint tests and exercises,

- Administrative: agenda of coordination meetings – animation – minutes – follow-up of actions decided,
- Operational: leadership in case of an event involving multiple operators,
- Referent and facilitator: operators are often very different regarding their missions, organisation, means, skills and mode of operation. Despite all these differences, the Coordinator must create and maintain an open-minded team, transparency, respect and mutual trust, which is indispensable to the overall functioning of the networks, the safety of the users, and to the level of service.

The main tasks of the "coordination structure" relate to the following points. The list is not exhaustive because it must be adapted to the particularities of each interconnected network:

- Assessment of potential risks, hazards, events and malfunctions to identify any risk or impact due to the interface between the different infrastructure and possible mitigation measures,
- Evaluation of the necessary information exchanges to ensure the required safety and level of service. Definition of the means to be implemented and the corresponding common procedures,
- Analysis of the procedures specific to each infrastructure, with particular emphasis on actions that could have an impact on other infrastructures,
- Preparation of a Coordinated Procedures Plan (CPP), with a clear description of the actions to be performed once one of the individual procedures is activated. It is important to clarify the roles and responsibilities of each operator of all affected infrastructures,
- Identification of the managers of each operator with the skills and powers to make decisions. Preparing a list with their name, position and phone number,
- Preparation of a Global Emergency Response Plan (GERP) in coordination with the emergency services and authorities. Analysis of the compatibility with the specific plans of each operator,
- Analysis of incidents occurring, to assess the effectiveness of the CPP and GERP or to prepare any changes if necessary,
- Organisation of joint training, as well as of any General exercises.

5.1.4. Examples of organisation

5.1.4.1. Prague (Czech Republic)

Hyperlink to introduce with the monograph sheets.

(see monograph sheets 2-4 and 2-5 for more information)

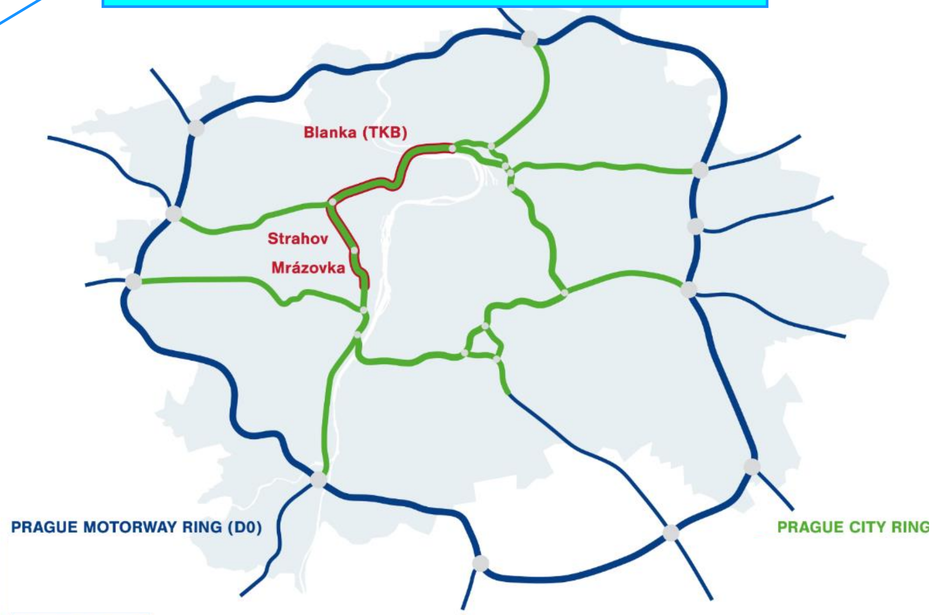


Figure 14 – Organisation of the Prague main road network

The main road network of the city of Prague according to the actually valid city urban plan (1999) consist of two ring roads and 7 radial roads (in different levels of realisation or operation). While the outer ring road is part of the national motorway network, the radials and the inner ring road are parts of the city network (different organisations). This example describes the situation of the inner-City Ring Road (actually 22 of 32 km overall in operation) with the tunnel complex Blanka and consecutive systems of tunnels Strahov and Mrazovka.

The organisational role overview is as follows:

- Operator A: TSK hl. m. Prahy, a.s. (city-funded organisation), tunnel department,
- Operator B: TSK hl. m. Prahy, a.s., area department,
- Operator C: TSK hl. m. Prahy, a.s., area department,
- Operator D: none,
- Operator E: none,
- Traffic management – traffic control: Police (national, traffic department),
- Traffic management – traffic information: TSK hl. m. Prahy, a.s., traffic information department,
- First Response units: Police patrols (national),
- Tunnel administrative authority: Prague transportation administrative authority,
- Road administrative authority: Prague transportation administrative authority,
- Control Centre: traffic management and tunnel technology controlled from separated locations.

➔ ***Operator A (TSK hl. m. Prahy, a.s., tunnel department)***

They are the operator of the underground road infrastructure, main road and street road network infrastructure. The role of this operator is as follows:

- NOT in charge of the traffic management inside the tunnel or on the accesses, but with the possibility to close the tunnel in case of fire,

- Assure the communication with the users ONLY in case of indisposition of TM operator (Police): emergency telephone, VMS (only via traffic information department), PA, broadcasting.
- Operation of all the technical equipment inside the tunnel excluding traffic lights and signals, variable road signs,
- Maintenance of all the tunnel equipment (subcontractors),
- Contribution to the safety inside the tunnel,
- Incident reporting, information of the emergency services and assistance to them when they arrive on the site,
- Operation Centre manned 24 hours a day and 7 days a week.

➔ ***Operator B, C (TSK hl. m. Prahy, a.s., area department)***

They are the operator of the main road infrastructure on the surface giving access to the tunnel: ex: urban motorway. The role of this operator is as follows:

- Operation and maintenance of all the equipment outside of the tunnels,
- In charge of the operation of the surface city network,
- Operation and maintenance of the traffic controlling equipment: traffic lights, signalling, variable road signs,
- In charge of the traffic management (not traffic control – only police can) of the road surface network in coordination with the police,
- Tunnel pavement maintenance,
- Contribution to the safety.

➔ ***TM operator – traffic control (Police)***

Responsible for the city traffic control (intersection lights, variable road sign systems – only tunnels and accesses are covered with, VMS in tunnels) – given by national law. The role of this operator is as follows:

- In charge of the traffic control inside the tunnel and on the accesses, can control VMS inside the tunnel, partially on the accesses (only the closest VMS, only Blanka for tunnels), city network traffic lights control,
- Assure the communication with the users: emergency telephone, VMS inside the tunnel, PA, safety information by radio communication,
- Contribution to the safety inside the tunnel,
- Incident reporting, information of the emergency services and assistance to them (access routes),
- Usually organised with,
    - supervision team in an operation centre manned 24 hours a day and 7 days a week,
    - intervention teams.

➔ ***TM operator – traffic information (TSK hl. M. Prahy, a.s., traffic information department)***

The operator of the City's VMS system, traffic information source for broadcasting and other sources. The role of this operator is as follows:

- NOT in charge of the traffic control inside the tunnel and on the accesses,

- Assure the communication with the users via VMS outside of the tunnels, partially controls several VMS inside the tunnels (only global city network information, with lowest priority in the tunnel).

➔ ***Organisation issues***

Separated control centres bring difficulties to communication in case of an incident in the tunnel (confirmation of information, etc.). The intention is to build one united centre for both the traffic and the tunnel technology operator.

5.1.4.2. Montréal (Canada – Québec)

(see monograph 3-1 for more information)

The Montréal Metropolitan Area includes three major urban highway tunnels more than one kilometre long:

- the Ville-Marie and Viger cut and cover tunnels located on the A 720 urban motorway, which crosses the city centre from east to west. The Ville-Marie Tunnel includes an underground interchange and several junctions for entrance and exits towards the surface road network,
- the Louis-Hippolyte-La Fontaine Tunnel, which crosses the St. Lawrence River through an underwater tunnel.

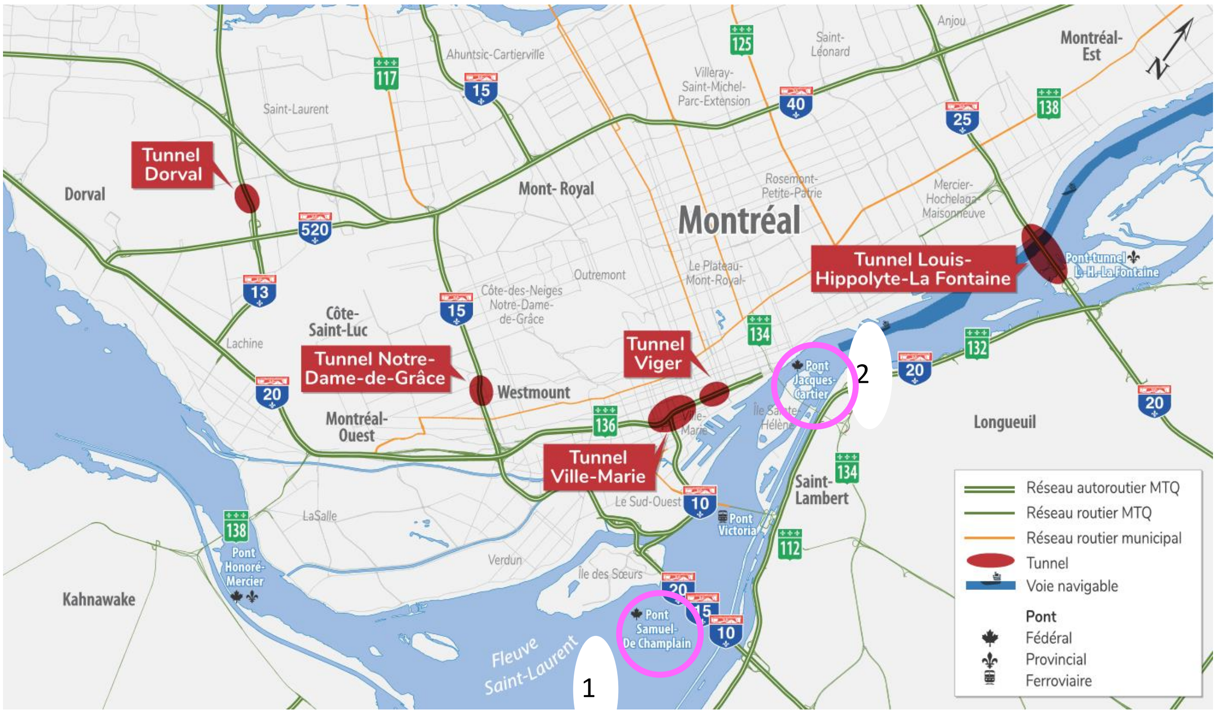


Figure 15 - Montreal Metropolitan road network - localisation of the tunnels

These three tunnels form part of the highway network belonging to the Province of Quebec and are managed by the Provincial Québec Ministry of Transport (MTQ). The MTQ is operator A and operator B as defined in paragraph 5.1.2.1 above.

The highway network also includes two short tunnels, namely the Dorval Tunnel under one of the runways at Montréal Airport (450 m) and the Notre-Dame-de-Grâce Tunnel (300 m), which its main equipment is reduced to lighting facilities.

The MTQ has two control and supervision centres:

- a control centre located in the Ville-Marie tunnel, which has a triple function: (a) the operation and safety of the Ville-Marie and Vigier tunnels and the maintenance of all their operating equipment - (b) the supervision (when required) of the equipment in the Louis-Hippolyte-La-Fontaine Tunnel - (c) the traffic management of the entire surface highway network, which includes the Metro and western Quebec. This Centre is located in the metropolitan Montréal area, which also includes two bridges crossing the St. Lawrence River (Samuel Champlain Bridge [1] and Jacques Cartier Bridge [2]), also under the federal domain,
- a control and supervision centre located at the Louis-Hippolyte-La-Fontaine Tunnel, responsible for operations, safety and maintenance of all the tunnel's equipment.

The City of Montréal manages the urban surface road network (avenues, boulevards and streets) and has an Urban Mobility Management Centre (CGMU). This centre has a video surveillance network and manages all the traffic lights at the main intersections. Ville de Montréal is operator C of paragraph 5.1.2.1.

The Ville-Marie and Viger tunnels include entrances and exits from and to the urban surface network, which constitute interfaces between the MTQ and the City of Montréal. For traffic management purposes, several interfaces with traffic lights are controlled by the City of Montreal. Other interfaces, however, do not have remote traffic management tools. Exchanges between the MTQ control centre and the City of Montréal control centre are therefore carried out by means of a telephone line. The City's control centre may adapt interface traffic management to the MTQ's request if necessary. A major exit from the tunnel on an urban boulevard managed by the city has special provisions. Traffic lights located at a crossroads near the tunnel exit automatically give priority to traffic coming out of the tunnel in the event of a major traffic jam in the tunnel or in the case of a special event like a fire.

5.1.4.3. Annecy (Haute-Savoie - France)

(see monograph sheet 2-7 for more information)

The Courier Tunnel is located in downtown Annecy and has a dual function: (1) allow the transit traffic underneath a large pedestrian area – (2) give access to underground car parks (capacity of 2,000 places) that are associated with a mall, a multiplex of cinemas, buildings for housing, as well as public spaces. The two tubes are partially built one above the other. They border a rail tunnel giving access to the railway station. The West-East tunnel gives access to underground car parks, arranged on two levels. Other accesses to this car park are also provided from the surface road networks.

Picture 11 – Annecy - Access to the car park

The tunnels and the car parks are operated by two municipal departments under the same Authority.

- The supervision centre for the car parks is located inside the southern car park. Its role is the management and the safety of the car park, as well as the surveillance of the toll booths. It is only open during the opening periods for the car parks (18 hours a day),

- The supervision centre for the tunnels is in the building of the City Hall. Its role is the technical management and the safety of the tunnels. This centre is operated 24 hours a day. It is also in charge of the supervision of the video surveillance network for the city,
- The two supervision centres have direct and permanent links between them (transmission cable and radio communication), which enable coordination in case of an accident or fire and the application of predefined and jointly agreed intervention procedures,
- The Fire Brigade is located less than one kilometre from the tunnel. Fire fighters are on site in less than 10 minutes after they have been alerted to the incident.

5.1.4.4. A 86 Duplex (France)

(see monograph sheet 2-8 for more information)

The tunnel is the only part of THE A86 ring road operated by the private company COFIROUTE; the rest of the ring road is operated by DIRIF (Regional Directorate for national roads in Île-de-France). The other roads directly connected to the tunnel are also operated by DIRIF, with local roads operated by the Hauts-de-Seine département (local authority) or towns in the immediate vicinity, particularly on the northern end.

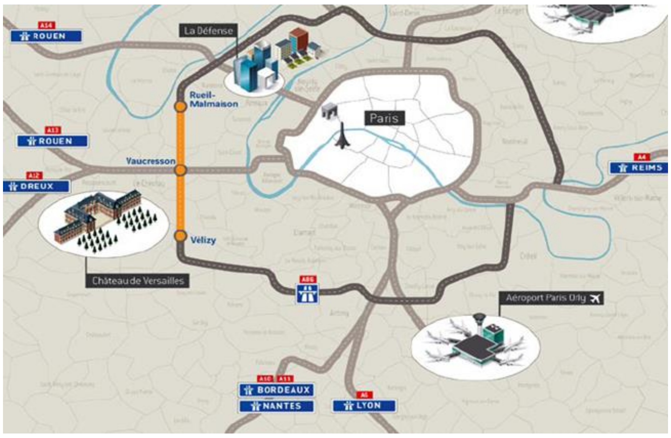


Figure 16 - situation of the A 86 Duplex Tunnel

The exchange of information between COFIROUTE and DIRIF is therefore strategic, for normal operation, planned closures or restrictions, as well as emergency situations. Exchanges also take place with the Hauts-de-Seine département.

No other infrastructure, such as car parks and public transport is in direct interaction with the tunnel.

5.1.4.5. Paris La Défense (France)

(see monograph sheets 2-10 and 2-11 for more information)

The tunnel network is connected to various road networks belonging either to the tunnel operator DIRIF (Regional State roads directorate for Île-de-France, i.e. Paris area) or to other operators such as the Hauts-de-Seine département.

This network includes interfaces with the "Voie des Bâtisseurs"(Figure 17), which itself includes many

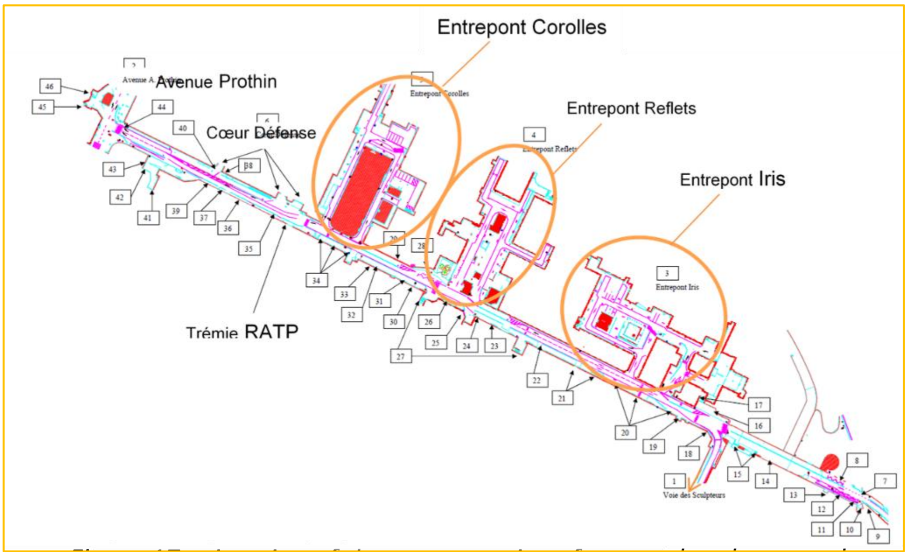


Figure 17 - situation of the numerous interfaces and underground connections with "la Voie des Bâtisseurs"

interfaces with public or private car parks, shopping or leisure centres, as well as office and residential buildings.

The control room operating the tunnel also monitors and regulates traffic on all highways owned by DIRIF in the Western part of the Île-de-France region; it is located at the western end of the tunnel network. The highways monitored by this control room include sections immediately upstream and downstream of the main branches of the tunnel complex, but not all roads are connected to it through entrance or exit ramps.

The control room routinely exchanges information regarding the planned closures of the tunnel network with the neighbouring operators:

- The Hauts-de-Seine département,
- The towns of Nanterre, Puteaux and Courbevoie,
- Paris La Défense, the agency in charge of operating the local roadways in La Défense district, many of which are underground, as well as public spaces which may be impacted by smoke, evacuation of the tunnel users or fire brigade intervention,
- SAPN, the company operating the highway west of the tunnel complex (including St Germain Tunnel),
- COFIROUTE, the company operating the A86 Duplex tunnel, to the south of the tunnel.

Coordinating maintenance works is crucial in this very dense area, where alternative routes should always be available to users.

For emergency situations, specific procedures are agreed upon between the various operators and integrated in the emergency plans of the tunnel.

Major public transport infrastructure is also present in the immediate vicinity of the tunnel network, including line 1 of the Paris metro, RER A (the busiest rail line in Europe), suburban train lines, trams, and a major bus station. There is a risk of smoke leakage from one tunnel to another, as well as a possible structural risk, and the unlikely situation of simultaneous events in two or more networks would be very difficult to manage. Therefore, emergency procedures also exist with the transit operators RATP (operator of the mass transit system in Paris) and SNCF (operator of the French National Railway network).

5.1.4.6. Düsseldorf (Germany)

(see monograph sheet 2-21 for more information)

The Kö-Bogen tunnel is a complex tunnel network in the city of Düsseldorf (Germany) with several tunnel tubes that are all connected. The tunnel contains the two main (primary) tubes “South-North” and “North-South” and two secondary branches on the both sides of them “South-West” and “North-West”. All tubes are unidirectional.

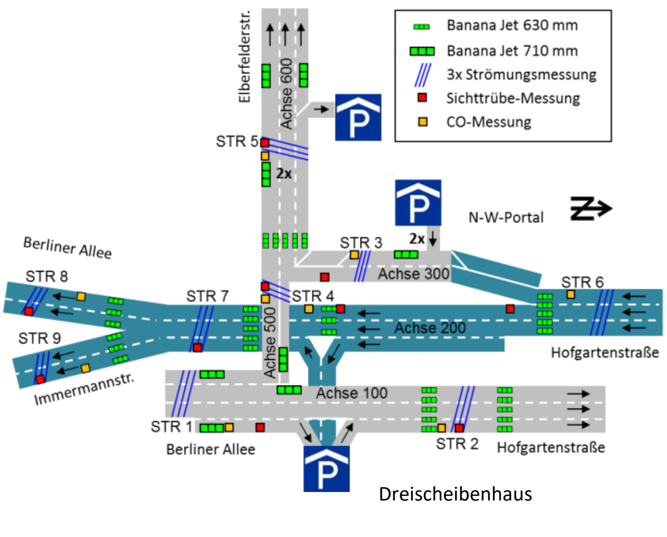


Figure 18 – Kö-Bogen complex

Furthermore, there are three underground car parks (“Kö-Bogen”, “Schauspielhaus” and “Dreischeibenhaus”). Two car parks (“Schauspielhaus” and “Dreischeibenhaus”) are accessible over an underground spindle that connects the two car parks with the tunnel.

The tunnel is operated by the city of Düsseldorf. The car park “Kö-Bogen” is a public car park and is operated by a private investor. The car park “Dreischeibenhaus” is a private car park for the employees of the Dreischeibenhaus, which is an office building. The car park “Schauspielhaus” is also a public car park by a private investor.

The four facilities Dreischeibenhaus, Libeskindgebäude (above Kö-Bogen car park), the underground spindle, and the tunnel itself are all connected. Thus, the interfaces in case of incidents are managed as follows:

Each facility has its own central fire alarm. If there is an alarm in one of these facilities, it will automatically be transferred to the central alarm of the other facilities according to the following system:

- Alarm in tunnel: transferred to Dreischeibenhaus, Libeskindgebäude and spindle,
- Alarm in Dreischeibenhaus: technical notification to the spindle,
- Alarm in Libeskindgebäude: technical notification to tunnel,
- Alarm in spindle: transferred to Dreischeibenhaus,
- The reset of the fire alarm is done manually.

5.1.4.7. AZCA Tunnel in Madrid (Spain)

(see monograph sheets 2-22 for more information)

AZCA is a Financial District in Madrid, with a rectangular surface of 618m x 305 m, where there are more than 1900 companies, distributed in several High-Rise Buildings, Offices and Commercial Centers. Some emblematic Buildings are Picasso Tower, Europa Tower, Castellana Tower (in the origin BBVA Tower) and Titania Tower.

AZCA Tunnel is an urban tunnel consisting of two distributor rings on two levels, with entrance and exit ramps towards surrounding streets as well as to several car parks belonging to the buildings located in the Financial Area.

Picture 12 - AZCA Financial District - photo from Wikipedia

The total number of parking spaces is estimated at 12,000 units.

Operator A is Ayuntamiento from Madrid (the Town Hall) who is responsible for the operation of AZCA Tunnel.

Operator C is responsible for the Public Underground Parking Management, which is EMT Madrid.

Operators D are those responsible for the private underground parking areas belonging to all the buildings above the tunnel. There are many operators due to the large amount of existing high-rise buildings, offices and Commercial Centres. They are responsible for the operation of the traffic lights that permit access into and out of the parking areas.

Operator T is the City Council Traffic Control Centre, which is responsible for the mobility inside the city of Madrid.

All operators work in cooperation and collaboration to permit the correct control of the traffic and safety inside the tunnels.

Figure 19 - Layout with the entrance and exit ramps to AZCA Tunnel

5.1.5. Tables for exchanges of information

5.1.5.1. Objectives

It is essential to establish operational guidelines among role players of the network in order to manage the interfaces between them and to ensure that the following may be achieved:

- The best possible traffic conditions to optimise smooth flow of road traffic, to reduce the risk of congestion and offer users an optimum level of service,
- The safety conditions of all users of the network under normal operating conditions, in reduced operating conditions, as well as during incidents, a breakdown, an accident or a fire.

This information exchange table depends on all the specifics of the network, the operators and the surrounding conditions. The following tables are only given as examples.

Like any operating document, safety or any procedure, these tables must be updated through the evolution of the network, its equipment, as well as during the updates of the emergency response plans.

5.1.5.2. Example based on the theoretical network of Figure 11

As an example of this network complexity and the need to analyse the interfaces between the operators concerning the general global management (under normal operational conditions and during incidents), and the safety of the users, some scenarios have been outlined.

The following scenarios showing the different interfaces and communication processes in Table 6 below have been developed to create awareness about the complexity of tasks being performed by operators of the tunnel networks. All these operators as discussed further below are required to work consistently together to improve traffic management, traffic flow and to promote positive travel experience to users in complex tunnel networks**.**

Scenario	Role Players	Type of interface
01	*C » A+T*	*Operator of urban surface road network C interacts with the main underground infrastructure operator A and the Traffic Management Authority of the Roads Network Operator T.*
02	*D » A+T*	*Operator of public underground car park D interacts with the main underground infrastructure operator A and the Traffic Management Authority of the Roads Network T.*
03	*A » D*	*Main underground infrastructure operator A interacts with the public underground car park D.*
04	*E » A+T*	*Operator of private underground car park E interacts with the main underground infrastructure operator A and the Traffic Management Authority of the Roads Network T.*
05	*A » E*	*Operator of main underground infrastructure A interacts with the operator of the private underground car park E.*
06	*A » C*	*Operator of public underground car park A interacts with the operator of urban surface road network C.*
07	*B » A+T*	*Operator of the main surface road infrastructure B interacts with the main underground infrastructure operator A and the Traffic Management Authority of the Roads Network T.*
08	*A » B*	*Main underground infrastructure operator A interacts with the operator B of the main surface road infrastructure.*

Table 6 – Scenario interfaces strategy

The detailed “tables for exchange of information” concerning this example is shown in appendix chapter 9.2.2 below.

5.2. TRAFFIC MANAGEMENT

5.2.1. introduction

Traffic management could be defined as the group of organisation rules and technical equipment consisting of detectors, reacting and informing devices, needed to control the traffic flow in defined transportation network. The traffic management objective is to ensure balance between global network traffic capacity, desired level of service and safety. The level and strategy of the traffic management could generally vary and depends on the level and depth of its automatisation and the organisation. Automatic traffic management system offers the possibility of real-time reaction on detected incidents or disruptions in the managed network, so the negative aspects for network user aspects - danger, time lost; environmental aspects and others could be minimised.

The organisation structure of the network traffic management could be in some cases more complicated because of different traffic operators for different infrastructure sectors like main underground infrastructure vs. main surface infrastructure or yet when this is compared to surface road network. The existence of several operators in the defined network brings high demands on the communication in terms of speed, effectiveness of transmission, reliability of information in case of incidents, but also the closures for maintenance, and on cooperation. Clear rules in the decision-making process has to be set to avoid starting the chain of problems in the whole traffic network (in a holistic view).

The road tunnels are usually equipped depending on length, traffic volume, etc. with its own traffic automatic management system including adjacent part of the approaching surface road, which is together with other technical systems controlled and operated from the tunnel control centre(s). This provision is because of considerable exposure to negative outcomes in case of occurrence of fire or other potentially catastrophic event. The main objective due to is to minimise the number of the users approaching the position of dangerous events, to enable smooth emergency services intervention and to avoid afterward collisions by the creation of fluent traffic diversions. That is why safety should take precedence over traffic movement in the tunnel traffic management generally. TMS is also useful for the smooth solution during less serious events.

Contrary to a “simple” tunnel, the complex underground structures because of branching require a wider range of traffic scenarios to consider the number of branches, capacity of the complex sections and of ongoing surface networks. While the complexes are situated mainly in dense urban networks, the probability of occurrence of at least minor incident is higher not only due to lane switching accidents and also the combination of incidents at the same time which is quite common. The disruption of the standard traffic flow could rapidly exceed to adjacent complex sections or network.

During design phase it is necessary for each planned and unexpected event to prepare traffic scenario, which has to be accepted by all stakeholders. The purpose of the system is to minimise the time between the incident occurrence and delivery of the proper information to all stakeholders and then implement the proper traffic management scenario should be chosen.

The main goal of the tunnel complex operation is to ensure, on the one hand, the balance between demands on availability and acceptable safety level on the other for the infrastructure users, as well as the safe maintenance staff at the nearby environment. This could be quite difficult, moreover, when the complex operation is influenced by several subjects/operators.

5.2.2. Traffic management tools

Traffic management implies good communication with users. Traffic management tools usually include lane control signals, crossing signals, variable speed limit signs, variable route signs. Communication tools like variable message signs, radio messages and other real-time traffic information provisions.

The traffic management could automatically react to the detected changes and starts preventive actions like informing drivers via VMS or lowering speed limits, closing lanes and, in the most critical situations, even closing the tunnel sections, ramps or the whole complex. The rules of the traffic management in connection with incident management have to be set with regard to safety criteria and minimal operating requirements, environmental aspects and emergency response planning.

To initiate the reaction of the traffic system the event has to be detected at first. The need for validation of the detected event is in a contradiction with the need for a short-time reaction. The reaction could be fully automatic, semi-automatic or manual. Fully automated system reacts immediately in real-time on detected events without need for manual initiation by the operator. One should be mindful to the fact that fully automatic systems may also trigger false alarms which are undesirable. Members of the public are sensitive to false alarms as this may discredit the effectiveness of the operation system entirely. On the other hand, with only manual reaction there is the risk of no reaction in case of the operator’s indisposition. The semi-automatic reaction based on short timeout for the validation of the detected event seems to be the optimal solution. Anyway, the possible undesired effects, consequences for the local area of the automatic actions should be considered.

❖ ***General recommendation, rules for traffic management***

- Respect general design and operational rules and guidelines for road signage.
- Avoid the use of signage which may create ambiguity to the road/tunnel users.
- Avoid the use of unknown road signs for the public.
- Set common decision-making rules for all stakeholders with clear position for the lead.
- Design the system as semi-automatic responsive in case of the detection of unexpected events.
- Consider the need of the still-light of all signs and signals during standard operation to avoid the overburden to drivers with excessive information.
- Inform approaching users of the capacity reductions, closures in the tunnel in advance.
- Prepare traffic scenario for route diversions, where possible for partial closures of the complex tunnel structure to minimise disruptions to normal traffic flow in the urban area.

5.2.3. Fluid operation

The fluid operation usually means the ideal situation when no further action for achieving the desired level of safety and availability is required. The TM tools of the tunnel complex then could be used to transmit traffic information from the surrounding surface traffic network.

5.2.4. Congestion

Congestion is a limiting traffic flow scenario which raises the risk of the rear-end collision at the end of the jam tail. It could be caused not only by traffic incidents in neighbouring road network, but also only by the dense traffic that may develop from time to time in the tunnel complex (in particular due to exit and access ramps and to the car parks connexions). The severity of this situation depends on the actual conditions – location (beginning, intermediate or end of the main tunnel, exit or entrance ramp, or foregoing or following surface sections), traffic time variation, how fast is the situation detected and traffic management reaction. Depending on the defined safety rules it could even lead to tunnel complex closure.

5.2.4.1. Congestion in front of an exit ramp

Congestion in this location may occur due to incidents on the exit ramp, but it is commonly caused by the insufficient capacity or obstacle in the follow-up surface road network, or due to the layout, the management or the equipment of the interface between the two networks. Several provisions could be recommended during the design stage; if it is not possible to solve expected problems in the design, then proper management procedures aimed to promote the tunnel user’s safety should be considered first priority.

❖ ***Provisions during the design phase may include***

- Accurate traffic forecast study also involving the neighbouring road network. The wider is the area covered as part of the network planning the better. A relevant traffic evaluation is necessary for setting the basic capacity of the main tunnel and ramps with due consideration to the number of lanes.

- Traffic capacity of the surface road network to which the exit is connected has to be considered. If there is a chance to design the form of the ongoing surface section, the demands on capacity vs. usual demands on traffic calming should be balanced. The surface road sections bearing the traffic function of the main tunnel infrastructure in case of its closure could be equipped with variable route signs and signals to increase the number of lanes or similar.
- Design of the interface with the surface and management of the connection. To have a better chance to clear the tunnel in case of emergency or emerging congestion it is a good approach to have interconnection at least the first traffic lights after the exit ramp with the main tunnel infrastructure (to ignite the "green wave" and let the traffic flow out from the tunnel with emergency situations).
- Width of the exit ramp is an important factor as more lanes increase the capacity of the ramp and gives a better opportunity to clear the main tunnel in case of the next section closure. But in case of the small ramp curve, it could enhance the risks during the lane switching. Anyway, the usual approach is to have sufficient construction width for at least two lanes equipped with a variable signs and signals system giving the users a proper route navigation.
- A longer exit ramp section parallel to the main tunnel provides better capacity and limits the impact of potential congestion on the continuous lanes of the main tunnel, provided that the behaviour of users is correct. Monitoring user behaviour and applying penalties to users who unduly block transit lanes is conducive to smooth traffic flow, less congestion and improved safety.
- Identification of the potential weak points with limited capacity in the design stage.
- A network often results from additional infrastructure along the time. Preliminary analysis of the impact of a new infrastructure on the whole system: compatibility – impact on traffic and safety.

❖ ***Management procedures***

- Coordination with the operators of the surface network to increase the capacity of exit traffic.
- Information to users inside the complex as well as other users approaching the complex where possible by means of VMS, radiobroadcasting, speed and traffic flow patterns.
- Temporary closure of exit or reducing the traffic entering the main tunnel is dependent on the geographic location of the whole complex in relation to the impacted road and tunnel networks.
- Ensure that unacceptable and dangerous behaviour demonstrated by some drivers in terms of overtaking, unexpected lane changing at exits or blockage of the through lanes are recorded by means of video survey and severely penalised.

5.2.4.2. General congestion of the main tunnel

Congestion in the main tunnel could occur in case of the incident, insufficient capacity or obstacle in the follow-up exit ramp, downstream section or follow-up main surface road.

❖ ***Provisions during the design phase***

- Identification of the potential areas susceptible to limited capacity. This may include locations of merging or exit lanes and steep grades.
- Ensure that traffic capacity of the main surface infrastructure downstream the main tunnel should be at least equal to the capacity of the main tunnel.
- Emergency lanes to mitigate the capacity problems during minor incidents.

❖ ***Management procedures***

- Information to network users about the traffic conditions (VMS, radiobroadcasting).
- Speed limit regulation upstream with penalisation.
- Eventual regulation of the main road and of the entrance ramps.
- Avoid risk of traffic jam inside the tunnel if the ventilation system is not able to manage the smoke in case of fire and a traffic jam => strong action on the traffic entering the tunnel or temporary closure.

5.2.4.3. General congestion of the car park entrance

Congestion of the car park entrance could occur in case of the full occupancy or incident in the parking facility.

❖ ***Provisions during the design phase:***

- The capacity of the car park must be designed according to the served facilities.
- Design of the interface with the surface and main tunnel management.

❖ ***Management procedures:***

- Coordination of operators of the car park to give proper and well-timed information on parking capacity.
- Information to users inside the complex and to the users approaching the complex if possible – VMS, radiobroadcasting, speed and traffic flow patterns, number of places available.
- Temporary closure of car park entrance.

5.2.5. Planned events

Planned events are the special situations, which will reduce the capacity of the complex (partial/full closure), that could be planned in advance to minimise the risk of drivers being surprised by the sudden reduction of capacity.

Planned events include:

- Maintenance works,
- Refurbishment works,
- Staff and emergency response training,
- Tests of technological equipment,
- Inspections,
- Others (cultural or sports events, or similar).

Maintenance works, most common planned events, are necessary for keeping the technological equipment of infrastructure in a good condition. With the complexity the number and the time required for the maintenance works is rapidly increasing. That is why the conditions for the maintenance of the equipment and construction regarding the operability during the maintenance works should be considered in detail particularly in the design phase.

5.2.5.1. Provisions during the design phase

- Coordination and elaboration of the global plan for all infrastructure and operators.
- More equipment and more complexity increase the risk of failure. During the design it is essential to analyse the reliability, the availability, location, the architecture of whole the equipment, the redundancy in order to assure that a failure of equipment has a limited impact on the whole system.
- During the design, consideration should be given to develop possibly solutions that can contribute to making maintenance, inspections and tests easier and less intrusive.
- Design the technological systems autonomously for each tunnel complex section, so the malfunction in one tunnel section does not lead to the closure of the other sections.
- Analyse the possible consequences of the capacity reduction during the maintenance works on the whole complex or network, other transportation modes; keep in mind also other cultural or sports events (traffic peak during abnormal hours) – usually matter of the administrative authority.
- Plan your maintenance and refurbishment actions to keep availability as much as possible and with less impact on the network capacity.

5.2.5.2. Management procedures

- Coordination with the operators of the surface network to increase the capacity of the detour.
- Public information (PR tools), information to approaching users (inside the complex; also, for the users approaching the complex if possible – VMS, radiobroadcasting): lane/ramp/section/complex closed, detour recommendations.
- Do the preventive maintenance of the technological systems. It can be planned, which is not the case with curative intervention following a failure.

5.2.6. Unexpected events

5.2.6.1. General description

Unexpected events may be defined as undesirable occurrence likely to have direct or indirect influence on the tunnel user safety. The available time to react is generally short. Contrary to planned events, there is also a strong necessity for management intervention, of which the traffic management is an important component to deal with. Instead of smooth transition, immediate change of traffic regime occurs in this scenario.

The possible unexpected events include:

- Vehicle breakdown or stopped.
- Presence of debris or objects on the roadway,
- Presence of pedestrians in restricted zones,
- Presence of animals on or near the roadway,
- Vehicles driving the wrong way,
- Accident leading to urgent safety assessments,

- Fire,
- Equipment technical failure or human unavailability,
- Structural failure,
- Weather-related incidents and other natural perturbations. These may include flooding, heavy rain, snow, storm, fog, including natural events such as earthquakes or human errors leading to wildfires,
- people strike or civil actions, disobedience, demonstrations.

A traffic scenario for each section of the complex including nearby network sections should be considered during the design stage.

General also rules for unexpected situations should be set. Particular design inputs may include time frequency and location. Optimally the traffic management and intervention strategies should be linked to type, volume, characteristics and frequency.

❖ ***Provisions during the design phase***

- Consider possible scenarios and outline traffic intervention strategies for tunnels and the adjacent network.
- Propose interconnected system of VMS and VRS on the approaching network and in the tunnel complex;
- Ensure that VMS are located in the appropriate distance where drivers have enough time for decision to change their route.
- Ensure that VMS are located before tunnel entrances to clarify the reasons of tunnel closures for the waiting drivers – to eliminate the driver's tendency to violate the traffic rules (and due to increase the risk of collision).
- For unexpected events the preferred access routes should therefore be clearly defined in the emergency plans (several scenarios may be distinguished), keeping in mind that alternative routes can always be used if required by unforeseen circumstances.

❖ ***Management procedures***

- The procedures for each infrastructure sector should be written for the widest reasonable range of foreseeable events, whether originating from the tunnel infrastructure or traffic, or from external human or natural factors.
- In particular, these procedures should describe the actions to be taken to close the tunnel complex partially (lanes, branches, sections) or completely.
- Minimal procedures should be available for unforeseen events of possible high severity; this category may include terrorist attacks, since the number of possible scenarios is very large.

5.2.6.2. Traffic incident

From the traffic management point of view, the traffic incident causes a sudden change of the route section capacity following with the rapid increase of the risk of collision. In the complex structures, several infrastructure sections could be affected by the incident impacts in a very short time. The overall traffic management reaction depends on the location and severity of the incident. In case of the incident in the parking lot, the level of restrictions would be lower than in case of fire in the main tunnel infrastructure.

❖ *Traffic incident with only impact on the traffic flow*

If the immediate impact of the incident is only a traffic perturbation, for example in the case of a breakdown, it generally results in closure of the affected lane(s), or branch(es) if they are blocked. Entrances or exits may be closed as a result. The incoming traffic may also have to be restricted or diverted so that congestion occurs on the surface network rather than inside the tunnel complex. The users of the tunnel complex and neighbouring network should be informed, as well as the neighbouring operators.

- Incident with only impact on the traffic flow (breakdown – light collision)
- Usually decides the operator, depending on the situation: closing a lane, closing a branch, closing a section, closing an entrance, regulation of the traffic entering the main tunnel, information of the complex/network users, information of the other operators involved, eventually temporary partial deviation of the main traffic.

In the case of an accident, the procedure should take into account the necessity of rapid intervention of the rescue services.

❖ *Incidents with a fire*

In the case of a fire incident, the closure of the affected tunnel entrance should be as quick as possible, even though this may cause longer delays for some users. Complete closure of the tunnel complex may not be necessary, especially for very large structures, but caution is recommended when outlining the procedure since the propagation of fire and smoke do not always follow normal expectations. Another priority is to clear the tunnel sections which can be affected by smoke. This may involve, for example, giving priority to the users exiting the tunnel onto the surface network, at the expense of traffic fluidity outside the tunnel. Finally, the access strategy for emergency services must be taken into account; it may differ from the one applied for an accident.

There are generally several closures and traffic management scenarios depending on the location of the incident. It is therefore important to confirm this location with as much certainty as possible. A default procedure (generally more conservative) should exist if the location cannot be determined with sufficient precision.

Scenarios involving fire in an annexe structure such as a car park should be studied specifically to assess the risk of smoke propagation to the tunnel (due to imperfect confinement by the ventilation system or possible structural failure), and the need for emergency services to use the tunnels to access the incident site. It may be possible to continue operating the tunnels, but caution is advised.

➔ *Provisions during the design phase*

Consider the traffic scenarios for each location in the complex with regard to possibilities of the affected tunnel section clearance (due to the smoke propagation), emergency access routes availability (should stay accessible also during the peak hours and congestion in the network due to the incident), possible network capability to absorb the diverted traffic.

➔ *Management procedures*

Apply the proper traffic/emergency scenario for the incident location according to the location of the fire.

If fire inside a car park without an impact on the whole complex: close the car park, the other sections of the complex may be maintained under operation.

5.2.6.3. Failure of equipment

The maintenance is a basic instrument to operate the infrastructure in a safe manner. But even in case of preventive maintenance approach sometimes the sudden equipment failure occurs. The probability of equipment failure is increased in complex tunnels, which generally have more equipment installed and interconnected. The actions to be undertaken in the various equipment failure scenarios should be pre-defined, along with the minimal operational requirements.

There are two types of scenarios which may impact the traffic in case of equipment failure:

- the failure requiring urgent maintenance on the traffic lanes (cameras, fire detection systems, safety lighting, etc.),
- the available equipment does not meet the minimal operational requirements, therefore mandating the closure of some sections, or the entire complex.

While the maintenance is described as ‘urgent’, or the closure as ‘immediate’, these situations do not create immediate danger for the users, and the associated procedures should be designed to minimise the risk of the a subsequent accident and the perturbations to traffic inside and around the complex.

5.2.6.4. Minimum Operational Requirement (MOR)

The purpose of this topic is to ensure that minimum operational requirements are achieved.

- Analysis of MOR in a tunnel complex has to be carried out in detail through open interaction between tunnel sections during the design stage, taking into account branches, ramps, sections, car parks, etc. MOR may eventually impose specific operational conditions such as velocity reduction, decreasing traffic flows, etc.
- Tunnel sections where MOR can no longer be achieved have to be closed until the system has been improved and minimum operation requirements reinstated. Sections where MOR remains acceptable should be maintained permanently in operation.
- Detail description of MOR and particular operational conditions. Complexity of the MOR for complex tunnel.

5.3. OPERATION – MAINTENANCE

5.3.1. Operation

The particularities for the operation of a tunnel network result from the complexity of the geometry and the equipment, the numerous interfaces with other operators and more fundamentally on the global organisation described section 5.1 “Organisation” above.

Basically:

- Each operator is responsible for the operation of its infrastructure,
- A “Manual” fixes the general organisation between the operators, the coordination and the common obligations. A “Coordination Committee” led by a “Coordinator controls and adjusts the eventual issues. This Committee ensures the return of experience with the other operators to improve the system and the efficiency,
- The operation does not differ a lot from the operation of “standard tunnels”. It may, however, require more means and more skills,

5.3.2. Maintenance Concept

Previous chapters have addressed the relevance of interfaces, interactions and interdependence between tunnel operators. This chapter will further expand the relevance of this in the context of the large underground and interconnected structures.

Maintenance in complex tunnels is a holistic and interrelated issue where a contribution of one sector must be proactively complemented by the contribution of other sectors. The purpose of maintenance in the underground and complex tunnel structures is to improve the serviceability of the infrastructure and to reduce operational costs. When maintenance is performed at the right time of the tunnel life cycle it optimises the available equipment, it minimises accident risks and largely contributes to public safety. Tunnel Operators, particularly those involved in the maintenance of large underground and interconnected infrastructures are reminded of the need for optimising their maintenance strategies to enhance public confidence in the use of these infrastructures by making them safer, effective and continuously available for use.

5.3.2.1. Strategic maintenance approach for tunnel networks

The strategic components related to maintenance in tunnel networks may be divided into four categories:

- The responsibility of each operator,
- The commitment of each operator in the context of overall maintenance strategy,
- Coordination between the operators,
- Best practices to be shared.

❖ ***Responsibility of each operator***

Each operator is responsible for safety level of his infrastructure, which contributes to global level of safety of the whole complex. Each operator is responsible for informing the main operator with demands on his maintenance demands of the others. As a basis, a global maintenance coordinating plan among all operators should be set and adjusted to the individual operator's. Focus on global benefit with a view of minimising time of the restricted operations is essential.

Figure 20 and Figure 21 below show individual and collective contributions of different operators. In this case, a total of 10 operators namely E1, E2, E3, D1, D2, D3, A, B, C, D and F respectively.

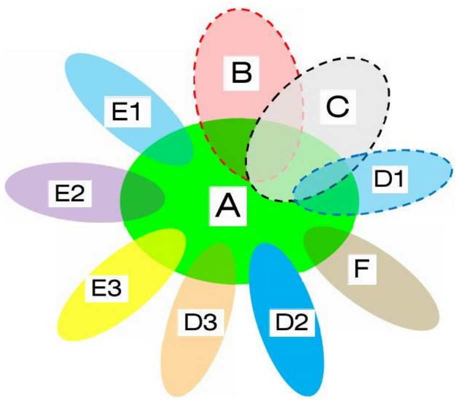


Figure 20 – interfaces between the operators

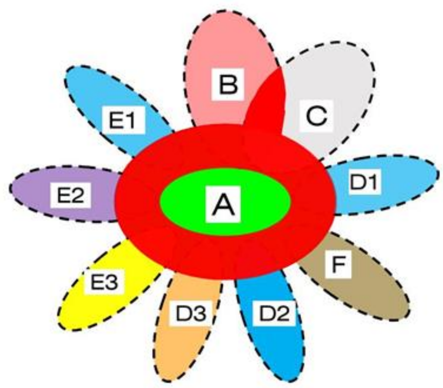


Figure 21 - field of individual and collective responsibility of the operators

The Figure 20 shows the field of each operator and the interfaces. The Figure 21 shows the fields of superposition (red circle) between the operators and the field of collective responsibility.

- The fields outside the "red circle" are the own responsibility of each operator, within the tunnel infrastructure maintenance system.
- For the fields marked by the "red circle", (fields of interfaces and superposition) the responsibilities of each operator must be clearly defined, and a detailed list of equipment must be established.

At same time, each operator has responsibilities that may be impacted by actions of other operators. A, is the main operator of the underground tunnel infrastructure and is responsible for the overall co-ordination and communication process.

The goal is to keep all the parts of the network available in standard mode if possible. This means that each operator must define the action needed for the maintenance of each device or component depending on prescribed intervals (preventive maintenance) or necessary time for defined actions to achieve MOR. The responsibility of each operator is therefore essential for the success of the entire organisation.

❖ *The commitment of each operator in the context of overall maintenance strategy*

This topic can be divided into two specific subcomponents. These are:

- The list of equipment under the responsibility of each Operator,
- The list of strategic equipment forming part of the collective responsibilities.

➔ *The list of equipment under the responsibility of each operator*

The strong argument to be made in this topic is that each operator is in the best position to take responsibility and the management of its own equipment. In this regard, as part of the operator's responsibility, the following must be particularly attained:

- Operators must be familiar with their own equipment systems installed in the tunnel. This will facilitate and enhance responsiveness when maintenance actions become crucial,
- Operators must have their fully updated inventory list forming part of their own assets,
- Operators must be familiar with the location of the equipment. This may improve the response time when a repair or maintenance action is required,
- operator should be at a minimum familiar with the performance characteristics of the equipment in the engineering framework,
- Added to the above is the competence and skills of the operator. It is extremely useful that a tunnel maintenance manager is equipped with the right skills, competence and knowledge so that he can perform his duties in the most professional manner,
- It is advisable that tunnel operators and maintenance managers be exposed to ongoing training and skill enhancement. This contributes to bridging the gap between the past and modern advancements in technology that will impact on the tunnel maintenance philosophy,

➔ *The list of strategic equipment forming part of collective responsibilities*

Further to the discussion outlined above it is crucial to acknowledge that the collective effort made by different operators will trigger combined responsibilities to all participants in the process. The following is thus crucial for the success:

- Develop and agree on the list of strategic equipment,
- Agree to the level of maintenance viability and reliability,
- A description as to how different tunnel equipment and systems can be used in a normal operation of a complex tunnel,
- The suggested environments in which the use of such equipment would be more of a benefit and successful,
- The technical operations manual can also be a technical benefit to benchmark the required performance levels.

❖ *Coordination between the operators*

The coordination process in the context of the interconnected underground complex tunnels entails the following:

➔ *Organisational Behaviour*

This refers to the need to develop a group work which is only achievable if the organisational behaviour is aligned to the need of the infrastructure. (*See 5.1 "Organisation"*).

➔ *Maintenance of one has implications on the others*

- Where interfaces are unavoidable, it is important that each operator does fully respond to its obligations timorously. This may have a direct impact on the road tunnel users on the overall quality of service being offered to the public. As an example, one can point out that change of illumination can be done by one contractor or by combining the work of two different operators to the same contractor. Where cost effectiveness may be maximised operators may agree to use the same service provider. This may have advantages in terms of completion time, operations continuity and consistency of outcomes,
- Interfaces are also unavoidable in certain situations. These trigger the relevance of teamwork, proactiveness and compromise. No works should be done for improvements but at the same time causing unpleasant situations to other tunnel operators.

Tunnel maintenance specialists are encouraged to keep in mind that complex tunnel infrastructures demand a complex and holistic effort beyond one individual's contribution. Only with a proactive input of expert on their own sector will contribute to the collective. It is therefore crucial to have some degree of harmony in terms of the individual task.

❖ *Best practices to be shared*

Several examples of good practices have been developed throughout the years, such as *[35] PIARC 2012R14 - Technical Committee on Road Tunnels - "Life cycle aspects of electrical road tunnel equipment",* and remain valid in the present days.

The primary advantage to be learnt from this is to promote the holistic contribution of all operators towards the effective tunnel safety.

Best practices in tunnel maintenance will also require a coherent effort from the key role players and stakeholders. This can be achieved by defining a set of principles and procedures which would-be set-in operator's procedure manual generally known as the inventory manual. Tunnel operators are accordingly encouraged to take cognisance all key components associated with inventory manual list which is applicable to their functions and has been developed by PIARC since many years.

Following reports published by PIARC for standard tunnels may also be pertinent for tunnel networks:

- *[16] PIARC 20012R12 – Technical Committee on Road Tunnels – “Recommendations on management of maintenance and technical inspections of road tunnels”,*
- *[17] PIARC 2017R02 – Technical Committee on Road Tunnels – “First steps toward a sustainable approach”,*
- *[35] PIARC 2012R14 - Technical Committee on Road Tunnels - “Life cycle aspects of electrical road tunnel equipment”,*
- *[34] PIARC 1999 - Technical Committee on Road Tunnels - “Road Tunnels: reduction of Operating Costs” - Ref.: 05.06.BEN,*
- *[12] PIARC 2004 - Technical Committee on Road Tunnels – “Good practice for the operation and maintenance of road tunnels (report 05.13)”*,
- *[36] PIARC 2016R01 - Technical Committee on Road Tunnels - “Best practice for life cycle analysis for tunnel equipment”,*

6. SAFETY

6.1. SUMMARY

The safety of the motorists and people within a "network of interconnected underground road infrastructure" is more complex to manage compared to conventional simple networks especially during the operation of emergency services. This is due to:

- The geometrical complexity of the network, its numerous branches and all the associated infrastructures,
- the multiplicity of the operators, their various cultures and level of experience, as well as their responsibilities between various facilities (operator F may have to manage his car park but also a building tower with its equipment),
- The multiplicity of the interfaces and the need for coordination and solidarity,
- Various difficulties the emergency services face, particularly the location of the event (especially of a fire), the return of information on the magnitude of the event and the condition of the users concerned, as well as the intervention strategies that require an excellent knowledge of the network, of the performance of the equipment and the aeraulic performances of the whole system.

All these elements were analysed independently in the previous chapters of the report where comments and recommendations were provided. The objective of this chapter is not to reassess all these elements, but to synthesise them by providing a holistic view which is essential for the implementation of effective facilities.

6.2. HOLISTIC VIEW

The holistic view concerns the main topics below

6.2.1. The location of an event

The event's description, magnitude and evolution are all essential information, which requires:

- reliable and redundant detection equipment,
- excellent co-ordination between operators and efficient means of transmission, equipped with a system recording the traceability of the event,
- a good knowledge of the network and all its specificities.

6.2.2. The multiplicity of the operators

The operator's various cultures, skills, experience and responsibilities between facilities require:

- the creation of a coordinating body to allow better understanding of all the operating systems, interfaces, installed equipment as well as the associated technologies,
- the designation of a Coordinating Operator, who will fulfil the fundamental role as a facilitator and to create a spirit of trust and solidarity among all operators,
- the analyse and implementation of action plans,
- a good knowledge and understanding of the capacity the performance of all the facilities and equipment installed, especially ventilation, as well as detailed knowledge of the condition of the equipment and their operability (failures – maintenance - loss of performance - etc.).

6.2.3. Emergency Services

Emergency Services must be familiar with the network, the performance of the installed equipment as well as the associated technologies, the aeraulic particularities, as well as the efficiency of each emergency scenario depending on the location, nature and magnitude of the event. They must be able to rely on the coordinating operator, who has the most knowledge and understanding of the whole system and its state, and to establish a trusting human relation with them. In the absence of all these elements, it is unlikely that they will be able to choose the right emergency intervention strategy. This requires:

- excellent knowledge of the network, which is usually difficult to ensure, especially in urban areas where there is a significant turnover of the fire brigade teams and staff not being utilised as much during emergency interventions. The knowledge of the network is difficult to convey, and the reading of drawings is often prohibitive and difficult to memorise. For a complex network, it is recommended to have all the data of the infrastructure and the facilities in the form of a virtual 3D model, which is more user-friendly and easily memorisable. The extension of BIM must be able to facilitate this transmission,
- a good knowledge of the performance and the operation of the ventilation systems, its aeraulic efficiency and the actual behaviour of the network. A virtual 3D model is also the best method for acquiring information and transmitting it. Many tunnels are equipped with a simulator, and for a complex network such a tool is highly recommended,
- comprehensive emergency intervention plans for all possible scenarios, integrated into a computer database. A fairly expert system can then suggest the best suited scenario that would have been carefully analysed and detailed. This saves time and avoids reinventing "hot" during an intervention of the scenarios that would have been carefully analysed and detailed. This should not, however, lose sight of the need for adaptations and responsiveness,
- establishing and maintaining a relationship of trust with the operators during visits, meetings, training or exercises and participation in meetings of inter-operator coordination dedicated to security and interventions. The emergency services often have knowledge of the other associated infrastructure (as the whole office tower of the F operator of a car park)

The human factor and the capacity for initiative and adaptation remains fundamental in order to cope with a large-scale event, but without prior reflections, specific tools, a well-established organisation, and without training, they will not be sufficient to manage the situation and ensure the safety of users, residents and stakeholders.

7. ACRONYMS

Term	*Definition*
1D	*One-dimensional*
3D	*Three-dimensional*
AID	*automatically incident detection*
ANAS SpA	*Italian roads and motorways network* *Azienda Nazionale Autonoma delle Strade S.p.A.*
BIM	*Building Information Modelling*
BMVI	*Federal Ministry of Transport and Digital Infrastructure* *Bundesministerium für Verkehr und digitale Infrastruktur*
CFD	*Computational Fluid Dynamics*
CNESOR	*National Commission for safety in road tunnels (France)*
CPP	*Coordinated Procedures Plan*
DG-QRAM	*Dangerous Goods Quantitative Risk Assessment Model*
DIRIF	*Regional Directorate for national roads in Île-de-France*
EC	*European Commission*
EIA	*Environmental Impact Assessment*
EU	*European Union*
FFFS	*Fixed Fire Fighting System*
FGSV	*Research Association for Road and Traffic e. V.* *Forschungsgesellschaft für Straßen- und Verkehrswesen e. V.*
FN-Curve	*F = Frequency; N = Number of Fatalities*
GERP	*Global Emergency Response Plan*
GPS	*Global Positioning System*
GSM	*Global System for Mobile communication*
MOR	*Minimum Operational Requirement*
PR	*Press Release*
QRA	*Quantitative Risk Assessment*
RA	*Risk Assessment*
RAMS	*Reliability, Availability, Maintainability, Safety*
RECTUR	*Recommendations for the design of low clearance urban tunnels*
SATNAV	*Satellite navigation*
TERN	*Trans-European Road Network*
TM	*Traffic Management*
TMS	*Tunnel Management System*
VMS	*Variable Message Sign*
VRS	*Variable Route Sign*

Table 7 – Table of acronyms

8. REFERENCES

[1] PIARC 2016R19 – Technical Committee on Road Tunnels – “Road Tunnels Complex Underground Road Networks”,

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[3] PIARC 2017R01 - Technical Committee on Road Tunnels – “Design fire characteristics for road tunnels”,

[4] PIARC 1999 - Technical Committee on Road Tunnels – “Fire and Smoke Control in road tunnels (Report 05.05.B)”,

[5] PIARC 2007 - Technical Committee on Road Tunnels – “Systems and equipment for fire and smoke control in road tunnels (Report 05.16.B)”,

[6] PIARC 2011R02 - Technical Committee on Road Tunnels – “Operation Strategies for Emergency Ventilation”,

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[9] PIARC 2008R04 - Technical Committee on Road Tunnels – “A guide to optimising the air quality impact upon the environment for road tunnels”,

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[12] PIARC 2004 - Technical Committee on Road Tunnels – “Good practice for the operation and maintenance of road tunnels (report 05.13)”,

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[14] PIARC 2008R03 - Technical Committee on Road Tunnels – “Management of the operator – emergency teams’ interface in road tunnels”,

[15] PIARC 2008R15 - Technical Committee on Road Tunnels – “Urban Road tunnels: recommendations to managers and operating bodies for design, management, operation and maintenance”,

[16] PIARC 20012R12 – Technical Committee on Road Tunnels – “Recommendations on management of maintenance and technical inspections of road tunnels”,

[17] PIARC 2017R02 – Technical Committee on Road Tunnels – “First steps toward a sustainable approach”,

[18] EUROPEAN UNION - Directive 2004/54 / EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network" (EC Tunnel Directive),

[19] Czech Government Law No. 80/2006 on Road Infrastructure, July 2006,

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[22] Czech Republic - TP 154 “Operation, administration and maintenance of road tunnels “,

[23] Czech Republic - ČSN (Czech technical standard) 73 7507 Design of Road Tunnels issued in 2006 (actual version is 2013),

[24] Czech Republic - TP 98 Road Tunnel Equipment, 2010,

[25] Czech Republic - TP 229 Safety in Road Tunnels Legal Force 12. 2010,

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[28] Germany - Road Tunnel Design and Operation Regulations (Richtlinien für die Ausstattung und den Betrieb von Straßentunneln), RABT, Edition 2003, (actual version is 2006),

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Straßentunneln mit einer Planungsgeschwindigkeit von 80 km/h oder 100 km/h), EABT-80/100,

[30] Italy - Law Decree n. 264,

[31] Italy- Codice di prevenzione incendi (Fire Prevention Code), 3rd of August 2015,

[32] Spain – Royal Decree-Law RD635/2006 about minimum safety requirements in Road Tunnels,

[33] Spain - Royal Decree-Law RD 393/3007 Basic Standard of Self-protection for centres, establishments and dependencies dedicated to activities that potentially may generate any emergency,

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[37] PIARC - Technical Committee on Road Tunnels - "Road Tunnels Manual",

[38] PIARC 2007 – report 05.16.BFR - « Systems and equipment for fire and smoke control in road tunnels»,

[39] PIARC 1999 – report 05.05.BFR - Technical Committee on Road Tunnels – «Fire and smoke control in road tunnels».

[40]

9. APPENDICES

9.1. TABLE OF THE MONOGRAPH SHEETS

A monograph sheet has been drawn up during the last cycle for most of the 27 "tunnels networks" investigated during the last cycle. Additional monographs have been established during the present cycle. The previous monographs and the new monographs are listed in the table below.

The hyperlinks of the right column of the table give direct access to the monographs.

continents	*countries*	*cities*	*Names of the tunnel's complexes*	*Mono-graph*
Asia	*China (CHN)*	*Changsha*	*Yingpan Road Tunnel*	*1-1*
		Chongqing	*Underground Ring Road in Jiefangbei CBD*	*1-5*
	Japan (J)	*Tokyo*	*Chiyoda*	*1-2*
		Tokyo	*Yamate*	*1-3*
	South Korea (ROK)	*Seoul*	*Shinlim-Bongchun and Shinlim-2*	*1-4*
Europe	*Austria (A)*	*Vienna*	*Kaisermühlen*	*2-1*
	Belgium (B)	*Brussels*	*Leopold II*	*2-2*
		Brussels	*Belliard*	*2-3*
	Czech Republic (CZ)	*Prague*	*Blanka Tunnel complex (3 tunnels)*	*2-4*
		Prague	*Mrazovka and Strahov*	*2-5*
	Finland (FIN)	*Helsinki*	*KEHU – service tunnel*	*2-6*
	France (F)	*Annecy*	*Courier*	*2-7*
		Ile-de-France	*Duplex A 86*	*2-8*
		Lyon	*Croix-Rousse (road tunnel + multimodal tunnel)*	*2-9*
		Paris-La-Défense	*A 14 / A 86 motorway interchange*	*2-10*
		Paris-La-Défense	*Voie des Bâtisseurs*	*2-11*
	Germany (D)	*Düsseldorf*	*Kö-Bogen Tunnel*	*2-21*
	Italy (I)	*Valsassina*	*Valsassina tunnel*	*2-12*
	Monaco (MC)	*Monaco*	*Tunnel sous le Rocher (2 interconnected tunnels with "Y" form layouts)*	*2-13*
	Norway (N)	*Oslo*	*Opera Tunnel (chain of 4 tunnels)*	*2-14*
		Tromsø	*Three interconnected tunnels with roundabouts and access to parking lots*	*2-15*
	Spain (E)	*Madrid*	*M 30 by-pass*	*2-16*
		Madrid	*M 30 Rio*	*2-17*
		Madrid	*AZCATunnel*	*2-22*
		Madrid	*Cuatro Torres Tunnel*	*2-23*
	Sweden (S)	*Stockholm*	*Ring Road – Northern link*	*2-18*
		Stockholm	*Ring Road Southern link*	*2-19*
	Netherlands (NL)	*The Hague*	*Sytwendetunnel (chain of 3 tunnels)*	*2-20*

continents	*countries*	*cities*	*Names of the tunnel's complexes*	*Mono-graph*
North America	*Canada / Quebec (CDN) / (QC)*	*Montreal*	*Ville-Marie and Viger tunnels*	*3-1*
	USA	*Boston*	*Boston Central Artery*	*3-2*
		Seattle	*Seattle Interstate 90 Mt. Baker Tunnel*	*3-3*
		Seattle	*SR 99 Alaskan Way Viaduct Tunnel through Seattle*	*3-4*
Oceania	*Australia (AUS)*	*Brisbane*	*M7 Clem Jones Tunnel (CLEM7)*	*4-1*

Table 8 - List of the monograph's sheets

9.2. TABLES FOR EXCHANGES OF INFORMATION

9.2.1. Introduction

9.2.1.1. General description of interfaces

The description made in different scenarios below not only provide the overall objective of the interface process but also the contribution of each individual player at any stage of the interaction process.

Basically, one role player will initiate the communication process by creating awareness to the relevant stakeholder about incidents, their nature and complexity, how serious they are likely to become and possible impacts where applicable.

The communication process can also be about normal traffic management processes where a joint effort among operators is required.

The stakeholder who normally receives the information, assisted by the available technology in operation will immediately develop an intervention strategy (application of the operational procedures) aimed to minimise the negative impact of the incident to road users or the public in general within the boundaries of the network in consideration. The next step is to communicate the proposed intervention strategy to those who are prone to be exposed to it using available communication channels and technology. This may entail one single solution or a multitude of them forming part of the overall strategic action.

In case of a fire incident, the forward strategy may include immediate evacuation of members of the public, direct action by the fire brigade and the start of the ventilation process using available jetting and extraction fans including the immediate closure of the tunnel infrastructure.

The overall objective is the safety of the road user, the protection of assets in terms of tunnel infrastructure, public and private car parks, existing and adjacent malls, and the promotion of public confidence towards the large underground and interconnected tunnel structures.

9.2.1.2. Contents and limitations of the examples

This information exchange table depends on all the specifics of the network, the operators and the surrounding conditions. The following tables are only given as examples, to illustrate the analysis mechanisms.

These examples discussed below are aimed to highlight "locations where incidents would be most likely to occur within a network". Furthermore, they would describe the list of essential scenario interfaces among the operators in pursuing of an acceptable solution or outcome. They are not aimed to be exhaustive and are not particularly aimed to describe all the procedures that need to be applied. They are aimed to create a general feel for a possible scenario concept.

Like any operating document, safety or any procedure, these tables must be updated through the evolution of the network, its equipment, as well as during the updates of the emergency response plans.

9.2.2. Examples of tables

9.2.2.1. Exchange of information from operator C ➔ A + T

Reminder	*Operator C – operator of the urban surface roads network* *Operator A – operator of the main underground infrastructure* *Operator T – traffic management*

State of information exchange by the Operator C	Actions by Operators A and T	Objectives
NORMAL OPERATION		
Congested traffic at tunnel exit	*Information is received by A and T. Then they take management actions of directing the traffic entering or inside the tunnel:* - *possible control at the entrance* - *rerouting of traffic* - *temporary entrance closure* - *information to the users.*	*Safety of road users by reducing the number of peoples blocked inside the tunnel.*
Congested traffic in the area front of a ramp entrance	*If the tunnel is congested and in coordination A+T:* - *actions of limiting traffic entering on the ramp to improve the traffic flow.* - *If not achieved, eventual closing of the ramp up to a point where it is safe to reopen*	*Improved traffic flow at ramp entry of the tunnel*
Works near the portals, or exit ramps with reduction of traffic volume, or blocking the traffic	*Actions of redirecting traffic to other areas including the option to close the exit ramps to improve the flow.* *Once the extreme situation is improved, reopen the exit for vehicle use.*	*Improved traffic flow at tunnel portals during maintenance works.*
INCIDENT OPERATION		

State of information exchange by the Operator C	Actions by Operators A and T	Objectives
Fire close to the entrance	*Necessary actions on specific ventilation procedures in the entrance ramp to minimise the risk of smoke entering the tunnel network.*	*Prevent smoke propagation inside the tunnel ramp and to promote safety for tunnel road users.*

Table 9 - Exchange of information from operator C to operators A + T

❖ Note: description and clarification of the table above

The table shows the interfaces between an operator of urban surface road network C interacting with the main underground infrastructure operator A and the traffic management authority of the roads network known as operator T. This table contains the nature of the problem, actions taken by operator A and the overall objective to be achieved.

➔ NORMAL OPERATIONS

The development of the communication strategy will depend on peculiarities on each individual tunnel and for this reason the need for establishing an effective communication strategy between tunnel operators is vital to facilitate and promote adequate response from the road and tunnels users. An example of this for normal operations in complex tunnel is discussed below with the outline of specific actions being proposed for each individual operator forming part of the communication and management processes of the tunnel. In this scenario, the communication interface is taking place between an operator of the urban surface road network (C), a main underground complex tunnel operator (A) and a Traffic management specialist (T). After receiving information from C on the development of traffic congestions in one specific exit ramp, Operator A in coordination with T will act by providing on time information as well as proposing mitigation measures for road users. The overall objective of this is to ensure that traffic flow problems in the tunnel are identified, discussed and addressed timely, to maintain and enhance safety for people within the tunnel environment.

The following communication steps are followed.

- Scenario 1: Congested traffic at the tunnel exit

The main objective is to promote road user safety and public confidence by reducing the number of people stranded inside the tunnel and to enable them to enjoy good travel experience in and outside the tunnel. To achieve this,

- The urban surface roads network contractor will communicate to the main underground complex tunnel that there is a predominance of congested traffic in the tunnel at the specified exit ramp.
- The main underground complex tunnel operator, with the assistance of the traffic manager will then take the following actions:
  - Provide, by means of variable message signs placed at specified network locations (including inside the tunnel), on time information to the road/tunnel users so that they can avoid if possible, entering the tunnel;

- In addition, he will propose alternative routes to be considered by road users as part of the traffic management plans;
- Operator A will also propose rerouting measures to road users in the tunnel by directing them to alternative exit points where traffic flow is improved.
- If all the above alternatives remain ineffective and the traffic flow worsens to unacceptable levels of service, Operator A is likely to close the tunnel until such time the traffic has fully exited from the previously congested exit point.

- Scenario 2: Congested traffic in the area in front of ramps entrance

The main objective remains to promote safety for the road user in the tunnel environment.

This scenario shows some traffic build up inside the tunnel and as a result there is a limited capacity for additional traffic. Ramp metering can be applicable for a limited time assess congestion but if the flow capacity remains restricted then the obvious solution is to close the entry ramp entirely.

As in the previous case, proper communication lines between the different operators is essential because effective mitigation measures will minimise the frustrations of road users. Furthermore, early warning for motorists followed by immediate actions prior to excessive congestion at the ramp entrance can only have a positive impact to all.

- Scenario 3: Works near portals, exit ramps, reduction or increase of traffic volumes blocking the traffic

Traditional maintenance and work activities near portals, tunnel entrances or exit ramps will cause traffic flow constraints leading to tunnel low level of service for road users. Similar to previous examples a proper communication flow between operators is essential to minimise unnecessary traffic congestions and to promote effective road safety for road users inside or exiting from the tunnel in all sectors of the tunnel environment. The role of the main tunnel operator supported by C and T remains crucial.

Operator A must also maintain alternative scenarios whereby several options such as redirecting, limiting entries, limiting exits can be applied in order to maximise the available space. Should these options fail to produce the required outcomes then the obvious solution is to close the tunnel until all traffic has been able to exit.

The decision of closing the tunnel must not be taken lightly as it will always create other traffic constraints in the existing network. They should be taken as the last resource if better options are not available.

➔ ***CASE OF INCIDENT***

There are also undesirable situations caused by incidents inside the tunnel

- Scenario 4: fire near the entrance

In case of fire incidents effort must be made to save human lives. The interface between an operator of the urban surface roads network (C), a main underground complex tunnel operator (A) and a Traffic management specialist (T) becomes even more critical.

Similar to the strategy adopted for the normal operations, the main objective in the case of fire remains to promote the safety of road users within the tunnel environment. This can be achieved by any of the following measures:

- Moving all people from the fire zone and adjacent areas to clearly defined exit points all people for safety,
- Denying all people who may not be aware of the prevailing fire access to affected zone incident,
- Providing additional information through VMS to road users within the geographic area where the tunnel is located.

Depending on the nature and the intensity of the fire other actions must be taken to curtail the size of the fire, such as initiating specific ventilation procedures by the Operator A in coordination with the traffic management specialist to prevent the smoke propagation inside the tunnel ramp as well as the use of firefighting systems or the fire brigade to contain the fire immediately.

9.2.2.2. Exchange of information from operator D ➔ A + T

Reminder	*Operator D – operator of a public underground car park* *Operator A – operator of the main underground infrastructure* *Operator T – traffic management*

State and information to exchange by operator D	Actions by operators A or T	Objectives
NORMAL OPERATION		
Car park is open *Parking spaces available*	*Information is provided by the operator to users inside the tunnel or before entering to the tunnel*	*Information on the number of parking spaces available.* *Users may get to the car park.*
Car park is full	*Information is provided by the operator to users inside the tunnel or before entering to the tunnel*	*Avoid car park users entering the tunnel and queuing in front of the car park entrance (risk of collision)*
Car park is closed	*Information is provided by the operator to users inside the tunnel or before entering to the tunnel*	*Avoid car park users entering the tunnel*
Car park is open but under maintenance and the capacity is limited	*Information to the operators A and T* *Awareness and monitoring*	*Information for the operator concerning the likelihood having the car park full with increasing possible risk of traffic jam*
INCIDENT OPERATION		
Fire inside the car park (car parc open). Operator D starts specific procedures concerning the car park: Ventilation – closing doors – alert to fire brigade – information to car park users present inside the car park	*Operators A and T start the special procedures: tunnel emergency ventilation – information of the users – eventual tunnel closure with rerouting of the traffic – etc.*	- *avoid queuing* - *prevent to expose users to possible dangerous conditions* - *facilitate access to emergency services*
Fire inside the car park when the car park is closed, and operator D is not present	*Possible fire alarm report to the operator A – special procedure to be defined for action by the operator A on behalf of operator D*	*Global safety management*

Table 10 - Exchange of information from operator D to operators A + T

9.2.2.3. Exchange of information from operator A ➔ D

Reminder	*Operator A – operator of the main underground infrastructure* *Operator D – operator of a public underground car park Operator*

State and information to exchange by operator A	Actions by operator D	Objectives
NORMAL OPERATION		
Queuing inside the tunnel in front of the car park entrance	*Eventual closing by operator D of the direct access from the outside if any, to give priority to the tunnel users*	*Increase tunnel safety*
Traffic congestion inside the tunnel	*Limitation of exit flow from the car park in direction of the tunnel* *Possible closing of this exit and rerouting to other exits if any*	*Avoid congestion increase – comfort and safer conditions for users*
INCIDENT OPERATION		
Fire inside the tunnel	*Information to operator D about the fire inside the tunnel* *Operator D starts the specific procedures for the car park: car park gate closing – activation of car park ventilation – information to car park users – etc.*	*Avoid extension of the fire or spreading of the smoke in the car park.* *Keep car park safe*
Fire inside the tunnel when the car park is closed, and no operator present.	*Special procedures must be defined for the emergency action of the operator A on behalf of operator D:* - *information of car park users* - *exit gates must be kept closed* - *activation of car park ventilation.* *Specific tools required: information of the car park users and activation of the ventilation system inside the car park must be possible from the control room of the operator A*	*Avoid placing car park users in dangerous conditions when entering the tunnel.*

Table 11 - Exchange of information from operator A to operator D

9.2.2.4. Exchange of information from operator E ➔ A + T

Reminder	*Operator E – operator of a private car park associated with buildings, commercial centres* *Operator A – operator of the main underground infrastructure* *Operator T – traffic management*

Table of information is like Table 10 above concerning the information exchange between operator D and operators A + T

9.2.2.5. Exchange of information from operator A ➔ E

Reminder	*Operator A – operator of the main underground infrastructure* *Operator E – operator of a private car park associated with buildings, commercial centres*

Table of information is like Table 11 above concerning the information exchange between operator A and operator D, with, however, the exception of the first column, last row. The operator E is a full-time present for the supervision of the buildings or the commercial, centres, and is in position to inform the users, to keep the exit door closed and to activate the ventilation system of the car park if required.

9.2.2.6. Exchange of information from operator A ➔ C

Reminder	Operator A – operator of the main underground infrastructure Operator C – operator of the urban surface roads network

State of information exchange by the Operator A	Actions by Operator C	Objectives
NORMAL OPERATION		
Free-flowing traffic	*Information is received by operator C can be transmitted to the users.*	*Global overview of the traffic conditions*
Queuing inside the tunnel in front of an exit ramp to the street network	*Instruction to apply the specific procedure to increase the flow of the traffic exiting into the urban traffic (traffic lights – police, etc.)* *Information for tunnel users, that the exit could be closed*	*Avoid queuing inside the tunnel and reduce risk of collision at the tail of the traffic jam*
Congested traffic inside the tunnel in front of a ramp entrance	*Entrance through the ramps may be closed by operator A* *Operator C:* - *Actions for rerouting the users* - *inform the users on its own network*	*Avoid increasing the congestion and traffic jams*
Maintenance works with reduction of traffic capacity inside the tunnel	*Possible closing of the exit or entrance ramps by tunnel operator.* *Possible reduction of traffic entering by the main tunnel entrance and creation of a deviation using surface road network.*	*Avoid formation of traffic jam inside the tunnel and risk of collision.*
INCIDENT OPERATION		
Fire inside the tunnel downstream an exit ramp to surface	*All entrances closed by the operator A* *Instruction to apply the specific procedure for managing the connection with a full priority to the exit traffic (remote signalling – police, etc.)*	*Clear the tunnel as soon as possible to improve the safety of the users*
Fire inside the tunnel	*All entrances closed by the tunnel operator* *Instruction to apply the specific procedure for managing the connection with a full priority to the exit traffic (remote signalling – police, etc.)*	*Avoid increasing the number of vehicles trapped inside the tunnel* *Clear the tunnel as much as possible*
Breakdown or accident	*Possible closing of the exit or entrance ramps by tunnel operator A.*	*Avoid formation of traffic jam inside the tunnel and risk of*

State of information exchange by the Operator A	Actions by Operator C	Objectives
	Possible reduction of the traffic entering by the main tunnel entrance and creation of a deviation using surface road network.	*collision.*

Table 12 - Exchange of information from operator A to operator C

9.2.2.7. Exchange of information from operator B ➔ A + T

Reminder	*Operator B – operator of the main surface infrastructure* *Operator A – operator of the main underground infrastructure* *Operator T – traffic management*

State and information to exchange by operator B	Actions by operator A and T	Objectives
NORMAL OPERATION		
Fluid Traffic	*Information is received by the operator. Could be provided by the operator to the users inside the tunnel or before entering to the tunnel*	*Global overview of the traffic conditions.*
Congested traffic at the exit	*Information is provided by the operator to users inside the tunnel or before entering to the tunnel.* *Start of the specific traffic management procedures according to traffic volume, congestion and blockage (reduce main traffic entrance – close the entrance from the ramps – diversion of the users to the exit ramps)*	*Avoid traffic jam inside the tunnel for safety reasons*
Congested traffic in front of the main entrance	*Information is received by the operator.* *Need to have traffic information and traffic conditions*	*Global overview of the traffic conditions*
Heavy maintenance work with reduced traffic capacity	*Information is provided by the operator to users inside the tunnel or before entering the tunnel.* *Coordination required in order to evaluate the impact on the traffic condition inside the tunnel and the specific procedure to follow.*	*Avoid a traffic jam inside the tunnel for safety reason (reduce the congestion)*
PARTICULAR OPERATION CONDITIONS		
Accident or breakdown close to the tunnel	*Information is provided by the operator to users inside the tunnel or before entering the tunnel: see congested traffic near the exit or close to entrance.*	*Avoid traffic jam inside the tunnel for safety reason*
Weather conditions	- *Information is provided by the operator: see congested traffic*	*Traffic management* *Safety information for the*

State and information to exchange by operator B	Actions by operator A and T	Objectives
	near the exit or close to entrance - *Information is provided by the operator to the drivers inside the tunnel as alert on the conditions at the exit (smog – snow – etc.)*	*users*
Fire close to the entrance	*Information is provided by the operator to users inside the tunnel or before entering to the tunnel.* *Start specific ventilation and other procedures*	*Prevent smoke propagation inside the tunnel and avoid traffic jam inside the tunnel for safety reason*

Table 13 - Exchange of information from operator B to operators A + T

9.2.2.8. Exchange of information from operator A ➔ B

Reminder	*Operator A – operator of the main underground infrastructure* *Operator B – operator of the main surface infrastructure*

State and information to exchange by operator A	Actions by operator B	Objectives
NORMAL OPERATION		
Fluid traffic	*Information is received by operator B. Operator A could provide to the users Information concerning traffic conditions Inside the tunnel and traffic on the ramps.*	*Global overview of the traffic conditions*
Congested traffic inside the tunnel	*Information is provided by operator B to users*	*Make users aware of the risk of queuing.*
Congested traffic inside the tunnel with important risk of queuing (high risk)	*Information is provided by operator B to users.* *Application of specific procedure with possible temporary traffic limitation at the main entrance and partial traffic deviation*	*Avoid risk of collision at the tail*
Heavy maintenance works with reducing traffic capacity	*Information on traffic conditions is provided by operator B to users.* *Application of specific procedure with possible temporary traffic limitation at the main entrance and partial traffic deviation*	*Avoid risk of collision at the tail*
INCIDENT OPERATION		
Traffic capacity reduction by accident or breakdown	*Information is provided by the operator to users.* *Application of specific procedure with possible temporary traffic limitation at the main entrance and partial traffic deviation*	*Avoid risk of collision at the tail*
Fire inside the tunnel	*Information is provided by operator B to users: tunnel closure* *Application of specific procedures for traffic management (deviation).*	*Safety conditions for the users* *Avoid increasing the number of peoples inside the tunnel*

Table 14 - Exchange of information from operator A to operator B

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