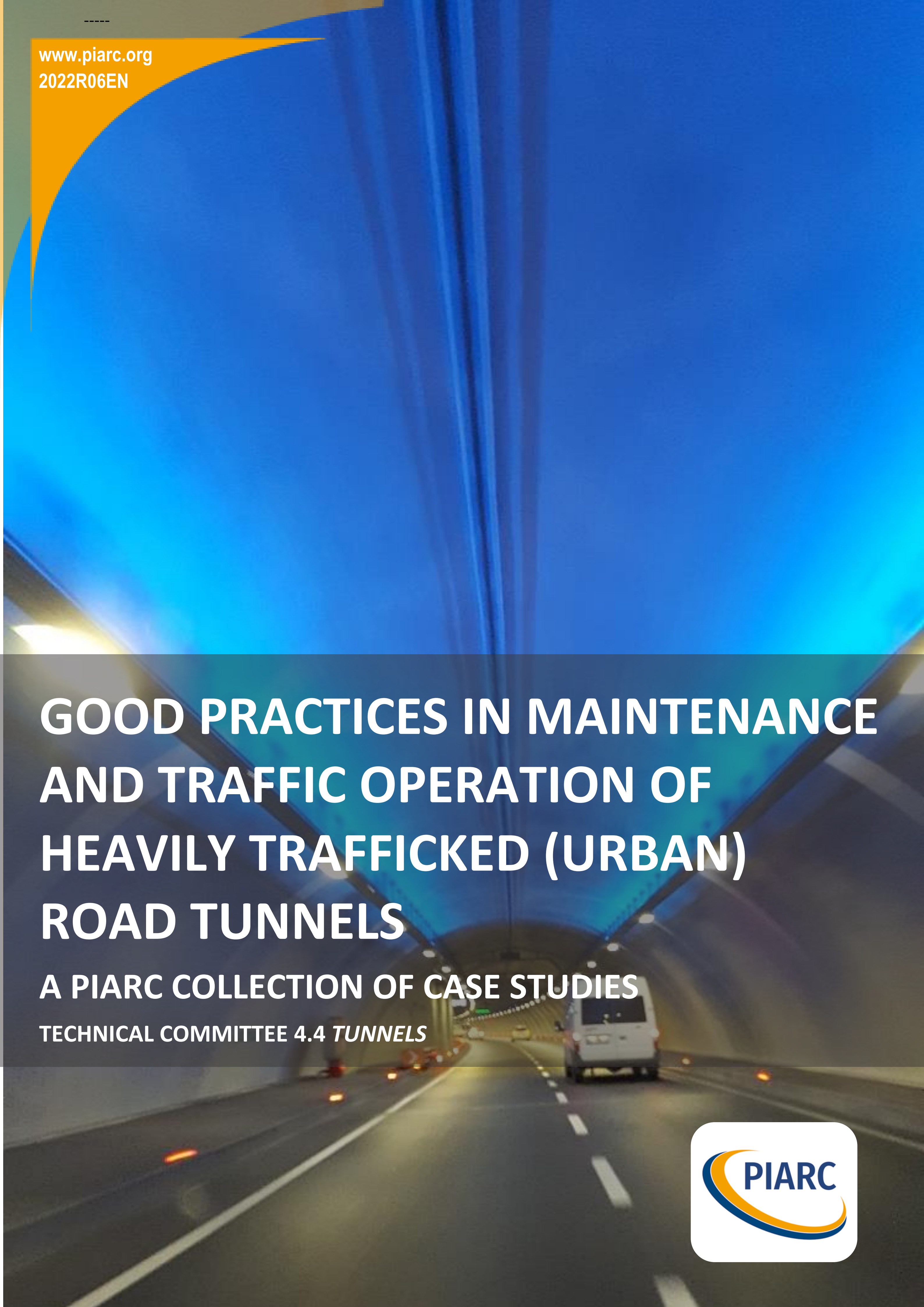


www.piarc.org
2022R06EN

GOOD PRACTICES IN MAINTENANCE AND TRAFFIC OPERATION OF HEAVILY TRAFFICKED (URBAN) ROAD TUNNELS

A PIARC COLLECTION OF CASE STUDIES

TECHNICAL COMMITTEE 4.4 *TUNNELS*

PIARC

STATEMENTS

The World Road Association (PIARC) is a nonprofit 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 2020– 2023 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.

This report is available from the internet site of the World Road Association (PIARC): http://www.piarc.org

World Road Association (PIARC)
Arche Sud 5° niveau
92055 La Défense cedex, France

International Standard Book Number: 978-2-84060-681-9

Front cover © Authors

MAINTENANCE AND TRAFFIC OPERATION OF HEAVILY TRAFFICKED (URBAN) ROAD TUNNELS

A PIARC COLLECTION OF CASE STUDIES

TECHNICAL COMMITTEE 4.4 *TUNNELS*

AUTHORS/ ACKNOWLEDGEMENTS

The report was prepared in the working group WG1 under the leadership of Arthur Tshibela KABUYA (B), working group leader and Urs WELTE (CH), working group co-leader.

We would like to thank the members of the working group who contributed a case study. It was only thanks to their active support and their expertise that this case study report was possible.

These active members were (in alphatical order):

- CHARCELLAY Pierre (France)
- CHIODINI Corinne (Norway)
- FREY Simon (Switzerland)
- KABUYA Arthur (Belgium)
- KLUGE Christina (Germany)
- LOH Alfred (Singapore)
- PAEMEN Inge (Belgium)
- RAKOSNIK Lukas (Czech Republic)
- SAJTAR Ludvik (Czech Republic)
- SHIRATORI Akira (Japan)
- Tillet Damien (France)
- WELTE Urs (Switzerland)
- WIERER Alexander (Austria)
- YEO Se Lay (Singapore)

Urs Welte (Switzerland) was the editor of the report, in coordination with Arthur Kabuya (Belgium). Fathi Tarada (United Kingdom) was responsible for the quality control of the English language.

The content of the report was reviewed by Jorgen Holst (Denmark), Nobuharu Isago (Japan), Ronald Mante (The Netherlands) and Nam - Goo Kim (South Korea).

The Working Group was chaired by Arthur Kabuya (Belgium) and co-chaired by Urs Welte (Switzerland).

The Technical Committee was chaired by Ingo Kaundinya (Germany) and Tiago Massingue (South Africa), Jean-Claude Martin (France), Rafael López Guarga (Spain) were respectively the English, French and Spanish-speaking secretaries.

EXECUTIVE SUMMARY

2022R06EN

MAINTENANCE AND TRAFFIC OPERATION OF HEAVILY TRAFFICKED (URBAN) ROAD TUNNELS

The aim of the case study collection report was to gather, evaluate and comment on international expertise related to maintenance and traffic management in highly trafficked urban road tunnels. A large number of cases were collected, which were particularly suitable for providing an insight into the implementation of these special requirements for urban road tunnels.

It became apparent that it was useful to divide the cases into 3 categories, which pursued similar goals.

- Implementation of the "quick responders" concept with different approaches
- Measures to organize work and to reduce nuisance to users during the renovation of tunnels
- New tools for maintenance and operation

The quick responders approach is generally considered to be an appropriate measure. However, local requirements must be carefully considered. Specially equipped motorcycles are recommended as suitable responding vehicles.

In the second category, various approaches are possible, and these should be tailored as closely as possible to the renovation project in question. Public information campaigns can be just as important as technically sophisticated traffic guidance installations and design adaptations.

New tools such as BIM (building information modeling) and CAFM (computer aided facility management) derived from it are future methods of viewing tunnels like "machines" that can be calculated as digital twins. The maintenance status of the components is continuously monitored and measures are derived from this. Probabilistic approaches, e.g. on the basis of the RAMS ISO-standard (reliability, availability, maintainability, safety), can be used to take failure probabilities into account. Such methods are already in use in some cases, but are particularly effective if the methodology can already be deployed during the initial design and construction phase.

CONTENTS

1. INTRODUCTION

As can be concluded from the previous reports of the Tunnels Technical Committee, the major complications in the operation of an urban road tunnel are connected with the large traffic volume and specific traffic characteristics. Urban traffic poses high demands for the management of traffic, incidents and maintenance, not only for the tunnel but also on the surrounding network. As an important item of infrastructure in the urban area in terms of economy and mobility, there is constant pressure to reduce the duration of closure of urban tunnels.

Case studies are particularly suitable for providing an insight into the implementation of these special requirements in terms of maintenance and traffic management in different countries. Experts from seven countries in Europe and overseas have presented their experiences, challenges and special solutions in these case studies.

The case studies can be roughly divided into three categories:

- Implementation of the "quick responders" concept with different approaches
- Measures to organize work and to reduce nuisance to users during the renovation of tunnels
- New tools for maintenance and operation

The case studies provide interesting insights into different approaches to solutions in different countries.

2. METHODOLOGY

The information comes from experts of the working group WG1, which discussed and deepened these topics at the working group meetings.

in order to obtain a unified grid, a structure of information was given, which included the following chapters (whereas the format is used as a guideline):

- Objectives
- Scope
- Requirements
- Technical challenges
- Non-technical challenges
- Lessons learned

3. IMPLEMENTATION OF "QUICK RESPONDERS" CONCEPT

Four case studies deal with the problem of being able to deal with incidents in the shortest possible time. These case studies deal with so-called quick responders approaches, especially with regard to the use of patrol squads and specially equipped motorcycles for first response to incidents of all kinds, including fires.

3.1. Quick Responders in Eurasia Tunnel Istanbul

3.1.1. Objectives:

The rapidity of the response to an incident in a tunnel is key for safety and asset protection, especially when a fire is declared or likely to. Within Eurasia tunnel, allowing only light vehicles, fires will be small in terms of heat release rate but might be difficult to attend to, due to potential traffic congestion upstream of the fire.

3.1.2. Detailed Requirements

Response time is very stringent: the time elapsed between activation of the appropriate response by the facility control room operator and the operator’s personnel attending to the incident site must not exceed 4 minutes on average over calendar month. For each incident, it shall not exceed 15 minutes. It is not expected that all fires can be extinguished by the operators with light equipment, but at least motor bikers will limit their spread. In any case, the fire brigades from both Asia and Europe sides will attend and take over responsibility once on site.

3.1.3. Technical Challenges

The challenges are to purchase and equip motorbikes to tackle fires, i.e. with light fire fighting equipment.

3.1.4. Non-Technical Challenges

Due to the length of the tunnel (4.5 km), it could be possible, if the fire were close to the portal, that the motorbikes could travel all the way from the portal in the direction of the traffic to attend the incident (4,5 km). Therefore it was decided, for periods during day time, to position a patroller in the middle of the tunnel to further reduce the intervention time; there is one motorbike on stand by in each deck so that the patroller can use one of them depending on the location of the incident.

3.1.5. Evaluation

The response time to incident is the relevant key performance indicator (KPI) to evaluate the efficiency of the arrangements. For the year 2020, we found the following good results, which indicate very short response times:

Type of incident (in tunnel)	Average intervention time
Accident	1 min 47 sec
Animal	2 min
Breakdown Vehicle	2 min 37 sec
Claustrophobia	40 sec
Debris	2 min 20 sec

Fire	30 sec
Pedestrian / Cyclist	40 sec
Stopped Vehicle	23 sec
Wrong Direction Vehicle	2 min 22 sec

Type of incident	Average Intervention time
Breakdown/Towed Vehicle	2 min 39 sec
Over Height Vehicle	27 sec
Stopped Vehicle	10 sec
Pedestrian / Cyclist	0 sec
Banned Vehicle	0 sec
Accident	5 min

3.1.6. Lessons Learned

"First response" must be clearly defined so that the roles of the patrollers (1st responders) and the fire brigades are clear; on that basis, training, competency and responsibilities can be defined. The proper arrangements must be made to provide the staff with fresh air while on standby in the tunnel.

3.2. Motorcycle Squad in Yamate Tunnel Japan

3.2.1. Objectives

Motorcycle squads have been introduced for speedy response to incidents/ abnormalities in long tunnels with a narrow hard shoulder. Especially in case of tunnel fire, the squad arrives at the site, sets up and conducts traffic regulation at early stage to prevent secondary disaster.

3.2.2. Technical/Non-Technical Challenges

Only the Yamate Tunnel motorcycle squad is designated as an emergency vehicle for road administrator in Japan. (There are cases of introducing motorcycle vehicles in the fire department.) The organisation of the motorcycle squad is a two-shift system (day shift and night shift) with 6 motorcycles (6 people) 24 hours a day.

The following subjects were resolved when setting up the motorcycle squad

- Acquisition of advanced motorcycle operation skills for the squad members
- A special protective jacket that protects the lives of the squad members
- Establishing bases on both side (portal) and at the centre (junction) of the tunnel
- Barriers used for closing road traffic were installed in advance because motorcycle squad are not able to carry equipment for road closure and/or traffic regulations

3.2.3. Evaluation

The situation and the cost/benefit was carefully evaluated over the years, with the following results:

- The quick dispatch and safety operation of the daily motorcycle squad have been evaluated by the Highway Traffic Police Corps of the Metropolitan Police Department, which is the traffic administrator.
- Since the establishment of the motorcycle squad in December 2007, there have been no accidents or difficulties during operation, except for injuries during training stage.
- The following is a comparison of the number of annual dispatches (accident / breakdown vehicles) and response time (receiving→ arriving) of the motorcycle squad with the traffic patrol vehicles in 2019.
- There are more than 500 dispatches per year, and they are being operated effectively.

Vehicle Type / Case	Motorcycle Squad（motorcycle）		Traffic Patrol Vehicle（four wheels）	
	Number of cases	Arriving time (ave.)	Number of cases	Arriving time (ave.)
Accident	277	12.5min	9,587	16.4min
Broken Vehicle	296	12.6min	8,425	17.3min
Total	573	12.55min	20,216	16.8min

The response time of the motorcycle corps is the time from receiving the incident and starting the engine at the base to arriving at the site.
For traffic patrol vehicles, excluding the number of vehicles that are without emergency dispatch.

3.2.4. Lessons Learned

There were many lessons learned so far; here the two main points:

- This is an example of specialising in the operation and management of the long tunnel with narrow hard shoulder.
- Taking advantage of mobility, it is possible to arrive at the site quickly even on a congested road, but the motorcycle squad cannot regulate traffic using the vehicle as a block like a traffic patrol vehicle (four wheels). Therefore, it is operated as an immediate response specialised for the Yamate Tunnel.

3.3. Contribution of Patrolling in the Operation of Urban Tunnels of Brussels

3.3.1. Objectives

In the operation of urban tunnels, incident management is of utmost importance. In the region of Brussels, the management of minor incidents is still unsatisfactory. To face this situation and in order to improve tunnel availability, it was decided that a call for tender for frequent patrolling of the tunnels and outer roadways would be issued.

Tunnels in the urban districts are primary communication arteries for the mobility and fluidity of traffic in the entirety of the agglomeration. An unprogrammed shutdown of any of them has an evident consequence on traffic in the outer roadways, already close to being saturated, and could disturb the flow significantly. The main objectives of patrolling are as follows:

- Ensuring frequent rounds.
- Ensuring tunnel availability and viability of the outer roadways.
- Intervening at the very start of a traffic incident so as to ensure the efficient protection of tunnels users and to avoid the propagation of a significant event (i.e. intervention by the first responders in case of the start of a fire).
- Intervening as quickly as possible in the case of a technical issue in a tunnel so as to reduce the impact on traffic.

- Preventing risks of potential malfunctions (mainly technical) by means of a visual control, or limiting their impact.

3.3.2. Technical Challenges

The principal technical challenges concerns the early detection of malfunctions that could, in the longer term, degenerate and impact traffic.

This challenge is vital in the region of Brussels-Capital as it aims to reduce as much as possible the breaching of the Minimum Operating Requirements (MORs), which consequently would require a shutdown of the tunnel.

The road administration can solve some of these problems by a visual control of the installation, by performing tests on several items of equipment, even by a wiping of some equipment.

In some cases, it is also possible to limit the impact of the (MOR) by the increase of patrolling in a tunnel. Typical examples would be the loss of a part of video surveillance or lighting, the malfunction of an aid station, etc. In these cases where the eyes and ears of the operator cannot be deployed on the field, it is possible to mitigate this by an increase in patrolling, allowed by the multiplication of rounds through the tunnel.

Another technical issue comes from the implementation of heavy infrastructure shutdowns. Brussels has several tunnel structures wherein the state of wear may force the tunnels in question to be closed for several weeks, if not months.

3.3.3. Non-Technical Challenges

The main non-technical challenge concerns user safety.

Generally, it takes about 30 minutes before emergency services can intervene efficiently in the tunnel. In an urban area, this delay may be increased due to the limited accessibility of the incident location (especially in tunnels). In addition, due to the large number of tunnels in Brussels (25 tunnels), the patrols have a much more profound knowledge of their layout than the emergency services do. Out of these 25 tunnels, 19 are over 500m long with two being over 2km long with an average of 36,000 cars per day (in the range of 20,000 to 55,000).

The fast arrival on site of the patrol allows an immediate intervention (10 to 15 minutes in average, 20 minutes in the worst case), and hence adaptive protection measures can be implemented quickly. The worst case to be treated is a rapid start of a fire. This incident can be fully handled by the patrols (without help from the emergency services) because heavy goods vehicles (HGV), lorries, and the transport of dangerous goods (TDG) are all prohibited in the urban tunnels. In addition, all patrol vehicles are equipped with means of fire mitigation (personal extinguishers for example).

Hence, thanks to 2-wheel motorisation (motorcycles, mopeds, scooters) it is possible for the patrols to intervene in all situations even in a highly congested place. This type of vehicle provides a precious gain of minutes (the average response time reported is about 8-10 minutes), enhancing the safeguarding conditions of users and potentially allowing them to tackle a fire if they have the appropriate equipment (as is the case in other European tunnels). An incident, amongst the most common ones in the tunnels of Brussels comes from vehicle breakdowns. The adoption of “push-vans” that can push vehicles allows the evacuation of the broken vehicle in an extremely short time span (where a classic tow truck would take hours to reach the vehicle at times of dense traffic).

3.3.4. Evaluation and Lessons Learned

For the moment, the specifications of the patrols are in its final writing phase. To evaluate the impact on the system, the service of Brussels Mobility in charge of the project has reached out to other operators that have applied the same approach. They have used their experience feedback and have considered the cases that are allowing notable improvements of the operations and the safety in tunnels.

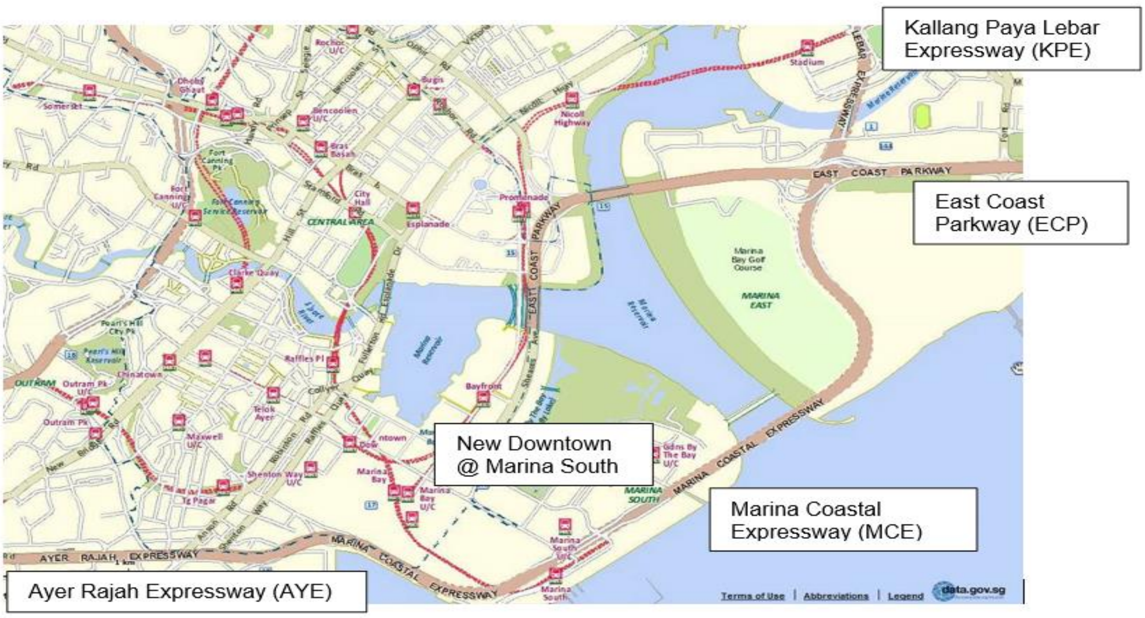
The main points were:

- Implementation of two simultaneous patrols ensuring at the same time a resolution of an incident and the continuous supervision of the other items of infrastructure.
- Possible use of 2-wheel vehicles allowing for a quick intervention in the case of highly congested traffic.
- Possibility to push vehicles out of the tunnel thanks to specially modified vans.
- Prevention of technical incidents by inspections is not yet possible up to present with such a level of regularity.

3.4. Fast response team in Marina Coastal Expressway (MCE) tunnel Singapore

3.4.1. Description

- The MCE is a 5km-long dual 5-lane expressway, of which 3.6km is an underground tunnel. The remaining 1.4km comprises of surface roads, depressed roads and viaduct structures. A 420m stretch of the tunnel runs under the seabed.
- It provides a strategic east-west link between Ayer Rajah Expressway (AYE) in the west, East Coast Parkway (ECP) in the east and Kallang-Paya Lebar Expressway (KPE) along the north-eastern corridor.
- The MCE was opened on 29 December 2013 and being an important link between East and West, it is critical to ensure prompt incident management in an urbanised environment.
- This case study discusses the importance of ground resources deployed to provide timely incident recovery, ensure tunnel safety and traffic connectivity.



3.4.2. Objectives

- Swift response to tunnel incidents and recovery.
- Ensure safe tunnel operations.

3.4.3. Technical challenges / Non-technical challenges

- Tunnel operations (enclosed environment) is critical and will require prompt incident detection, response and recovery.
- Road tunnels are equipped with automatic incident detection cameras, surveillance cameras, air monitoring sensors, linear heat detectors, fire suppression systems, electronics signboards, etc. and these are managed by officers stationed in the Tunnel Operations Control Centre 24/7.
- It is also important to have a team of 24/7 ground resources to respond to traffic incident sites in the tunnel.
- The Land Transport Authority (LTA) Traffic Marshals on motorcycles and Vehicle Recovery Services tow trucks (EMAS) are on standby to be deployed.
- These ground resources are required to reach incident site within 8mins upon activation and to clear/ tow simple breakdown cases within the next 8mins upon arrival. The 8mins target (for both response and clearance) are set out as Key Performance Indicators (KPI).
- For accidents with minor injury, the LTA Traffic Marshals are trained by the Traffic Police to conduct On Scene Investigation to expedite incident recovery. Accident cases resulting in serious injury and fatality will still require the presence of Traffic Police officers to conduct investigation. In these scenarios, the LTA Traffic Marshals and EMAS Recovery Crew will assist with traffic control.

LTA Traffic Marshal and EMAS Vehicle Recovery Tow Trucks

3.4.4. Evaluation

- The Tunnel Operations Control Centre monitors the traffic condition and will implement a set of pre-programmed knowledge-based actions & advisory messages during situations of traffic congestion or incident(s).
- The deployment of ground resources comprises of both fast response LTA Traffic Marshal (LTM) on motorcycles and EMAS recovery tow trucks (ie. Vehicle Recovery Services - VRS) have helped to ensure that any traffic incident within the road tunnel is attended to and cleared as expeditiously as possible.

- Since the opening of MCE Tunnel in 2013, the ground resources have generally fulfilled their KPI in ensuring attendance and clearance of incidents by positioning these resources at strategic locations, which is are in the proximity of the MCE tunnel.
- This has had the effect of ensuring that most traffic incidents in the MCE tunnel are swiftly resolved for the benefit of commuters.
- The prompt response of ground resources has met the objectives set out:
  - Ensure safety of motorists involved in an incident
  - Expedite incident recovery
  - Prevention of secondary accidents
  - Ensure the continuity of tunnel operations
  - Perpetuate an efficient traffic flow

3.4.5. Lessons Learned and Recommendations

- Having a team of officers in the Tunnel Operations Control Centre to monitor and manage the road tunnel is important and remains critical.
- It is equally important to have a team of fast response ground resources to attend to incidents in a road tunnel environment.
- These ground resources should be properly trained and possess adequate knowledge and competency to manage a good variety of incidents such as minor accidents, vehicular breakdown and fallen objects.
- The ground response strategy in deploying a team of LTM on motorcycles and a team of VRS on tow trucks enables LTA to deploy agile, well-equipped and competent ground forces round-the-clock, regardless of incident type. LTMs are able to reach incident scenes fast to provide immediate reassurance and assistance to motorists in distress. At the same time, VRS on their arrival, will provide the technical expertise required to recover incident-vehicles of all types.
- A robust monitoring regime that is complemented by a team of agile and competent ground resources will provide a steady platform for road authorities to ensure safe and efficient road tunnel operations.

4. MEASURES TO ORGANIZE WORK AND TO REDUCE NUISANCE TO USERS DURING CONSTRUCTION AND RENOVATION

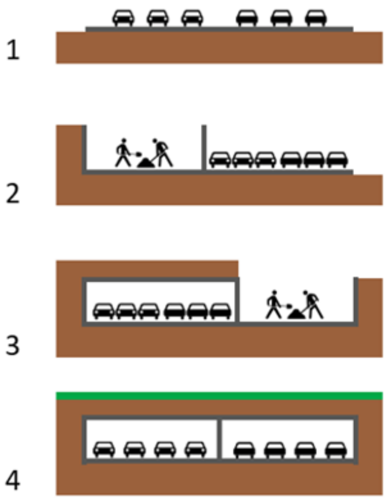
4.1. Safe Traffic Management during the Construction of Tunnels on a Hamburg Motorway A7 / E45

4.1.1. Objectives

The A7 / E45 is a cross-regional European north-south route and in the Hamburg metropolitan region (Germany) influenced by high volumes of commuters with up to 150,000 AADT over 2X3 lanes and short distances between the motorway exits / entries. To improve capacity an extension of the motorway with one additional lane per direction was required. The motorway passes through an urban populated area and therefore the need for adequate noise protection / reunification of urban quarters made it necessary to cover the motorway at three sections.

The resulting three motorway tunnels (appr. 0.5, 1 and 2 km long) north of the existing 3 km long Elbe Tunnel have to be built without substantially interrupting the traffic flow on the A7 / E45 and the surrounding urban network.

Each of the three new two-tube tunnels (Schnelsentunnel, Stellingentunnel and Altonatunnel) is to be constructed in the following major steps:

 	• Construction of the first tube with ongoing traffic on the motorway along the construction side (2). • Bi-directional traffic in the first tunnel tube during construction of the second tube (3). • Bi-directional traffic in the second tube to retrofit the first tube for one-way traffic. • Closure of the motorway for appr. one weekend to retrofit the second tube for one-way traffic. • Opening both tubes for the regular one-way traffic operation with option to switch back to bi-directional traffic for maintenance / refurbishment (4).

4.1.2. Detailed Requirements

Various measures have been developed in order to meet the requirements for network availability without compromising tunnel safety during the construction period (while also being beneficial for the final state). To assess tunnel safety, quantitative risk analyses have been carried out. Different approaches had to be evaluated resulting in the following major elements in the area of traffic management:

Structural

- Niches for ventilation and traffic equipment in the tunnel ceiling to provide clearance of appr. 4,85 m (to operate safely without an automatic height control which leads to interruption of traffic).
- Maximised lane width plus hard shoulder in the final state for being able to operate bi-directional without reducing capacity and safety to an unacceptable extent.
- Physical separation of traffic directions through steel elements during bi-directional traffic with a maximum height of 60 cm in order to be surmountable by tunnel users and emergency services in the event of an incident.
- Manually operated gates in the physical separation before and after the tunnels in regular intervals for emergency vehicles to cross.
- Hydraulic movable gates in the physical separation in the tunnel for disabled persons in regular intervals.

Technical

- Variable traffic signs and lane control signals for bi- and uni-directional traffic
- Movable barriers in central reservation (to switch to bi-directional traffic in case of major refurbishment or maintenance in the final operating state).
- Co-ordination of traffic lights in the adjacent urban road network to prevent vehicles queing back on the motorway and into the tunnels.
- Variable message signs at motorway entries indicating diversions to alternative roads in case of a tunnel closure.
- Quick incident detection and localisation via automatic video detection, inductive loops / radar sensors (congestion, stopped vehicle, obstacles, …).

Organizational

- Speed limit 60 km/h during bi-directional traffic (80 km/h in the final state).
- Congestion monitoring and management via tunnel control center (temporary speed reduction, lane or tunnel closures to reduce the number of vehicles in the tunnel).
- Close interaction between construction site, emergency services and tunnel operator regarding adequate provision of escape ways and emergency routes subject to the progress of construction.
- Dedicated professional fire brigade for the tunnels which also assists to keep the motorway clear (e.g. removal of broken-down vehicles) – on site in 5-10 minutes.
- Installation of permanent traffic co-ordinators during construction period in order to communicate with the public, politics, press, authorities and associations.
- Computer aided co-ordination of all major road construction works within the area of Hamburg to avoid negative interferences (ROADS Software).

4.1.3. Technical Challenges

- Automatic video detection systems need extensive calibration in order to minimize false alarms without compromising the required detection rate – this needs time and requires resources (experts).
- The hydraulic movable gates were implemented by a specifically developed solution. Regular inspections and optimisation (control of pressure and free movement) were necessary.

- Step-by-step realisation, testing of and training on new equipment demands a lot of technical effort (especially with running traffic safely next to the construction site).

4.1.4. Non-Technical Challenges

To ensure traffic flow throughout the construction process with just a few weekends of partial motorway closures possible, very thorough analysis and planning of all phases were required at an early project stage, in order to specify the requirements within all contracts of the project (availability and safety).

With many different parties involved, the essential permanent co-ordination requires outstanding project management skills, in combination with a high level of technical understanding and detailed knowledge of traffic flow on the motorway and the city's road network.

4.1.5. Evaluation

After about four years in the construction process, and two tunnels almost finished, it can be said that the elaborated traffic management elements lead to an acceptable level of availability of the motorway and adjacent areas in the city. Although congestion did occur regularly (especially at peak hours), the tunnel tubes have been built and operated without an overly increased incident rate. Due to a close accident and congestion monitoring, critical spots could be quickly identified, and in most of the cases remedied by (for example) additional traffic signs, modified road marking or relocation of interweaving areas (dynamic process).

The regular briefing and training of emergency services and operators on each construction phase produced a high quality in incident response and therefore minimized reduction of availability.

4.1.6. Lessons Learned and Recommendations

- The more prolonged congestions occur, the lesser is compliance with lane closures via lane signals (lane closures to minimise the number of vehicles in the tunnel). Compliance can be efficiently enforced by audio messages over loudspeakers from the tunnel control center (TCC).
- To calibrate automatic video detection systems in highly trafficked tunnels one needs well trained experts and also a good care for the operators in the TCC who have to deal with a lot of false alarms in the first weeks. To avoid unexpected costs it is recommended to precisely describe the expected level of quality and the necessary expert support within the contracts.
- Carry out as detailed as possible all traffic routing in construction phases already during early design stage in order to provide quick access for emergency services. Make this requirements a binding element in the building contacts, e.g. how many access points have to be provided, the required heights and widths for emergency vehicles passing through the construction site and the minimum time for contractors to clear the access routes from construction equipment in case of an incident.
- From the perspective of tunnel safety (and to avoid unexpected costs) it is crucial to establish the safety concept in a very early design stage and provide it at all project stages continuously to all involved parties - from designers to contractors. Take into account that the safety concept might need to be updated when unexpected changes in planning or in the construction process occur.

4.1.7. Further Information

Some of the above mentioned elements of safe traffic management during the construction of the new tunnels may also be applicable for existing two-tube tunnels undergoing major refurbishment or maintenance with bi-directional traffic in the unaffected tube.

4.2. Availability-optimization for traffic at tunnel Amras Austria

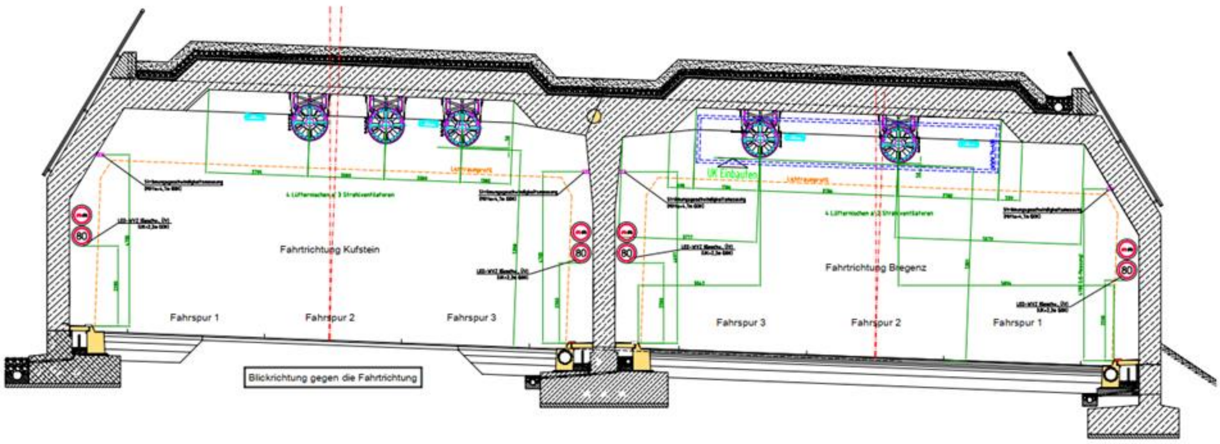
4.2.1. Objectives

Discussion are normally held in the planning phase with regards to economic-technical decisions at the interface between construction and operation. In the Amras tunnel near Innsbruck, such a discussion was held and a decision was reached with respect to the necessity for vehicle height control. Instead of installing a vehicle height control system, the safety equipment in the tunnel was placed higher, so that the height control could be omitted.

According to the Austrian guideline for the installation of safety equipment in tunnels, a height control device is required if operational and safety components are installed below a height of 5.3 m above the road surface. Usually jet fans are affected by this regulation.

4.2.2. Detailed Requirements

The Amras tunnel has a traffic load of about 90,000 vehicles per day. Should a height control device be installed ahead of the tunnel, there is a high probability that the device would trigger an alarm (correctly or incorrectly) several times a day. Each activation of the height control device would be associated with a stop of traffic. This would lead to extensive congestion, especially during rush hours.



After a detailed evaluation of the situation, it was decided to build separate fan niches in the ceiling of the tunnel structure. The niches are about half a meter higher than the actual tunnel soffit. This is sufficient to place the jet fans at a minimum height of 5.3 m above the road surface, thus eliminating the height control devices at the portals.

4.2.3. Technical Challenges

While the scope of the safety equipment was reduced by this approach, the construction work of the tunnel was somewhat complex. Since the construction of ceiling niches are state of the art in the construction of buildings, the challenges could be overcome.

4.2.4. Non-Technical Challenges

The non-technical challenges were the different responsibilities of such approaches. While the height control equipment and the jet fans are the responsibility of organizational unit A, the responsibility for the construction work lies with department B and the operation with group C. The technical modification is very simple - the underlying coordination efforts were immense.

4.2.5. Evaluation

For the decision making process a cost evaluation of both variants was carried out. The result showed that the two approaches do not exhibit significant cost differences.

4.2.6. Lessons Learned and Recommendations

The lessons learned of the example are that simple alternative approaches in planning can often lead to major optimisations in operation. The example shown is interesting in so far as a change in technical equipment - without additional costs - leads to a noticeable improvement in the availability for traffic. In doing so, several disciplines have to be balanced. On the one hand construction work vs. operation and on the other hand building department vs. safety department.

4.3. Refurbishment of the Hallepoort-tunnel in Brussels : a global and proactive traffic nuisance reduction programme

4.3.1. Main Objectives: Maintaining the Viability of the City

The Hallepoort-tunnel is an urban tunnel in the centre of Brussels (Belgium) through through which almost 40,000 vehicles pass every day.

As the Hallepoort-tunnel is an important part of the Brussels road network, the aim was to reduce the inconvenience during the renovation works, both for the tunnel users and for local residents. This is why a fully-fledged nuisance reduction plan was drawn up, which could only succeed thanks to close cooperation between engineers and communication specialists.

The main objective was to preserve the viability of the capital by ensuring that the city did not become completely clogged up during the road works in the Hallepoort-tunnel. That is why a great deal of attention was paid to keeping the tunnel accessible when organisating the renovation of this important urban tunnel.

When planning the tunnel closures, the impact on traffic was taken into account on the basis of available data and carefully calculated simulations.

It was found that during a tunnel closure, traffic moves to other roads in the city and on many of these roads the traffic is often (almost) at a standstill. Adding the tunnel traffic would have created major problems that would have endangered the mobility and economic viability of the city.

4.3.2. Accompanying Measures

In order to compensate for nuisance, a certain number of mobility plans and alternative measures were implemented :

- Hyper-coordination zone: Following the first tunnel refurbishment a coordinating committee for construction sites ensures the coordination between various roadworks. It advises positively or negatively on a proposed construction site and the diversion routes.
- Infrastructure adaptations: Temporary lanes, traffic islands and bus lanes were set up in order to organise traffic in such a way as to limit inconvenience. The traffic lights were also adjusted to limit traffic jams in the area.
- Diversion routes and alternative means of transportation: the fewer the motorists who resort to diversion routes, the better the nuisance could be channelled. That is why the choice of alternative routes and alternative means of transport were explicitly put forward.

The commuters had access to various Park & Ride-parkings with transfer facilities to public transport.

From far outside the capital, drivers have been advised to use alternative routes to reach Brussels. Instead of driving straight into the city centre, they were recommended to take the ring road to avoid the working site.

Organising a modal shift: The public transport companies made an extra effort by increasing their offer and a secure cycle route for cyclists was set up near the tunnel.

Pragmatic communication, focusing on solutions: A pragmatic campaign with meaningful messages was chosen. This made more sense than polishing up the bad image of road works with creative ideas. Distributing accurate and valuable information to the right target groups at the right time was necessary.

The format of a weather report announcing climate change formed the inspiration for the communicative approach. Each phase of the road works was the subject of a new proactive communication campaign.

4.3.3. Technical Approach

The renovation of the Hallepoort-tunnel took place in six different phases, each with its own challenges.

4.3.3.1. Before the Start

In the neighbourhood of the Hallepoort-tunnel there are two important hospitals and also numerous large employers. Several information meetings were organised and an ombudsperson was available 24/7 throughout to deal with specific questions and problems.

Flyers were distributed at the most important intersections, selected on the basis of traffic figures. Other means such as an announcing pavement sign and stewards. Another flyer, with specific information, was distributed to local residents.

4.3.3.2. During the Construction

- A website was set up with general information about the reason for the renovation as well as clearly visible infographics showing whether the tunnel was open or closed. The alternative routes and means of transport were immediately put forward.
- Flyers were distributed to motorists at the most important intersections in the neighbourhood.
- A general leaflet distributed door-to-door to local residents in the surrounding municipalities explained the whole reason for the works.
- Social media to easily and quickly reach the right people with up to date informations about the roadworks (mainly Facebook and Twitter).
- A partnership was formed with Waze (navigation app). Thanks to geotargeting, motorists in the neighbourhood were able to see the message about the road works.
- A radio spot to inform commuters about the nuisance was implemented.
- Infographics were used throughout the whole campaign to indicate when the tunnel was (partly) opened or not.
- Posters were provided as a means of communication for the hospitals and major employers.
- An email campaign for companies was set up.
- Very selective use was made of the outdoor advertising network in order to cover the different access roads leading to the Hallepoort tunnel.
- An entertaining animation video told the whole story of the renovation.
- Press relations were also part of the communication plan: a press release was issued at the start at every phase change, and press visits were organised regularly.

4.3.3.3. After the Renovation

At the end of the renovation of the Hallepoort-tunnel, a grand rave party was organised in cooperation with a popular disco nearby. Everyone could apply for free tickets.

4.3.4. Evaluation

From the outset, everyone was convinced of the importance of being able to respond quickly to changing circumstances. Thanks to this, combined with the massive communication actions and the rather dramatic messages about the expected traffic problems, the expected nuisance did not materialise.

Given that the budget for the entire communication campaign was only 238,786 euros - barely 0.625% of the works themselves - one can speak of a large return on investment.

4.3.5. Improvement Points and Recommendations

Despite the positive results, a number of improvement points and recommendations can be made for the future.

- An important problem is the often late decisions of the Coordinating Committee for Construction. As a result, only little time was available between taking a decision on a phase and/or diversion and mapping out its consequences. This often makes it difficult to adapt the accompanying measures and communication actions to them.
- Specifically for the Brussels context, the high turnover and multilingualism of the population limits the efficiency of communication.
- It is advisable to provide for a fixed percentage of tunnels for each (large) construction site for improved nuisance reduction measures. This includes the means of communication but also the means for additional measures such as, for example, the extension of the public transport offer.
- It is also advisable to appoint an annoyance mitigation coordinator for all large construction sites. This can ensure that all measures to reduce nuisance are coordinated and negotiate with the various stakeholders in order to take measures (public transport companies, smart mobility operators, parking agencies, etc.). This person can also act as the link between the stakeholders, the client and the people responsible for communication.

4.4. Traffic Management Measures during the Refurbishment of Tunnels in Oslo

4.4.1. Objectives

The Norwegian Public Roads Administration is completing this year the refurbishment of most tunnels in Oslo following minimum safety requirements from the EU directive on tunnel safety. Even if the tunnels were originally constructed to a high standard, all technical equipment had to be replaced because of the short remaining lifespan on some items. The application of new electrotechnical requirements, the availability of new systems and the structural changes in most tunnels, made it easier to replace equipment and infrastructure than to reinstate the existing ones.

In addition, some structural elements (pavements) had to be repaired or improved, technical buildings in all the tunnels had to be extended, and systems for treatment of water from tunnel washing had to be put in place.

Some tunnels required major structural transformations and needed a complete closure 24/7 (24 hours a day, 7 days a week) for shorter or longer periods:

- In the Smestad tunnel, an older cut and cover tunnel, the clearance had to be increased in in order to implement a passive fire protection on the ceiling and walls. This 500m long older cut-and-cover supports its own deviation route which could have collapsed in case of a fire. The increasing of the clearance was made by removing the pavement and digging up the ground.
- In the Granfoss tunnel, the construction of a concrete tunnel over the road intersection between two tunnels was conducted simultaneously with the renovation of the tunnels. The concrete cover was built to link together two existing rock tunnels for noise protection of the surroundings and urban development.
- In the Ekeberg/Svartdal, which are two parts of the Opera tunnel, connected by a ramp system, large parts of the pavement had to be upgraded because of the thermal isolation underneath.
- In the Vålereng tunnel, the southern end of the tunnel had to be significantly reinforced for approximately 40 m in both tubes for supporting the future railway infrastructure above the tunnel.

For the other tunnels of the program, there was no acceptable alternative to night closure.

This led to an extensive refurbishment and a complicated planning schedule. In Oslo, 30% of the main roads (E18, E6, Ring 3) run in tunnels, so congestion can be created in the closest tunnels on the same road. A major issue is that the main roads are deviation routes for each other, so it was not acceptable to renovate tunnels simultaneously on both roads.

Road	**Tunnel**	**AADT**	**Length**	**Opened**	**Working period**	**Closure**
Ring 3	Smestad	46000	500m	1983	2015-2016	One tube 24/7
E6	Bryn	68000	300m	1969	2016-2017	One tube 24/7
Ring 3	Granfoss	45000	2300m	1992	2015-2017	One tube 24/7
Ring 3	Tåsen	59000	1300m	1999	2016-2018	Night work only
E6	Opera - Ekeberg/Svartdal	76000/ 11000	1580m/ 1300m	1993/ 2000	2017-2019	One tube 24/7 in few months, then night closing
E18	Opera – Festning/ramps	60000/ 14000	1800m/ 600m	1990/ 1996	2019-2020	Night closing
E6	Vålereng	68000	800m	1989	2020-2021	One tube 24/7 in few months, then night closing

Notice that the Oslo network includes several tunnels outside the renovation program:

Ring 3	Løren	58500	1200m	2013	Between Tåsen and Bryn
E18	Opera - Bjørvika	73000	1100m	2010	Immerged concrete tunnel, part of The Opera tunnel, linking Festning, and Ekeberg/Svartdal

Rv162	Vaterland/ Hammersborg	13000	380m/ 370m	1990	Urban tunnels used as a deviation route for Bjørvika/Festning

Wherever possible, contracts state that work is only to be performed at night, and if necessary with some shorter closures during holiday periods.

The diversion of traffic during upgrading works is challenging, because of the lack of alternative routes in urban areas. For NPRA (Norwegian Public Road Administration), it was a deliberate choice not to provide information about detour options on local roads, mainly based on traffic-safety considerations. The presence of trucks outside the main traffic arteries, potentially getting stuck on a narrow road, could eventually lead to chaos in large parts of the network.

The traffic volumes could potentially lead to a collapse of the traffic management system, thus a major issue was to reduce traffic volumes by making road users change their habits, i.e. avoiding rush hours or choose other transportation modes. NRPA worked thoroughly with that issue, by involving various users: association of car drivers, transport firms, schools, local associations, work places and media, in order to find effective measures.

4.4.2. Detailed Requirements

Various measures have been developed in order to meet the requirements for network availability without compromising tunnel safety during the working periods. Different approaches had to be evaluated resulting in the following major elements in the area of traffic management:

Technical requirements

- Variable traffic signs and lane control signals for bi- and one-directional traffic
- Collapsible delineators on a rail to separate lanes with bidirectional traffic in one tube
- Quick incident detection and localisation via automatic video detection (congestion, stopped vehicle, obstacles, …)

Traffic management measures

- Speed limit 50 km/h during bi-directional traffic (70 km/h in the final state).
- Variable message signs indicating congestion, alternative routes
- Information signs with an incentive to late changes for increasing the capacity
- Short term bus and taxi lane, and restrictions for electrical vehicles in this lane (only vehicles with at least two persons were allowed to use the lane)
- Short term solution with shuttle buses from and to parking areas outside the city

Organisational measures

- In order to be able to learn from experiences from one tunnel to another, one contract was established with one lead consultant, assisted by a large number of sub-consultants. We started off with one short tunnel, transferring knowledge from every tunnel to the next contracts.
- Planning of the works was produced as a schedule over several years, in dialog with other infrastructure managers (rail and public transport) with their own schedule of new building and renovation works.

4.4.3. Challenges

- Night working necessitates good organisation for efficient starting and safe ending of the shifts. The tunnel must be controlled and safe enough to re-open for traffic every morning. The works must be conducted so a minimum level of functionality of the equipment inside and outside of the tubes under renovation is ensured.
- It is necessary to implement risk-reducing measures when minimum requirements are not fulfilled because of the ongoing work, e.g. lack of CCTV during shorter periods was compensated with patrolling for detecting incidents and providing help to the road users.
- Recommending other transportation modes in the holiday periods, while trains and metros were impeded by their own tunnel renovation programs, necessitated flexible and dynamic information.

4.4.4. Evaluation

After about 6 years in the refurbishment process, the level of availability can be defined as acceptable. Although congestion did - and still does - occur in rush periods, the traffic system has never collapsed.

Two surveys have been conducted by the Institute of Transport Economics before and after the most challenging periods of the refurbishment program: before the first closure (Smestad tunnel) and before the most challenging closure (the short but heavy trafficked Bryn tunnel) . They show that information strategies have different effects on the target groups, and succeeded in their goals of calming traffic by changing user behaviour, prevent a chaotic traffic situation and especially making the situation acceptable for travellers and inhabitants.

A light reduction in traffic has been registered, mainly due to changes of transport mode (walking and cycling) for the most local travelers, and times of travelling. The effect of each traffic reducing measure has not been precisely evaluated. But they were part of a plan A, and led to such a satisfying situation as a “package” that plan B, containing different measures, was not used.

4.4.5. Lessons Learned

- It was possible to obtain an acceptable level of traffic management inspite of significant capacity reduction by the use of information campaigns, but they had to be precisely tailored to the target groups, both travellers and inhabitants, in order to succeed.

- The first campaign (Smestad tunnel - AADT 45000 veh/d on two lanes) had clear elements of mass-media scaremongering (congestion and chaos), aiming at reducing traffic drastically in the first days, before it gradually came back to its normal volume though with a 5-15 km/h lower average speed.
- In contrast, the second campaign (Bryn tunnel - 68000 veh/d on two lanes) was more multi-faced and lasted longer. Through massive neighbourhood information and use of social media, this campaign extensively encouraged and advised travelers on how congestion could be avoided if people travelled less by cars during the refurbishment phase.
- Further, the campaign directed social media posts and digital advertising towards specific groups at specific times, and by doing so, tailored the messages and opened interactive communication.
- Open and concrete information on the works to be done, showing the importance of it, increased acceptance from the users and created a rather positive attitude (only 3-5% of the travelers were "strongly unsatisfied"). By these means, it led to an increased adaptative behaviour

5. NEW TOOLS FOR MAINTENANCE AND OPERATION

5.1. CAFM AND BIM TO MAINTENANCE IN CZECH REPUBLIC

5.1.1. Objectives

After commissioning (2015) the Blanka Tunnel Complex (BTC), the tunnel manager decided to additionally create a Computer-Aided Facility Management (CAFM) system including the Building Information Modelling (BIM) system. In addition to saving on administration, operation and maintenance costs, the tunnel manager expects optimisation of maintenance processes and activities, simplification of control activities, and a reduction of maintenance time.

5.1.2. Technical Challenges

For information support of BTC administration and maintenance processes, the development of its own CAFM system is underway. The CAFM system uses databases of semantic data from the BIM model. The geometric component is used to visualise specific parts of the equipment or parts of the structure.

The CAFM system includes an analytical part, enabling the analysis of alarm logs from the tunnel control system. This creates an extensive set of data that can be purposefully evaluated by data mining techniques and thus serve to predict maintenance and service. Common statistical tools are applied (ANOVA, regression, neural networks, factor analysis). When processing the complete volume of records for more than 5 years of operation, these may be tasks reaching the volume of big data, so they are not run in the system by default, but the data are analysed externally in appropriate software tools (e.g. Statistica).

5.1.3. Non-Technical Challenges

If BIM is applied continuously during the design and implementation of the construction, the accumulation of information about the construction and installed equipment is gradual. The resulting set of information then can be consolidated without the risk that the data is inaccurate or incomplete. Because BTC is already in operation, it is necessary to create and verify a new detailed database of equipment. This task is very demanding, including the checking and verification of the accuracy of data and information. Time and effort incur additional costs in the implementation stage as opposed to being incurred in the design stage.

5.1.4. Evaluation and Specific Benefits

In addition to its own specific benefits, the implementation allows the stakeholders (manager, investor, designers, etc.) to get acquainted with the process and pitfalls of creating these systems. The knowledge gained can then be used not only in the implementation for tunnels already under operation, but especially in the design phase of future, even more complex tunnels. The tunnel manager assumes that the impact on life cycle costs will be positive over time.

Specific benefits of BIM in general during the operation or reconstruction phase are:

- Clearer management of the facility - quick access to quality information.
- Effective maintenance - quality information ensures more qualified decision-making, predictive maintenance.
- Efficient use of energy - optimization of energy balance.
- Effective implementation of maintenance and operation changes.

- Facility life cycle cost management - BIM allows you to evaluate the Whole Life Cost (WLC) instead of only the investment costs and to reduce the life cycle costs.
- Efficient data transfer between the BIM model and the CAFM system - especially semantic data which serve as a connection between the systems.

5.1.5. Lessons Learned and Recommendations

For the successful creation of CAFM on BIM data, it is necessary to determine the sorting characters and identification not only for the equipment, but also for parts of the facility (buildings, floors, rooms). This structure must be present in the BIM data, ideally already in the design phase. The logic of writing and retrieving information should be uniform and unchanging. However, their determination depends on the needs of administration and maintenance; it cannot be determined only from the point of view of the designer or contractor. BIM and CAFM are not separate systems, but must form one logical unit. Already at the design stage, there should be a clear idea of how the construction will be operated, managed and maintained.

It should also be borne in mind that the availability of the relevant data and their qualitative parameters are a necessary condition for their subsequent analysis. Therefore, the Data Management System (DMS) for records management (documents, photographs, etc.) is also implemented in CAFM/BIM. It is also necessary to work with metadata for these documents and ensure that their structure is compatible with BIM data.

5.1.6. Further Information

In the BTC, the CAFM / BIM system is now used for service management (fault reporting and registration), registration of authorised organizations and persons, registration of events by time and location and management of fire safety equipment. Typical examples of usage on a daily basis, are the planning of the daily work schedule, continuous registration of performed activities and transfer of records of performed maintenance directly to the system, where activities are assigned to each individual device. The registration and management of spare parts and the maintenance system is now being prepared.

5.2. RAMS in Gotthard Rail Tunnel Project Switzerland

5.2.1. Objectives

In the Gotthard Base Tunnel the European standard EN 50126 “RAMS - Reliability, Availability, Maintainability, Safety” was carried out from the planning to the integration. It is therefore a good practical and general example of how RAMS can be applied.

5.2.2. Technical Challenge

The completion of the railway tunnel was subject to strict operational requirements. These were defined using disturbance classes. The influence on the railway system was thus quantified.

Class	Influence on Railway System	Example
1	No longer than 1h influence on timetable stability. The sum of delays of directly affected trains is less than 10 minutes	Emergency braking of a train because of system failure Local outage of GSM-R for 1 minute
2	More than 1h influence on timetable stability. The sum of delays of directly affected trains is more than 10 minutes	Disturbance of wheel-counting apparatus driving on sight

3	Immediate blocking of one track section as result of failure or for fault repair	Switch points not in final position and impassable Rail breakage (ultrasonic failure) Enduring outage of overhead contact line
4	Immediate blocking of more than one track sections (one track) or total blocking (both tracks)	Total failure of signalling / safety devices Total outage of GSM-R

The disturbance classes define the reliability requirements. On this basis, complex calculations are necessary to know the required reliability of the individual systems. Fault trees, statistical data, manufacturer's specifications and other sources of information can be used for the calculations.

Examples: derived requirements for the power supply system

Subsystem	Availability
High voltage power supply	99.941%
Low voltage power supply	99.936%
Power supply transverse tunnel	99.852

The basic principle of reliability prediction and integration of single results of one subsystem into the complete tunnel system is necessary. This includes e.g: basic component data, RAM-interfaces, reliability calculations, disruption protocol.

5.2.3. Calculation of Reliability Values

The procedure for the calculations can be summarised as follows (simplified):

Description: The failure mode, the cause and the various effects of a failure must be known. Therefore the interrelationships of the systems must be known in detail with all interfaces.

Certificates: As many specifications, benchmarks and, if possible, statistical data are needed from the technical systems as possible. However, many manufacturers are very reluctant to release data.

Basic Data: In addition, basic data are required; especially MTBF (Mean Time Between Failures), MTTR (Mean Time To Repair). Here, too, data from the manufacturers are rarely available; in many cases, these data are not even known to the manufacturer or are guarded as trade secrets.

Of particular importance for tunnels are the average repair values MTTR; they are decisive for a rapid restoration of operation. For example, a UPS (uninterruptible power supply) can have an MTBF value of about 40 years with an MTTR of 8 h. An electronic component can have MTBF values of up to 250 years; however, the MTTR value is comparable to that of a UPS, e.g. 4 – 8 h. Based on the now known relationships in the fault tree, it can now be decided that spare parts are also required for a component with an extremely low probability of failure.

Remark: There is a large amount of freely available data for statistical values of reliability data; much information can be found under the term "US Military Handbook", MIL-HDBK.

5.2.4. Lessons Learned

The application of RAMS in the railroad environment has shown that this is possible, but requires immense effort. It is only feasible if precise requirements exist and the technical installations can be specified very precisely. The additional engineering effort only makes sense in large projects and also requires an employer who is willing to pay for the additional effort.

5.3. DIGITAL TWINS FOR TUNNEL VENTILATION – A TOOL FOR DEVELOPMENT, TESTING AND COMMISSIONING

5.3.1. Objectives and Summary

Current trends show that underground facilities become generally more and more complex. In addition, since the occurrence of large fire incidents, standards regarding tunnel safety have increased. At the same time, especially for urban and heavy trafficked tunnels, availability and maintainability become more and more important. Hence, more and more complex systems must be installed and maintained in shorter and shorter time windows.

Within the various safety equipment in a road tunnel, tunnel ventilation has one of the highest degree of complexity in terms of control systems (e.g. longitudinal airflow control for smoke management in many countries). Therefore, a big effort is required for implementing, testing, and commissioning as well as maintaining the control system. Using conventional methods, it is difficult – if at all possible – to conduct all the required tests in the workshop or on site. By using a digital twin of the tunnels aerodynamics and ventilation equipment, the control system can be developed, tested, and commissioned in a more reliable and more efficient way.

The Tunnel-Ventilation-Simulator is such a virtual twin, able to simulate aero- and thermodynamics of an underground facility in real time and able to interact with the control system of the tunnel ventilation.

5.3.2. Scope

The tunnel ventilation system heavily contributes to safety in the event of fire aiming at allowing the tunnel users to escape by managing smoke, heat, and pollutant propagation. This incorporates not only powerful fans but sensors and controls too. In most countries, detailed guidelines on system design are given by national standards. The Federal Roads Office (FEDRO) standard ASTRA 13001 is applied in Switzerland (available in German and French from www.astra.admin.ch). But regarding the controls of the ventilation system, corresponding standards are often missing or are very rudimentary. As the tunnel ventilation has one of the highest degree of complexity in terms of control systems, new tools for testing are needed in order to cope with this degree of complexity and the number of tests to perform.

5.3.3. The Project

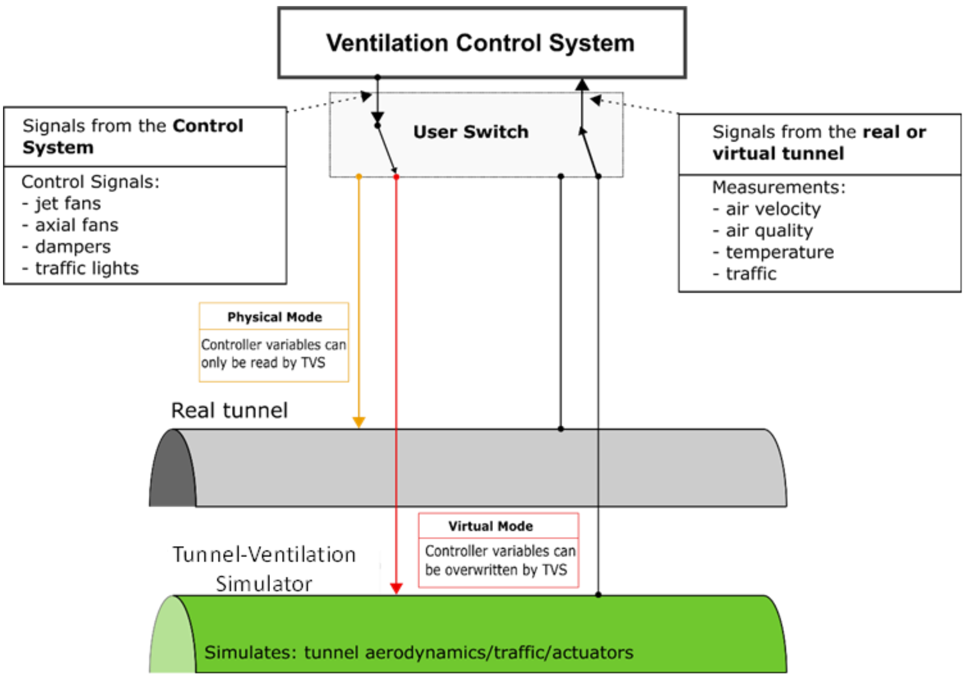
The Einhausung Schwamendingen (EHS) in the urban area of Zurich, Switzerland is a project extending an existing two bore tunnel (length: 800 m) by enclosing the existing road to a total covered length of about 1,800 m. The highway A1L is one of the primary axes leading to the city-centre with a daily traffic volume of about 100’000 vehicles per day. The enclosure of the highway creates a unique park on its roof, reunites the city districts separated for decades by the trafficked 4-lane highway, and reduces significantly the emissions (noise and pollution) to residents. To prevent a traffic breakdown, the service level of the road must be maintained during the except for short, isolated periods (only at night).

In terms of the ventilation system, the project has some special features. The tunnel is equipped with 12 exhaust fans per tube instead of 2, as it is usually the case in a “standard” smoke extraction system. Also, different types of jet fans (differently powerful and differently driven) are used. Some of them can only blast in one direction due to their positioning at the portals. In the context of the optimising of the project, the future ventilation system must become operational at the time when there remains a gap of 200 metres between the existing tunnel and the newly built enclosure. At this time, natural ventilation can no longer guarantee tunnel safety in case of fire. Besides the impact of the gap on aerodynamics, some components of the ventilation system will not yet be available. Due to these circumstances proper commissioning of the control system is not possible when using traditional means. The use of a digital twin offers significant advantages.

5.3.4. The Digital Twin for Tunnel Ventilation

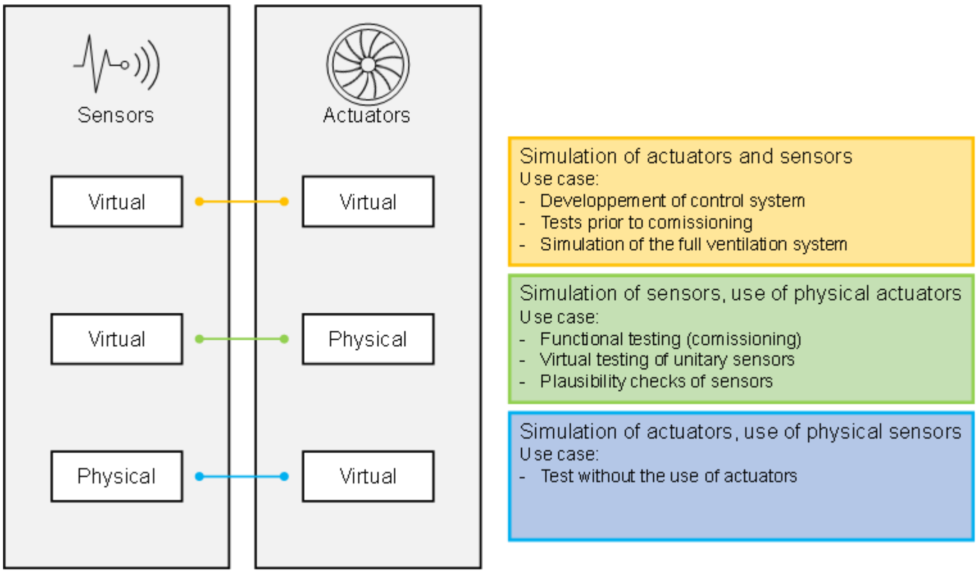
The Tunnel-Ventilation Simulator (TVS) is a virtual representation of the tunnel that allows the control system to interface and interact with its virtual actuators and virtual sensors. Using a sophisticated modelling technique, the TVS simulates in real time the aerodynamics and thermodynamics of an underground structure, considering traffic (volume, composition, speed on every lane), environmental conditions (temperature and wind, ambient pollutant concentrations) and, if desired, fire events. The TVS also incorporates the specific ventilation equipment (jet fans, dampers, exhaust fans for smoke extraction, exhaust fans for environmental protection, sensors), an incident detection system (thermal sensor and smoke detectors) and tunnel closure equipment (here: traffic lights). The ventilation control system communicates to the real field level and to the digital twin using exactly the same interface technology (e.g. OPC UA). Based on the values from the simulator, the control system will react, adjust its outputs, and therefore interact in real time with the digital twin simulating and visualising itself the effects.

Generally, the Tunnel-Ventilation Simulator acts as standalone entity and is set up without interfering to the tunnel design and construction process. Only the interface between the simulator and the ventilation control system needs coordination with the control system developers. For the algorithms of the control system, no difference is made whether input/output are connected to real or virtual equipment. Having a sufficiently accurate aerodynamic model of the tunnel, no adjustments must be made regarding the multiple parameters on the control system is deployed on site. The principle of the Tunnel-Ventilation Simulator as a “digital twin” of the real tunnel is shown below.



The Tunnel-Ventilation Simulator uses separate communication channels for the physical and the virtual tunnel. Therefore, the operator of the control system can constantly choose whether he wants to use actuators and sensors of the real tunnel or the virtual tunnel even once the tunnel is in operation. Using different communication channels, no mix up of real and simulated values can be made once the Tunnel-Ventilation Simulator is connected.

Besides full virtual testing and commissioning, the Tunnel-Ventilation Simulator allows to combine virtual and physical equipment as shown below, resulting in even more possibilities to test and maintain the ventilation system.



5.3.5. Advantages of the Digital Twin for Tunnel Ventilation

By using a digital twin for tunnel ventilation, one can overcome general difficulties during the implementation, testing and commissioning of the control system. On the developer side, the use of the digital twin allows for signal testing as well as functional testing during the implementation of the control system. During testing, the Tunnel-Ventilation-Simulator offers significant advantages compared to traditional test scenarios, as concrete scenarios can be tested and reproduced multiple times. When used as batch or in a time accelerated way, the tests can be performed in a very efficient way or even without assistance. The digital twin also allows one to overcome some of the general difficulties of commissioning a ventilation system on site, in particular the lack of possibilities to consider different filling levels (tunnel resistance), different initial conditions, and the effect of a fire (buoyancy).

By the using the Tunnel-Ventilation Simulator within the Einhausung Schwamendingen, the control system can be fully tested and commissioned for the final stage as well as for all the intermediate stages, independently of the construction progress on site (civil works and equipment installation). Further advantages resulting from the use of the Tunnel-Ventilation Simulator for a project in general as well as specifically for the Einhausung Schwamendingen are as follows:

Realistic test conditions: The functional tests of the ventilation control system can be carried out with realistic, interactively variable scenarios. The input-values used in the tests have a reference to physics and to the specific object. They are not part of the control system or any other test environment of the supplier. In particular, the functionality of the control loops can be tested and optimised in advance. Special cases (e.g. effects of a unit failure) can be tested realistically.

Early test date: The functional tests of the ventilation control system can be carried out in advance compared to tests on site. By this, it is possible to reduce the risk of delays due to unexpected problems. In addition, it can be determined at an early stage whether the control system supplier has followed the design specifications. If necessary, measures can be initiated at an early stage.

Repeatable tests: The Tunnel-Ventilation Simulator allows comprehensive functional tests to be carried out. The otherwise empirical tests can be repeated multiple times using exactly the same test scenario. This minimises the risk of unaddressed special cases or undetected faults.

Functional testing for intermediate building stages: The tightly timed construction programme and the continuously changing building stages do not allow the functional capability of the system to be tested for all intermediate states without the use of the tunnel ventilation simulator. The risk of faulty states and thus reduced safety in the event of a fire incident is reduced to a minimum.

Validation of new software versions: The tunnel ventilation simulator allows new versions of the ventilation control software to be tested virtually using a set of object specific standardised scenarios (non-regression tests). Software updates can therefore be rolled out entirely without on-site tests and without restricting the availability of the traffic route.

Reduction of environmental impacts: Due to the urban location and the special ventilation system, the tests generate a vast amount of noise emissions. These arise on one hand during the commissioning of the single extraction units (during daytime) and during the commissioning, testing and optimising of the complete ventilation system (during night-time). Instead of testing all scenarios on site and optimising parameters, the Tunnel-Ventilation Simulator allows one to carry out most of the tests and optimisations in a workshop. The on-site tests are limited to random samples. This greatly reduces noise pollution for residents, especially since the ventilation tests primarily take place at night and the smoke extraction units are not soundproofed (pure fire ventilation). Furthermore, virtual tests also reduce energy consumption as none of the high-powered fans will be used.

5.3.6. Technical and non-technical challenges

During the development of the TVS, multiple technical challenges had to be met. First and foremost, modelling and simulating the relevant physics in way that allows for real-time numerics and signal exchange, without being restrictive regarding for example the tunnel length, number of portals or amount of equipment. Furthermore, the project-wise interface Tunnel-Ventilation-Simulator – ventilation control system appears to be a technical challenge even though a standard communication technology is used (OPC UA). Unfortunately, there are some limitations regarding the support of variable classes and types depending on the used OPC UA environment.

Many of the advantages resulting of using a digital twin for the tunnel ventilation system cannot directly be translated to financial benefit for the tunnel owner. Furthermore, the use of digital twins is, not yet state of the art. All the above results in the need to justify in depth the additional cost implied by the digital twin for tunnel ventilation.

5.3.7. Lessons learned

As the project is still under construction, the number of lessons learned is limited. Nevertheless, an important lesson is that the decision whether a digital twin is used or not should be taken as early as possible. This allows for proper implementation of the interface in between the ventilation control system and the Tunnel-Ventilation-Simulator.

6. CONCLUSIONS AND NEXT STEPS

The report shows that case studies are particularly suitable for providing an insight into the implementation of special requirements in terms of maintenance and traffic management of heavily trafficked road tunnels in different countries. It has proven useful to group the case studies into three categories, which are:

- Implementation of the "quick responders" concept with different approaches
- Measures to organize work and to reduce nuisance to users during the renovation of tunnels
- New tools for maintenance and operation

The quick responders approach is generally considered to be an appropriate measure. However, local requirements must be carefully considered. Specially equipped motorcycles are recommended as suitable responding vehicles.

In the second category, various approaches are possible, and these should be tailored as closely as possible to the renovation project in question. Public information campaigns can be just as important as technically sophisticated traffic guidance installations and design adaptations.

New tools such as BIM (building information modeling) and CAFM (computer aided facility management) derived from it are future methods of viewing tunnels like "machines" that can be calculated. The maintenance status of the components is continuously monitored and measures are derived from this. Probabilistic approaches, e.g. on the basis of the RAMS ISO-standard (reliability, availability, maintainability, safety), can be used to take failure probabilities into account. Such methods are already in use in some cases, but are particularly effective if the methodology can already be used during the initial design and construction phase.

The case studies provide interesting insights into different approaches to solutions in different countries, but it also became apparent that each case must be considered on its own merits. The findings cannot simply be transferred to other tunnels or situations. Further, more in-depth analyses are needed in each individual case.

The next steps are now to deepen and further explain the findings of the case studies in a full technical report. Questions like: In which cases is the application of a special maintenance and operation method worthwhile? How can the cost-benefit ratio be estimated? To what extent is specific expertise needed for the implementation of such methods? will be addressed and corresponding recommendations formulated.

7. GLOSSARY

Term	Definition
AADT	Annual Average Annual Daily Traffic
BIM	Building Information Modelling
BMS	Battery Management System
CAFM	Computer-Aided Facility Management
CAN	Controller Area Network
CCTV	Closed Circuit Television
CBA	Cost Benefit Analysis
GSM-R	Global System for Mobile Communications – Railway or GSM-Railway is an international wireless communications standard for railway communication and applications
MCE	Marina Coastal Expressway Singapore
MOR	Minimum Operation Requirements
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OPC UA	Open Platform Communications – Unified Architecture; a platform independent communication standard
RAMS	Reliability, Availability, Maintainability, Safety; based on European Standard EN 50126
RAM	Reliability, Availability, Maintainability; based on European Standard EN 50126
TVS	Tunnel Ventilation Simulator
WLC	Whole Life Cycle or Cost

World Road Association (PIARC)

La Grande Arche, Paroi Sud, 5e étage, F-92055 La Défense cedex