www.piarc.org
2017R02EN

# ROAD TUNNEL OPERATIONS: FIRST STEPS TOWARDS A SUSTAINABLE APPROACH

Technical Committee 3.3 *Road Tunnel Operations*
World Road Association

WORLD ROAD ASSOCIATION
MONDIALE DE LA ROUTE
AIPCR 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 2012 – 2015 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)*
*Tour Pascal B - 19e étage*
*92055 La Défense CEDEX, FRANCE*

*International Standard Book Number: 978-2-84060-470-9*
*Frontcover © PIARC Technical Committee C3.3 Road Tunnel Operations*

# ROAD TUNNEL OPERATIONS: FIRST STEPS TOWARDS A SUSTAINABLE APPROACH

Technical Committee 3.3 *Road Tunnel Operations*
World Road Association

# AUTHORS/ACKNOWLEDGMENTS

This report was prepared by working group 1 "*Sustainable Road Tunnel Operations*" of Technical Committee C3.3 "*Road Tunnel Operations*" of the World Road Association PIARC.

The contributors to the preparation of this report were:

- Véronique AURAND (France), secretary of the working group,
- Frédéric HERVE (France)
- Yannick MALLET (France)
- Jean-Claude MARTIN (France), chairman of the working group,
- Tshibela Arthur KABUYA (Belgium)
- Kristin VAN DER AUWERA (Belgium)
- Ronald MANTE (The Netherlands)
- Urs WELTE (Switzerland),
- Nikolaos VAGIOKAS (Greece)
- Fernando PORTUGES (Spain)
- Massimiliano FRESTA (Italy)
- Carlo BARBETTA (Italy)

Additional data was provided by:

- Alexander WIERER (Austria)
- Wei LIU (China)
- Hideto MASHIMO (Japan)
- Wah Onn Adrian CHEONG (Singapore)
- Nam-Goo KIM (South Korea)

This report was edited by:

- Kristen DROUARD (France) for the English version,
- Jean-Claude MARTIN (France) for the French version.

The translation into French of the original version was provided by ADT.

Within the Technical Committee, Harald BUVIK (Norway) was responsible for the quality control of this report.

The Technical Committee was chaired by Ignacio DEL REY (Spain). Marc TESSON (France), Fathi TARADA (United Kingdom) and Juan MARCET (Argentina) were respectively the French-, English- and Spanish-speaking secretaries.

2017R02EN

# ROAD TUNNEL OPERATIONS: FIRST STEPS TOWARDS A SUSTAINABLE APPROACH

In terms of sustainable development, the current situation in the field of infrastructure varies greatly from one country to another. Certain countries have laid down regulations; a few have set objectives to be achieved, while others have no regulations at all. So far, the World Road Association has not issued any recommendations for road tunnels which reflect the current 'State of the Art' in various countries. This document has therefore been produced as an initial means of making up for this shortfall.

The main focus of the report is on tunnels already in use. However, as the options available for the operation of a tunnel are closely linked to the design and construction stages, the scope has been extended to all phases in the tunnel life. New tunnels are taken into account, with a range of economic, social and environmental aspects that could be considered when appraising schemes. Therefore, the construction phase and, most importantly, the design phase have been included in the reflections.

An international survey was conducted in order to obtain as much information as possible. Many responses were received. This helped provide us with a broader vision of sustainable development practices. This report describes the results obtained from countries which answered.

Firstly, the report defines the concept of sustainable development and, in particular, its relevance to road tunnels. It then examines existing regulations across the world, focusing particular attention on regulatory texts and requirements applying to road tunnels. Given the constant and rapid changes in this area, we cannot strive to be exhaustive.

The report then goes on to provide an inventory of the main methods that can be used to assess the impact of initiatives undertaken within a sustainable development approach.

Special attention is then paid to initiatives undertaken in the field of road tunnels, with both traditional cost-reduction actions and actions that encompass a more sustainable development approach.
The report ends with recommendations and, to conclude, avenues for future studies in the field of sustainable development.

## SOMMAIRE

**1. SUSTAINABILITY** .......... **5**
1.1. THE GENERAL CONCEPT .......... 5
1.2. THE THREE PILLARS .......... 5
1.3. BALANCING THE PILLARS OF SUSTAINABILITY AND COST EFFECTIVENESS .......... 7
1.4. APPLICATION WITHIN THE FIELD OF ROAD TUNNELS .......... 8

**2. EXISTING FRAMEWORKS FOR SUSTAINABILTY** .......... **15**
2.1. NATIONAL REGULATIONS .......... 15
2.2. REQUIREMENTS APPLICABLE TO ROAD TUNNELS .......... 16
2.3. TUNNEL MANAGERS OR TUNNEL OPERATORS POLICY .......... 17

**3. EVALUATION METHODOLOGIES** .......... **21**
3.1. REQUIREMENTS .......... 21
3.2. SCOPE .......... 21
3.3. EXAMPLES OF METHODOLOGIES .......... 22
3.4. SUMMARY .......... 23

**4. OPERATING COSTS AND SUSTAINABILITY** .......... **25**
4.1 CONTEXT .......... 25
4.2. OBSERVATIONS .......... 25
4.3. ACTIONS TO REDUCE TUNNEL OPERATING COSTS .......... 26
4.4. ACTIONS THAT REFLECT A MORE SUSTAINABLE APPROACH .......... 30

**5. RECOMMENDATIONS** .......... **40**

**6. CONCLUSION** .......... **42**

**7. BIBLIOGRAPHY / REFERENCES** .......... **43**

**GLOSSARY** .......... **44**
**APPENDICES** .......... **45**

**1. APPENDIX A: QUESTIONNAIRE** .......... **45**

**2. APPENDIX B: SUMMARY OF THE ANSWERS TO A SPECIFIC QUESTIONNAIRE ADAPTED TO FRENCH SPEAKING ROAD TUNNEL OPERATORS** .......... **50**

**3. APPENDIX C: FLOW DIAGRAM FOR DECISION MAKING** .......... **52**

**4. APPENDIX D: EXAMPLE OF SOCIAL CONTRACT CLAUSES** .......... **53**

**5. APPENDIX E: CASE STUDIES** .......... **54**

# INTRODUCTION

With the world population increasing, and several natural resources running scarce, sustainable development has justifiably become a topic of interest in various domains of society in the past decades. The field of infrastructure is no exception. However, within this field, there are few guidelines and best practices available that specifically address the sustainability of road tunnels. Moreover, so far, the World Road Association has not issued any recommendations for road tunnels which reflect the current 'state of the Art' in various countries. This is understandable from the viewpoint that road tunnels are just a small part of the road network as a whole. On the other hand, when you take into account that road tunnels are complex and expensive objects, with a life cycle that normally spans more than 100 years, it becomes clear that the concept of sustainable development is of great relevance here. This report was therefore developed as an initial means of making up for this shortfall.

**Scope and aim of the report**

The main focus of the report is on tunnels already in use. However, as the options available for the operation of a tunnel are closely linked to the various stages which preceded its commissioning, the thought process must be extended to all phases in the life of an underground construction. The construction phase and, most importantly, the engineering phase, must therefore be included in the reflections and taken into account in any recommendations.

More precisely, this report aims to:

- Provide guidelines to owners and operators, as well as designers and constructors and/or contractors, on taking into account the sustainability aspects of a tunnel during its life cycle, as well as the possibilities of combining sustainability with a reduction of operation costs;
- Present an overview of current (best) practices and recommendations in this field.
- Highlight initiatives that extend beyond a traditional cost-reduction approach.

In relation to this aim it should be noted that, although the concept of sustainable development is generally applicable, its implementation can differ for various types of operating organizations (public or private or public-private partnership). However, for practical reasons, the recommendations in this report are of a general nature. This means that further "*tailoring*" is needed for specific cases.

**Structure of the report**

Firstly, the report defines the concept of sustainable development and, in particular, how it can be applied to road tunnels. It then examines existing regulations across the world, focusing particular attention on regulatory texts and requirements applying to road tunnels. Given the constant and rapid changes in this area, we cannot strive to be exhaustive. The report then goes on to provide an inventory of the main methods that can be used to assess the impact of initiatives undertaken within a sustainable development approach.

Special attention is then paid to initiatives undertaken in the field of road tunnels, with both traditional cost-reduction actions and actions that encompass a more sustainable development approach. The report ends with recommendations and avenues for future studies in the field of sustainable development.

**Working method**

The information and recommendations contained in this report stem from individual contributions and suggestions made during working group meetings. Moreover, questionnaires were sent out to all member countries of the tunnels committee. The numerous responses received from these countries have provided us with a broader vision of sustainable development practices. Responses were received from European countries (Austria, Belgium, Spain, Greece, France, Italy, The Netherlands and Switzerland), in addition to China, South Korea, the USA, Japan and Singapore. Additional input was provided through a survey conducted in French-speaking countries.

This report describes the results obtained from countries which answered the questionnaires and survey. The recommendations contained in this report have been the subject of in-depth discussions within the working group. They were also presented and discussed on several occasions within the Technical Committee C3.3, then approved by the latter.

The questionnaire template is provided in *appendix A*. The list of answers received within the scope of the survey conducted in French-speaking countries is provided in *appendix B*.

# 1. SUSTAINABILITY

This chapter introduces the concept of sustainable development in a very general way, without going into in-depth details, and then shows how this concept can be applied to road tunnels at different stages of the life cycle (design, construction, operation).

## 1.1. THE GENERAL CONCEPT

The "*sustainable development*" concept may have a slightly different meaning from one country to another, and its scope may vary. We can nevertheless consider that the Brundtland Report[1] and the 1992 Rio Summit[2], set a general framework, and established globally-recognized principles.

According to the Brundtland Report, sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The sustainable development concept is based on three main pillars:

- **Social**: meeting needs in terms of health, education, housing, employment, etc.;
- **Economic**: creating wealth and improving living standards;
- **Environmental**: preserving species, natural resources and energy resources.

In the different fields or areas where this concept can be applied, the end-goal of a sustainable development approach is to find a balance between the three pillars and preserve this balance over the long term.

This sustainable concept is currently a concern for developed countries, but it can be used for developing countries or countries in transition as well, with equal relevance at least.

## 1.2. THE THREE PILLARS

Contrary to certain common beliefs, the concept of sustainable development does not solely rest on the objective of preserving the environment. It also aims to meet social needs and economic requirements. It is thus generally represented by three pillars which should roughly have the same weight.

[1] "*Our Common Future*", a report written by Gro Harlem Brundtland, then Norwegian Minister of the Environment, and submitted to the United Nations in 1986

[2] The Earth Summits are meetings of world leaders organized by the UN and held every ten years since 1972, aimed at defining ways of promoting sustainable development at global level. The first summits were held in Stockholm (Sweden) in 1972, Nairobi (Kenya) in 1982, and Rio de Janeiro (Brazil) in 1992.

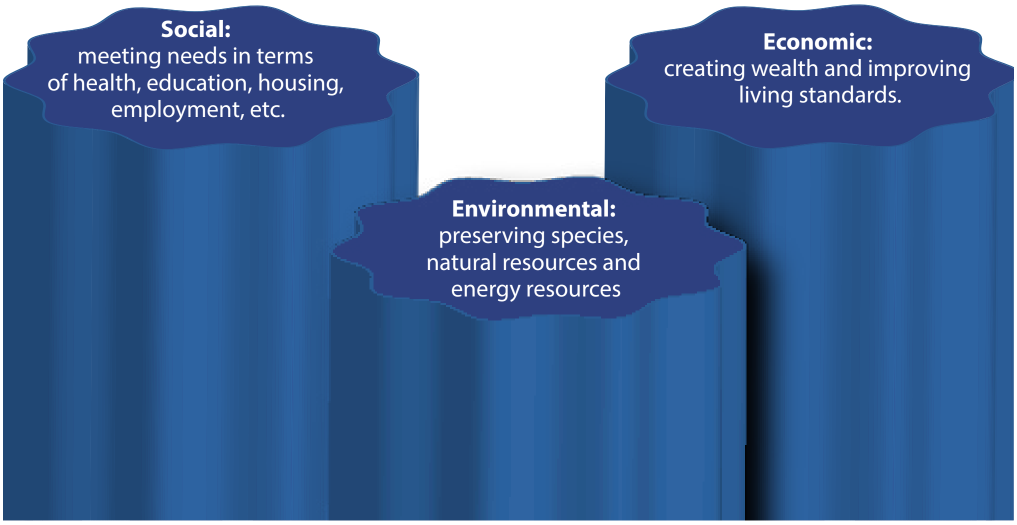



*Illustration 1 - The three pillars of sustainable development*

These pillars are not independent, they interact with one another. The diagram below illustrates this phenomenon:

- If the economic and social pillars are both addressed, then the process is equitable;
- If the economic and environment pillars are both addressed, then the process is viable;
- If the environmental and social pillars are both addressed, then the process is bearable.

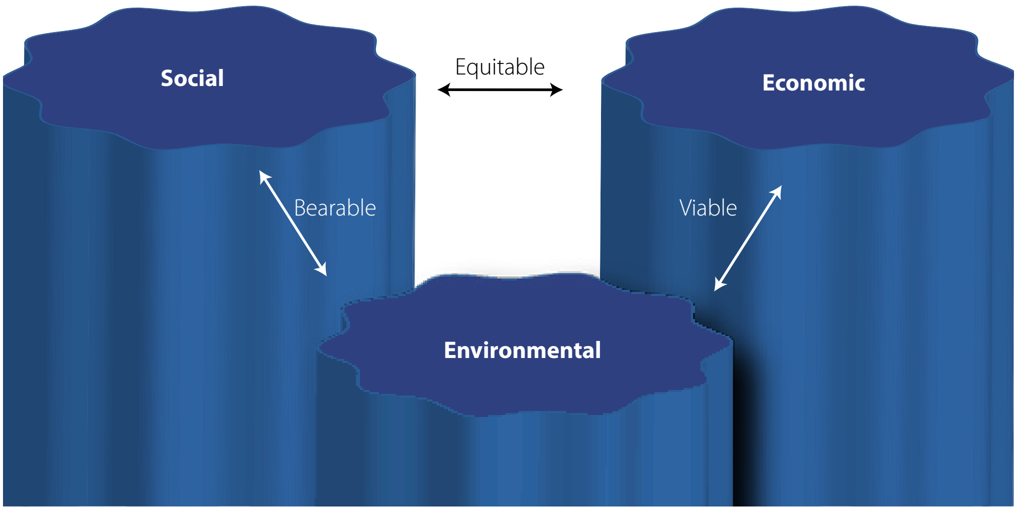



*Illustration 2 - Interaction between the pillars of sustainable development*

The interactions between the three pillars are usually represented as follows:

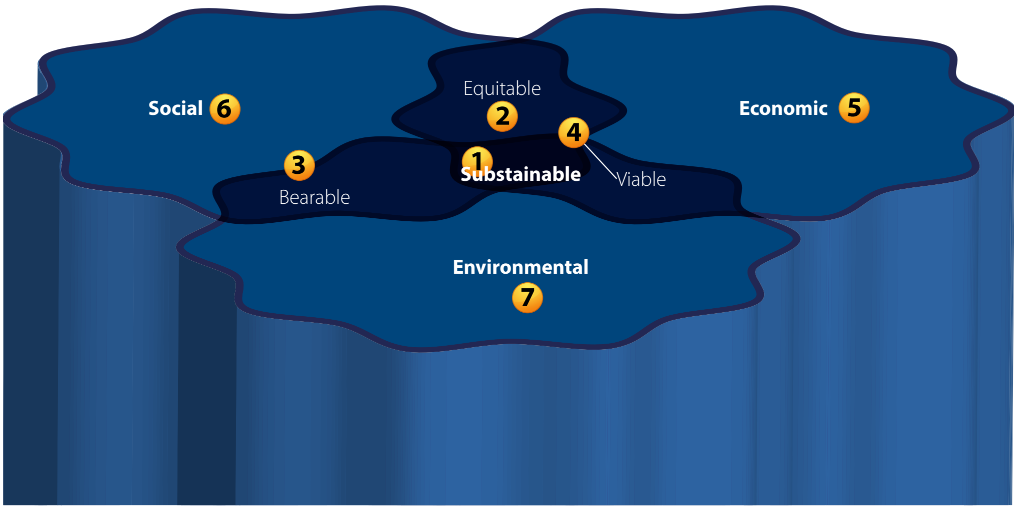



*Illustration 3 - Interaction between the three pillars of sustainable development*

Legend:

1. Sustainable measures, supporting all 3 pillars of sustainability
2. Equitable measures, supporting the economic and social pillar, but not the environmental pillar
3. Bearable measures, supporting the social and environmental pillar, but not the economic pillar
4. Viable measures, supporting the economic and environmental pillar, but not the social pillar
5. Economic measures, supporting only the economic pillar
6. Social measures, supporting only the social pillar
7. Environmental measures, supporting only the environmental pillar

### 1.3. BALANCING THE PILLARS OF SUSTAINABILITY AND COST EFFECTIVENESS

As can be derived from section 1.2, a measure (or a set of measures) can only be considered truly sustainable, if all the three sustainability pillars are supported. In practice, this is hardly ever the case. The construction of a new tunnel, for example, may be beneficial for the economy, and may also have social benefits, but may not always be positive for the environment as a whole, although some positive effects may occur (such as the reduction of vehicle emissions through a reduced distance of travel) and the negative effects are very often are mitigated to some extent.

Thus, in many cases, even on a societal level, the choices made in the field of sustainability are the result of a compromise. Pillars are balanced, using methods like a multi-criteria analysis or a societal cost-benefit analysis to quantify and/or weigh the economic, social and environmental effects of a certain measure being considered (like the construction of a new tunnel).

A multi-criteria analysis may be qualitative, semi-quantitative or fully quantitative, with weight factors being used to express the considered importance (according to the applicable policy) of the various aspects. Thus, one can balance the economic, social and environmental effects of the measure and decide whether or not to implement it.

In a societal cost-benefit analysis, all the effects of a measure (e.g. costs of congestion, diversions, etc.) can be taken into account, quantified and expressed in monetary terms. This makes it possible to add up the economic, social and environmental costs and benefits during the life cycle of the measure, and determine whether or not it is cost effective on a societal level. However, even if this proves to be the case, this doesn't necessarily mean that the measure is sustainable. After all, the measure may be cost effective because the positive economic effects more than compensate the negative social and/or environmental effects. To determine if the measure is truly sustainable, the measure should be cost-effective for all the three pillars. But, even if that is the case, the costs and benefits could be divided unequally between the relevant stakeholders, which means that not everybody will automatically be happy with a certain measure, even if it would be sustainable on a societal level.

## 1.4. APPLICATION WITHIN THE FIELD OF ROAD TUNNELS

### 1.4.1. Starting point of the study

Before we apply the three pillars of sustainable development to road tunnels, we need to set the starting point of our study. The reflection required (and which may involve a sustainable development approach) on whether a road tunnel needs to be built or not, is not covered by our study. We have considered that the decision to build a road tunnel (including its technical specifications) has already been taken by the competent authorities and that the other available solutions had been examined beforehand (bridge, viaduct, open-air road, etc.), but dismissed.

Nevertheless we should have in mind that sustainable development represents a holistic approach of all involved sectors and parameters, as well as an acceptable and balanced weighting of economic, social and environmental objectives. Sustainability accentuates the integrated nature of human activities and therefore the commitment to coordinate planning and design among the sectors, disciplines and groups involved in a project.

Regarding safety, it is a basic condition linked to the three pillars: social (in terms of human aspects), economical (in terms of impacts of accidents) and environmental (environmental damage in case of pollution).

### 1.4.2. Relative influence of each phase of a tunnel's life cycle

The concept of sustainable development may be applied to different fields or sectors, including that of road tunnels, in particular for the operation of this type of infrastructure.

Before we examine this, let us recall that the operation of a road tunnel is highly dependent on the design and construction phases which precede its commissioning. More precisely, it is necessary to take account of the effect of solutions opted for during a project's design phase on subsequent operating conditions. In other words, this means that, if the chosen solution is not ideal, it will be very difficult to optimize it throughout the tunnel's life cycle.

This type of impact is also felt during the tunnel construction phase. Indeed, if the tunnel was not built with care and if its equipment was not installed under high-quality requirements, the gains that can be made during the operating phase will be fairly modest.

A previous PIARC report [2] provides an estimate of the impact of the various phases of a tunnel project on operating costs. The data is presented below and shows the considerable importance of the design phase.

| TABLE 1. IMPACT ON OPERATING COSTS | |
|---|---|
| Design / study | 60 – 80% |
| Building / construction | 10 – 30% |
| Operation / tunnel lifespan | 10 – 30% |
| | 7.3. 10 – 30 % |

The relationship between the cost of maintenance and the level of influence exercised on these costs can be shown diagrammatically (see figure below). The planning phase (study/design) is normally 3 to 10 years, the building/construction phase 2-3 years while the operation phase may be from 5 to 20 years for installations/equipment and 80 to 100 years for the tunnel structure. This does not include for possible refurbishment activities.

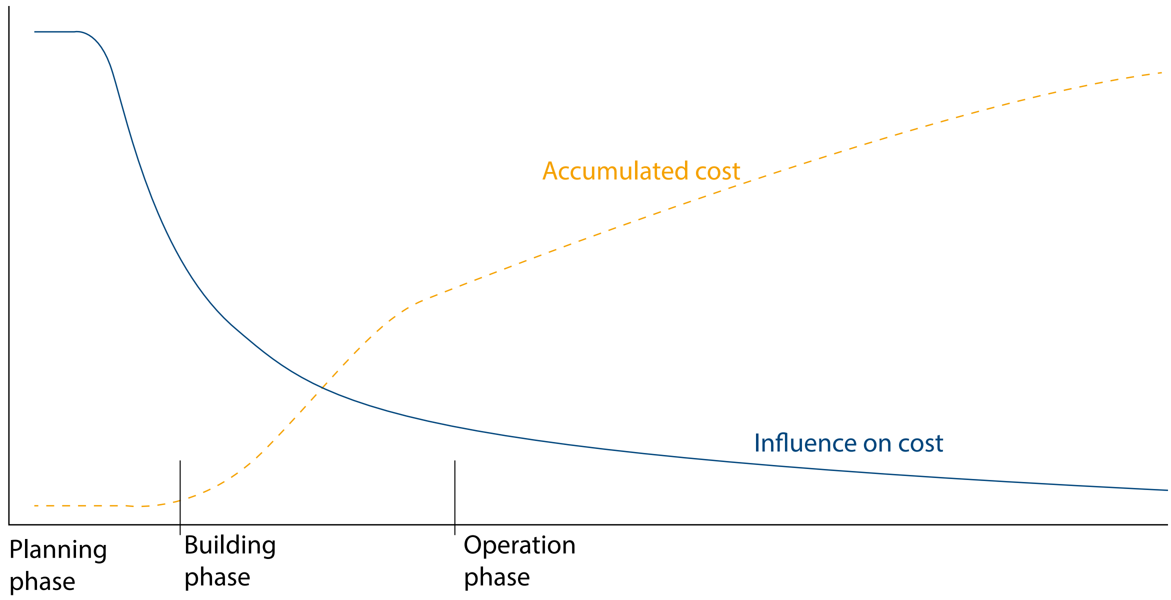



*Illustration 4 - Relationship between the cost of maintenance and the level of influence exercised on these costs*

The impact of the upstream phases, especially the design phase is considerable. Consequently, while the aim of this report is to apply the concept of sustainable development to the operation of road tunnels, an approach of this type must be extended to the upstream phases, notably the design phase.

### 1.4.3. Design / Study phase

**Economic pillar**

A tunnel creates wealth. On a national level, the main part of this wealth creation is due to reduced travelling time, notably for goods transport. It should be noted that the economic benefits of investment in road tunnels are a very complex matter and mostly related to subjective evaluation by decision makers.  However, the economic arguments behind the decision to build a tunnel will largely consider the benefits of doing so against the costs.

The potential benefits from constructing a tunnel may consider the following range of issues:

Road user benefits – due to change in travel time and vehicle operating costs
Journey time reliability benefits – changes in the journey time reliability of the network.
Wider economic benefits – job and housing support, potential for regeneration, agglomeration economics.

The decision making evaluation behind the costs for installing a new tunnel will need to consider three main elements: investment, operating and maintenance costs. Construction and maintenance costs will need to consider the impacts on road user travel time and vehicle operating costs during scheme construction (see below).

The benefits and costs to different user groups could be considered in terms of car use (commuting, business, other journeys), bus and coach, LGV, HGV to provide some examples.

In terms of investment costs, this could include the cost of acquiring land. The costs of the planning and construction would need to be considered; as would the cost of introducing any road user charge (if this was required).

Regarding road user charging - this might be considered as one means of ensuring the economic sustainability of the tunnel operations, particularly for river crossings for two main reasons. Firstly charging as traffic management would manage demand and secondly revenue generated by the user charge scheme would help pay for the new tunnel.

Other aspects that should be considered include the road safety benefits (or costs), impact on indirect tax revenue – due to change in amount of fuel purchased and the associated impact and how a tunnel might impact on wider resilience of network operations.

(See: *http://content.tfl.gov.uk/st-economic-assessment-report-silvertown-tunnel.pdf*)

On a local level, this wealth corresponds to construction and operating revenue.

During the design phase, the optimization of the cost of construction of the tunnel is therefore a stage not to be left out. It will be necessary to take account of the cost of ownership of the tunnel, i.e. the tunnel's construction cost plus the cost of its operation over its entire useful life.

The new tunnel will also improve the living standards of all those who will use it, in particular by reducing their travelling time.

With any economic appraisal, sensitivity testing would be advised.

**Social pillar**

The impact of a tunnel on housing conditions and health may be positive for the residents who will no longer suffer from sound nuisances as they will disappear with the construction of the tunnel. It may sometimes be negative for people living near the portals of the tunnel (if the tunnel was badly designed) who will be subjected to increased sound nuisances or higher pollution levels. The installation of noise barriers could therefore be considered a measure for sustainable road tunnel operations.

In addition, we need to examine the impact that the road tunnel may have on the economic attractiveness of areas which previously had poor access conditions.

The points mentioned above on economic appraisal should also be viewed through the lens of social benefits or costs. For instance, by creating new links through the construction a tunnel, the journey time for someone commuting to work could be greatly improved and this would yield not just economic but social benefits – for instance with greater time with family and friends through a reduced commute time.

Other aspects for consideration for sustainable options could be feasibility for walking and cycle ways, with measures such as dedicated cycleways that could be used by pedestrians being built into the design at the outset.

**Environmental pillar**
The primary aim of environmental protection is to reduce the impact on air, water and ground to a long-term acceptable level.

The benefits of the construction of a tunnel should consider the benefits in terms of greenhouse gas reduction, arising from reduction in travel time and vehicle operating costs.

The preservation of the species living around the tunnel may require the set-up of special measures. These measures may be aimed at restoring passageways for certain species or preserving reproduction areas. In some cases, the position of certain technical facilities may be modified (ventilation units, extraction shafts, etc.).

In order to avoid the exceptional presence of these species on the roadway or in the tunnel (which can present significant risks for drivers and for the species in question) specific measures like fencing or enclosures may be necessary.

The use of natural resources should be carefully examined in the design phase, if possible by favouring materials which have the lowest carbon footprint, or by recycling materials already used elsewhere. Also, to minimize the use of energy resources, the design should take into account the energy consumption during both the construction phase (adapt the design to less energy-intensive construction methods) and the operational phase of the tunnel.

### 1.4.4. Construction phase

**Economic pillar**
It is reminded that design studies must be undertaken with care in order to optimize overall tunnel costs. These studies lead to the choice of certain characteristics for the structure and the installation of certain equipment. Consequently, during the construction phase, it is necessary to ensure that all the planned technical specifications are implemented and that the identified objectives are attained. Finally, it is important to be particularly vigilant with regards to financial aspects, so as to ensure that the cost of works remains within the overall allocated budget.

**Social pillar**
From a social point of view, the construction phase can have quite different effects: either positive or negative.

For inhabitants in the vicinity of the works site, it is clear that the works can pose a nuisance (traffic disruptions, noise, dust, etc.). Suitable measures must therefore be taken to reduce such forms of nuisance, so that residents are disrupted as little as possible.

On the positive side, it is during the construction phase that the impact on employment is the greatest. Tunnel construction requires considerable manpower over a long duration, especially if the size of the tunnel is substantial. This manpower is not necessarily local, but more often than not a considerable part of this manpower is hired near to the works site. Moreover, non-local manpower has an indirect impact on the local economy (hotels, restaurants, etc.).

**Environmental pillar**
With regard to the three components of the environmental pillar (conservation of species, resources and energy), the construction phase has considerable impacts. A tunnel should be built in such a way that the impact on the environment is as low as reasonably practicable. Selected suppliers must:

- apply a sustainable process for building material production and means of transport,
- reduce the distance required to transport building materials to the site,
- use energy-friendly equipment, etc.

All the actions planned for the conservation of animal species present in the vicinity of the works or in the vicinity of the finished tunnel must be undertaken in strict compliance with the environmental specifications outlined during the study phase.

### 1.4.5. Operation phase

As we have already mentioned, the most significant gains will be those obtained at the earliest stages of the project. Unfortunately, this means that the possibilities of applying the sustainable development concept are more promising for a tunnel in the project phase (tunnel to be built) than for a tunnel already in use.

Four main elements should be considered in terms of this pillar: routine tunnel maintenance, reactive tunnel maintenance, lifecycle maintenance and tunnel services (electricity and water).

On top of that, when you apply sustainability principles, as described in section 1.2, at the level of a tunnel manager that is operating a tunnel, additional limitations are to be considered:

- The possibilities for the tunnel manager to support sustainability (on a societal level) in all the three pillars is very limited ;
- The tunnel manager has his own budget to take into account. Preferably, the measure has to be cost effective in terms of the tunnel operation. After all, if a measure is cost-effective on a societal level (for instance: reduction of travelling time, expressed in value of time) this doesn't mean that the measure is cost-effective for the tunnel manager himself (for instance, because of higher investment or maintenance costs).

Still, the tunnel manager can support sustainability during the operation phase, by:

- Improving the measures planned and implemented in the design phase and construction phase, based on an evaluation of the effectiveness in practice. For instance: the measures to preserve certain species, the energy consumption of the tunnel, the air quality around the tunnel, etc.;
- Improving the operating procedures, for instance to enhance traffic flow or to reduce energy consumption, or to reduce nuisance for the people in the vicinity of the tunnel;
- Optimizing the maintenance of the tunnel, by using sustainable methods, or by reducing the non-availability of the tunnel;
- Taking sustainability into account when planning a refurbishment of the tunnel (see design phase and construction phase.

**Balancing sustainability and cost-effectiveness**
In an ideal situation, the measures taken by the tunnel manager are both sustainable and cost-effective (not only on a societal level, but also for the tunnel manager himself). However, as indicated before, in most cases a compromise has to be found, balancing the 3 pillars of sustainability on the one hand, and cost-effectiveness on the other hand.

Since this report is focused on sustainability, the minimum requirement for a measure to be called "*sustainable*" should be that the total effect on all the three pillars is better than, or at least equal to, the present situation (see the definition below).

**Sustainable measure:**
Measure (or set of measures) that, on a societal level, has a positive overall effect on each of the three pillars of sustainability, or at least doesn't have a negative overall effect on one or more of the pillars, as compared to the present measure or situation.

**Cost effective measure:**
Measure (or set of measures) that, for the tunnel manager or operator, has lower life cycle costs, or at least doesn't have higher life cycle costs, as compared to the present measure or situation.
Thus, for the consideration of measures supporting sustainability, the tunnel manager could apply the following decision matrix.

**TABLE 2. DECISION MATRIX**

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">COST-EFFECTIVE MEASURE?</th></tr>
<tr><th>No</th><th>Yes</th></tr>
<tr><td rowspan="2">SUSTAINABLE MEASURE?</td><td>No</td><td>Don't implement the measure</td><td>Consider if the cost effectiveness weighs up to loss of sustainability, according to the applicable tunnel operations policy, and determine whether or not to implement the measure</td></tr>
<tr><td>Yes</td><td>Consider if the sustainability weighs up to loss of cost effectiveness, according to the applicable tunnel operations policy, and determine whether or not to implement the measure</td><td>Implement the measure</td></tr>
</table>

For more details, refer to the decision-making flow chart (see *appendix C*). This decision tree is based on practices in the Netherlands. It can be used by a tunnel manager who wishes to implement sustainable actions, but who must be sure of the cost-effectiveness of the envisaged measures.

### 1.4.6. Overview of sustainability according to the tunnel status

The table below summarizes the results which may be expected in three situations:

- New tunnels for which the concept may be applied at the earliest stages and cover the tunnel structure itself and its equipment, operating procedures and personnel (including training and raising the awareness of personnel on sustainable development);
- Existing tunnels in which a large-scale refurbishment or upgrading programme will be implemented. The scope offered is not as broad as for a new tunnel. However, a sustainable development approach can be used for the equipment to be renovated. This renovation may have an impact on several pillars: impact on the economic pillar (maintenance cost), of course it may nevertheless have an impact on the social pillar (e.g. the new equipment may reduce sound nuisances) and the environmental pillar (through the use of equipment which consumes less energy while providing the same service);
- Existing tunnels where no major refurbishment is envisaged. The only possibilities will consist in optimizing operating parameters, and possibly raising employee awareness on sustainable development.

TABLE 3. IMPACT ON A SUSTAINABLE DEVELOPMENT APPROACH

| Pillar | Issue | Tunnels in project stage | Tunnels to be refurbished or upgraded | Existing tunnels |
|---|---|---|---|---|
| Economic | Wealth creation | Strong | Moderate to low | Very low |
| | Improvement of living standards | Strong | Moderate to low | Very low |
| Social | Impact on nearby housing | Strong | Moderate to low | Low |
| | Impact on human health | Strong | Moderate to low | Low |
| | Impact on employment during construction (or refurbishment) | Strong | Moderate | Non applicable |
| | Impact on employment during operation | Non applicable | Strong | Strong |
| | Economic attractiveness | Strong | Low | Very low |
| Environmental | Preservation of species | Strong | Moderate to low | Low |
| | Preservation of natural resources | Strong | Moderate to low | Very low |
| | Preservation of energy resources | Strong | Moderate to low | Low |

The above table gives an overview of the benefits of a sustainable development approach for the various issues we have identified, according to the status of the tunnel (in the project stage, to be refurbished or existing). Some of the issues are very general and it may be useful to detail their content. Such is the case for the improvement of living standards, the impact on housing and the preservation of energy resources.

The improvement of living standards primarily concerns the reduction of travel time for tunnel users, as well as the safety offered by a new route, in particular in the tunnel. Moreover, for this improvement to be worthwhile it must be durable, i.e. the tunnel must not be closed too often. Therefore, the quality of the maintenance will also be taken into account.

The impact on nearby housing and human health can cover various concerns: air quality, water quality, noise level and the quality of the land surrounding the tunnel.

Lastly, the preservation of energy resources will concern the optimised operation of the tunnel's numerous facilities (lighting, ventilation, etc.).

## 2. EXISTING FRAMEWORKS FOR SUSTAINABILTY

This chapter examines existing regulations across the world in term of sustainable development, with a focus on regulatory texts and requirements applying to road tunnels.

It ends by presenting sustainable development policies implemented by some tunnel managers or tunnel operators.

### 2.1. NATIONAL REGULATIONS

The sustainable development concept first emerged in the early 1990s. Since that time, the issues have been structured through the implementation of regulations and/or laws at various levels. Agenda 21 is an action plan for the 21st century; it was adopted by 173 heads of state at the 1992 Earth Summit in Rio de Janeiro. In 1997, a Protocol known as the "*Kyoto Protocol*" was adopted during the 3rd United Nations Convention on Climate Change. We can also mention the Global Compact, a UN initiative launched in 2000 to encourage businesses worldwide to adopt socially responsible policies. In 2001, the European Council of Göteborg adopted a European strategy for sustainable development.

At country level, numerous initiatives emerged. Here are a few examples (non-exhaustive list):

- **In Austria**: In 2003 the Federal Ministry of Economic Affairs and Employment, in collaboration with other institutions, established guidelines for the preparation of sustainable development reports.
- **In Belgium**: At federal level, there is the law on "*coordination of the federal policy for sustainable development*" (1997). This law foresees a cycle of continuous improvement with a Federal Plan every four years and a Report every two years.
- In France: In 2007, the «Grenelle de l'environnement» laid down new regulations concerning environmental issues.
- **In Germany**: In April 2002, the German government adopted the first national sustainability strategy which has since been reviewed and accompanied by a set of sustainability indicators.
- **In Greece**: According to the Greek Constitution, article 24: "*The protection of the natural and cultural environment constitutes a duty of the State and a right of every person. The State is bound to adopt special preventive or repressive measures for the preservation of the environment in the context of the principle of sustainable development…*" Relevant laws: Law 2742 for the "*Land Use Planning and Sustainable Development*", Law 2508/1997 on "*Sustainable urban development of cities and settlements in the country*", Law 1650/1998 on "*Protecting the environment*", General Framework for Spatial Planning and Sustainable Development (2008).
- **In Italy**, at a national level, the "*Decreto Legislativo 5th October 2006 n. 264*", transposes the European Directive into an Italian law and defines both the minimum safety requirements and the framework for risk assessment application, in order to evaluate different sustainable solutions.
- **In Japan**: At the national level, there is the law on "*foundation of environment policy*" (1993). This law sets the basic idea for establishing an environment-friendly society in sustainable development.
- **In the Netherlands**: The obligation to perform an assessment of the impacts on the environment of certain planned activities, such as infrastructure projects, is regulated in the Environmental

Management Act (In Dutch: Wet Milieubeheer).

- **In Singapore**, the Environmental Protection and Management Act was established in 1999 to provide for the protection and management of the environment and resource conservation. The Singapore Sustainability Blueprint was launched in 2009 in order to improve Singapore's resource efficiency, enhance the urban environment, build Singapore's capability and expertise in sustainable development solutions, as well as build an environmentally responsible community.
- **In South Korea**: At the national level, there are several laws entitled "*Act on Low carbon and Green growth*" (2013), "*Act on the Promotion of the Development, Use and Diffusion of New and Renewable Energy*" (2004), "*Energy Act*" (2006), and "*Sustainable Transportation Logistics Development Act*" (2009). These laws promote sustainable and economic development and management.
- **Spain** approved the "*Spanish directive for efficiency in projects*" in 2010, with the general aim of saving project costs and reducing environmental impacts.
- **In Switzerland**: The strategy of the Federal Department of the Environment, Transport, Energy and Communication (DETEC) on the principle of sustainable development was published in May 2001.

While it is very incomplete, the above list makes it possible to draw a few conclusions. The situation varies greatly from one country to another: some countries have laid down laws or regulations; others have set guidelines; others have not produced any regulatory text. Moreover, even in the countries where regulatory requirements are non-existent, we note that the concept of sustainable development is known and is, at any rate, being considered in numerous current debates.

## 2.2. REQUIREMENTS APPLICABLE TO ROAD TUNNELS

In the previous section, we saw that the regulatory context varies greatly from one country to another. As concerns tunnels in particular, the situation varies significantly: certain countries which have general regulations have no specific texts for tunnels; conversely, other countries, who may not have general regulations, have set requirements for tunnels (regulatory texts, recommendations, etc.). In most cases, existing requirements do not specifically apply to tunnels. Instead, they usually apply to road projects or infrastructure construction projects.

Here are a few examples of requirements which may apply to tunnels and/or buildings (non-exhaustive lists).

In Greece, all tunnelling projects must have an environmental license according to the environmental Law. The Greek Ministry for Infrastructure, Transport and Networks has drawn up the "*Guidelines for Design of Electromechanical Tunnel Installations*" (2002, lighting, ventilation system, power supply, water supply, fire detection and fire-fighting system, traffic management system, communication, SCADA, etc.). Furthermore, in 2004 the "*Guidelines for ordinary maintenance of electromechanical tunnel installations*" were adopted. Risk analysis methodologies have been adopted at the national level in order to support decision making for safety measures and arrangements.

In Japan: "*The Environment Impact Assessment Law*" was enacted in 1997. According to this law, the corporation who carries out a large-scale project, including a long road tunnel, has to predict and evaluate the impact on the environment. If the predicted impact is significant, the project must be improved to be more environmentally friendly, or stopped.

The Spanish Ministry of Public Works has produced several documents which specifically concern tunnel lighting, such as "*Recommendations for road and tunnel lighting (1999)*" or "*Standard for energy efficiency in public lighting (2008)*", along with several technical reports.

In the Netherlands, tunnel availability requirements are documented in the Rijkswaterstaat Tunnel Standard that was developed during the past 2-3 years. Parts of the Tunnel Standard (regarding the prescribed tunnel equipment) are included in the legislation (ministerial regulation under the tunnel safety act) for state owned road tunnels. However, the availability requirements will not be part of the legislation, since this is outside the scope of the Warvw and the European directive. Also, the availability of the state owned road network is already the responsibility of the Ministry of Infrastructure and the Environment, thus making additional legislation in this field unnecessary.

In Italy, the ANAS "*Linee Guida per la progettazione della sicurezza nelle Gallerie Stradali*", are general guidelines applied to the design of M&E systems and to safety issues for the road tunnels owned directly by ANAS. The document, which has general technical validity, suggests requirements for installations from a safety and environmental point of view and proposes a risk assessment methodology to support decision making by the Tunnel Operating Body.

In South Korea, like in other countries, the "*Act on Environmental impact assessment*" was established in 1977. Large-scale projects such as urban development, the construction of industrial estates, energy infrastructure, harbours, railroads, roads, airports, etc. must evaluate the impact on the environment, during and after the construction of the project. For road tunnels, the impact of excavation during construction and air pollution during operation are frequent issues.

In Singapore, environmental impact assessment studies are conducted for large scale infrastructure projects including long road tunnels. The National Environmental Agency (NEA) of Singapore sets targets and guidelines for ambient air quality and noise in Singapore.

The requirements presented above highlight the fact that of the three pillars that constitute the concept of sustainable development:

- the environmental pillar is often the one that is handled the best, particularly in relation to aspects concerning the preservation of natural and energy resources,
- the economic pillar is also handled fairly well, in particular the creation of wealth,
- the social pillar is not always dealt with as well as the other two.

### 2.3. TUNNEL MANAGERS OR TUNNEL OPERATORS POLICY

We saw earlier that the regulatory texts or requirements that exist in certain countries tend to relate more to the study and construction of a structure. This is completely logical insofar as, as we have seen, design has a huge impact on operation. The application of the concept of sustainable development will lead to much more satisfying results if it is applied as early as possible. A person entrusted with operating a road tunnel (or any other type of structure) will struggle to do so sustainably if a sustainable development approach was not taken to the structure's design.

However, despite operation regulations, which are currently neither very comprehensive nor restrictive, many tunnel managers or tunnel operators have taken initiatives.

These initiatives are consistent with a sustainable development approach. Although they stem from the concept itself, they are rarely carried out as part of a global strategy and they only address one of the three pillars. Remember that a global strategy consists, on the one hand, in addressing the three pillars, and on the other, addressing all issues with the same level of detail.

Taking these three pillars and the same themes as previously presented, the table below identifies initiatives that a tunnel manager or a tunnel operator may take in relation to an existing structure.

**TABLE 4. POSSIBLE INITIATIVES FOR A TUNNEL MANAGER OR TUNNEL OPERATOR**

| Pillar | Issue | During operation | During refurbishment |
|---|---|---|---|
| Economic | Creation of wealth | Very few (by optimizing procedures, staff and operating costs) | Very few |
| | Improving living conditions | Maintaining the level of traffic, reducing the number of closures | Improving the quality of the carriageway, reducing the number of closures |
| Social | Impact on nearby housing | Controlling emissions and noise pollution | Reducing emissions and noise pollution |
| | Impact on safety for users | Very few (only procedures) | Many |
| | Impact on employment (during the refurbishment) | Non applicable | Possible (employment of local workforce) |
| | Impact on employment during operation | Very few | Very few |
| | Economic attractiveness | Maintaining global service levels | Improving global service levels |
| Environmental | Preserving species | Maintaining any strategies in place | Increasing the number of strategies |
| | Preserving natural resources | Non applicable | Using recycled materials |
| | Preserving energy resources | Optimizing the operation of equipment | Using equipment that is more energy efficient |

As can be seen in the table above, the initiatives that an operator can take during the operation of the structure, or even during its refurbishment, relate to:

- Improving living conditions;
- The impact on nearby housing;
- The impact on safety for users;
- The impact on employment;
- The economic attractiveness;
- Preserving species;
- Preserving natural resources (mainly for a refurbishment);
- Preserving energy resources.

If we were to create the same list by taking into account the information that operators gave in their responses to the questionnaire[3] we would see that the initiatives which have been taken recently concern, for the most part, the environmental pillar with actions relating to the preservation of

[3] The questionnaire is included as an appendix

natural resources (selective sorting, recycling) and, in particular, actions relating to the preservation of energy resources (monitoring energy consumptions, optimizing energy supplies).

Only a few countries seem to have social requirements regarding impact on employment during operation (Belgium for example, see *appendix D*).

This situation seems to suggest that for road tunnel operators, the concept of sustainable development is primarily seen as an approach relating to the environment, particularly the preservation of energy resources. This can also be explained by the fact that the actions taken to preserve energy resources systematically result in cost reductions. Currently, for road tunnels, just like everywhere else, optimizing expenditure is a major issue.

In the Netherlands, the main requirements for the operation of state-owned tunnels are safety and availability, where safety is a basic condition for the availability of the tunnel. Reliability requirements for the tunnel's technical installations are derived from the main requirements for safety and availability. The design and maintenance of the tunnel therefore aim to achieve the lowest possible life cycle costs, under the condition that safety and availability requirements are always met. Other aspects, like environmental aspects and town and country planning aspects are also taken into account in the planning stage of a tunnel, but mainly at the road network level, since the tunnel is only an object within a larger network and the environmental effects are mainly determined by the network as a whole. All the alternatives for the road are studied and the preferable solution is chosen on the basis of a kind of multi-criteria analysis. In the design phase, the impacts of the tunnel are taken into account in more detail, but with the aim of meeting the legal requirements (and basically nothing more). Energy consumption is also taken into account, but as a part of the life cycle costs, since there is no legislation in the field of energy consumption.

In France, several steps have been taken by operators: optimising electrical consumption, selective sorting, pooling maintenance procedures, collecting effluents in basins, etc. None of these steps form part of a national approach; they are initiated locally by a variety of different operators. The results are not systematically examined. For those which are examined, they are often considered to be satisfactory insofar as they reduce costs.

In Greece, collection of effluents (tunnel road surface liquids) in basins is more or less obligatory, according to the environmental regulations. These effluents are disposed of in final receiver tanks in accordance with environmental requirements. Regulations stipulate that the tunnel operator must assess if sustainability weighs up to the loss of cost effectiveness and determine whether or not to implement the measure. Tunnel managers have taken initiatives in order to optimize electrical consumption (use of LEDs, and some designs have made provisions for solar panels - photovoltaic energy). In addition, following approval by the Administrative Authority, tunnel managers, in cooperation with emergency services, are grouping together several tunnels in order to create a joint control centre. Problems are encountered with availability of emergency services.

In Spain, tunnel managers, have adopted several measures focusing mainly on economic goals, but also taking into account safety standards and environmental concerns. These actions are taken on their own initiative, or following recommendations from the Ministry of Public Works, and are inspected on a regular basis.

In Italy, several tunnel managers have started to adopt and evaluate tunnel management improvements, mainly for economic reasons. ANAS has created a working group "*Gestione de esercizio delle gallerie stradal*" to establish measures focused mainly on economic goals for new projects and maintenance of current installations, taking into account safety standards and environmental concerns.

In South Korea, impact of excavation during construction and air pollution during operation are frequent issues for road tunnel operators.

In Singapore, the tunnel operator utilizes an array of Intelligent Transport Systems (ITS), which includes a variety of applications such as traffic detection, traffic monitoring, travel information displays, real-time control, and communications networks etc., in order to manage incidents in tunnels and mitigate traffic congestion to ensure safety of road users and maintenance crews working in the tunnel. With reduction in traffic congestion, vehicles can travel at optimal speed and reduce unnecessary fuel usage while cutting down on pollution.

# 3. EVALUATION METHODOLOGIES

As described previously the concept of sustainable development is based on three pillars. Therefore, for any innovation planned or already enacted, it is essential to assess the advantages and disadvantages, taking into account the three pillars.

This chapter gives an overview of the different methodologies that can be used in the various countries to incorporate sustainability into the life-cycle of a project: the planning phase, design phase, construction phase, and operating phase.

## 3.1. REQUIREMENTS

Conducting a thorough evaluation requires a methodology and relevant sustainability indicators: monetary evaluation, qualitative evaluation (sustainability rating methodology: e.g. use of a set of indicators. The main indicator could be energy consumption, possibly energy consumption per tube km).

For example, we need to know how sustainability is handled in spatial planning, how the cost effectiveness of the various sustainability measures is taken into account in the design phase, and how sustainability is taken into account in the analyses. We also need to know:

- if sustainability plays a role in the choice of building materials,
- how energy use is taken into account;
- what concept is used for management and maintenance;
- if the focus is only on technical measures or on organizational matters or procedures.

Evaluations must enable a complete assessment of the advantages and disadvantages of any innovation planned or already enacted. This implies three things:

- Any evaluation has to be all-inclusive;
- It has to take into account the entire life-cycle of a system;
- It has to be conducted at different stages (design, construction and operation).

Any evaluation, which is worth its salt, has to judiciously select innovations, as they may seem to be good ideas at the time, but on closer examination, are not. This is often the case for materials which are too complex or sophisticated to use over time or fail to keep their initial promises.

## 3.2. SCOPE

Almost all the existing methodologies to incorporate sustainability in the life cycle of a project are used for buildings. Some of them may be partially or totally used for tunnel projects.

All these methodologies have one thing in common: they all take into account the entire lifespan of the project (or in our case the tunnel). So they deal with the study/design, implementation/construction and operation phases. Some of them even address the issue of reprocessing the materials and equipment at the end of their life cycle.

The vast majority of these methodologies set many requirements at the study/design phase, less at the implementation/construction phase and very few during the operation phase. Along with these very comprehensive methods, there are several countries which also impose requirements in relation to equipment (either in terms of energy consumption or carbon footprint).

## 3.3. EXAMPLES OF METHODOLOGIES

### 3.3.1. NISTRA

In Switzerland, in 2003, the Federal Roads Office (FEDRO) established a method to evaluate road infrastructure projects while taking account of sustainable development objectives (NISTRA). NISTRA is a general methodology applicable for tunnels.

This methodology is based on Swiss norms and standards to define sustainability indicators for road infrastructure projects. It is dedicated to the design phase and is partially usable for other phases.

The project evaluation is performed on the basis of 39 indicators covering the three pillars of sustainability: environmental, economic and social. NISTRA uses defined indicators grouped into economic, social, environmental, monetary and non-monetary indicators for a qualitative cost/benefit analysis. It is an easy-to-use but time-consuming method if conducted completely. Calculation tools are available on the Internet as freeware.

The results are monetized (in Swiss currency) or quantified (in points) or they are represented qualitatively (in words). The results are presented in a clear table. Conflicts of interest which are inherent to road projects become visible.

### 3.3.2. BREEAM (Building Research Establishment Environmental Assessment Method)

In Great Britain, the Building Research Establishment Environmental Assessment Method (BREEAM) created in 1990 is a method of assessing the environmental performance of buildings. It was developed by the Building Research Establishment (BRE), a UK research entity.

This method uses performance measures, which are set against established benchmarks, to evaluate a building's specification, design, construction and use. The measures used represent a broad range of categories and criteria from energy to ecology.

In 2010, a BREEAM in Use certification was published for buildings in use.

### 3.3.3. LEED (Leadership in Energy and Environmental Design)

In North America, Leadership in Energy and Environmental Design (LEED) is a standardisation system for high-performance green buildings created by the US Green Building Council in 1998.

This method is used in the USA to assess the environmental quality of a project. It is based on a rating system for the design, construction, operation, and maintenance of green buildings, homes and neighbourhoods. Points are awarded within major credit categories such as Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality.

LEED EB OM is used to certify existing buildings in term of operation and maintenance.

#### 3.3.4. DUBOCALC

In the Netherlands, the Rijkswaterstaat (a public institution managing traffic by road and waterways throughout the Netherlands) uses the DuboCalc calculation module to evaluate the sustainability of materials and energy for construction projects in civil engineering.

This Dutch software tool calculates and compares the environmental impact (the use of materials and energy) of design alternatives for infrastructure projects or works. It allows for a quick and easy judgment of the sustainability of a design. Thus, DuboCalc can be used alongside the CO2 performance ladder as an instrument to select the most economically advantageous tender. The use of DuboCalc depends on the type of project. Criteria for its use are:

great degree of freedom in design and implementation;
significant environmental results in certain elements of the project.

The way the DuboCalc calculation of the tender (offered alternative) is taken into account as a fictional price discount on the offering price, is determined per project and described in the selection and award criteria that go with the invitation to tender.
DuboCalc is based on a life cycle analysis (LCA) methodology. The model takes into account all the relevant environmental effects (or risks) during the entire course of the project or work (from the construction, to the demolition and recycling phase, or "*from the cradle to the grave*"). The environmental impacts are expressed with the aid of the Environmental Cost Indicator (ECI).

#### 3.3.5. UNI Standard

In Italy, UNI (Entre Nazionale Italiano di Unificazione) has defined the Standard for Tunnel Lighting, based on the CIE 88-1990 and CIE 140-2000, combining safety standards with energy consumption requirements. The UNI standard has become National standard with ordinance dated 14th September 2005.

### 3.4. SUMMARY

In the following table, the scope of each methodology is indicated for the different stages in the lifecycle of a road tunnel.

As we said before, two of these methodologies are used for buildings projects (LEED and BREEAM) and two are used for infrastructure projects (NISTRA and DUBOCALC). These latter two methodologies can therefore be applied to road tunnels.

**TABLE 5. SCOPE OF EACH METHODOLOGY FOR DIFFERENT LIFECYCLE STAGES**

| Methodology | Design phase | Build phase | Operation phase |
|---|---|---|---|
| NISTRA (Switzerland) | Usable | Partially usable | Partially usable |
| DUBOCALC (Netherlands) | Usable | Usable | Usable |
| LEED (North America) | Usable | | Usable (LEED EB OM) |
| BREEAM (United Kingdom) | Usable | | Usable (BREEAM in USE) |

# 4. OPERATING COSTS AND SUSTAINABILITY

## 4.1 CONTEXT

A few decades ago, budgetary concerns were mainly focused on construction costs, and particularly civil engineering costs, since expenditure in this area was much higher than that for equipment installation. Provisional operating costs often took the form of a rough estimate, as on the one hand there were hardly any maintenance costs for civil engineering elements and on the other hand equipment operating costs were considered moderate (in relation to global investment costs for the tunnel as a whole).

This rough estimate of operating costs often resulted in an allocation of insufficient financial resources and many operators had to undertake cost-reduction actions.

Since the early 2000's, new regulations mean that the share of equipment costs in the overall costs of a road tunnel has increased considerably. Equipment operating costs have consequently also increased. Efforts have been made to better estimate equipment operating costs, but without really taking into account the notion of equipment lifespan.

With the increase in the number of equipment items and their complexity, cost reductions have become a major issue for tunnel operators.

More recently, the concept of lifecycle costs has emerged (investment costs + operating costs throughout the lifespan of a given item of equipment) and is increasingly applied, notably thanks to PIARC reports [2] and [5]. Nowadays, when choosing between different equipment solutions in the design phase, the notion of lifecycle costs is taken into account.

Nevertheless, the fact remains that whatever the choices made in the early stages of a project, the budgetary constraints of many countries mean that most tunnel operators are always on the lookout for ways of reducing equipment costs as much as possible.

Finally, there is a gradual tendency for cost-reduction measures to be adopted within a sustainable approach.

## 4.2. OBSERVATIONS

Cost reduction measures have been instigated by tunnel operators for many years now and due to the financial crisis, they are on the increase. A large number of measures undertaken or scheduled are undeniably focused on reductions in energy consumption. Whilst this type of action takes into account the environmental pillar by fostering the preservation of energy resources, it could give the reader the impression of a rather narrowed-down sustainable development approach, since two of the fundamental pillars have not been taken into consideration. It should therefore be reminded that in a sustainable road tunnel operations approach, all three pillars should be taken into account: economic, social and environmental.

In fact, certain cost reduction measures can even have a negative impact on the other two pillars. Each initiative is not necessarily beneficial for all three pillars. Consequently, care must be taken to ensure that any measure carried out to improve one pillar is not detrimental to the two others.

However, it can be noted that within such cost reduction strategies, there is a gradual move towards a more sustainable approach. A certain number of innovative actions have been conducted with a clear step towards sustainable development, encompassing all three pillars. It has been observed that many countries have strategies and targets for energy savings. However, there are legal requirements that need to be met.

The following two sections summarize the current situation, with:

- Section 4.3 focusing on the reduction of operating costs;
- Section 4.4 presenting actions that reflect a more sustainable approach.

## 4.3. ACTIONS TO REDUCE TUNNEL OPERATING COSTS

As we saw earlier, the optimization of initial investments is a major concern for road tunnel designers, owners and operators. In addition to investments, it is necessary to take into account operating costs within a sustainable development approach. This section examines this subject in more detail. First, the various components of the operating cost of a road tunnel are identified. Then, the relative influence of each component is evaluated. Finally, cost reduction paths are presented.

Information on identifying the operating costs of a tunnel, as well as the appreciation of their respective weight is, in some cases, taken from previous PIARC reports [2], [3] and [4].

### 4.3.1 Identifying a tunnel's operating costs

Tunnel costs include energy and power supply, tunnel washing and cleaning, staff (control, maintenance and emergency crews), maintenance (preventive and corrective) and reinvestment (needed for refurbishment).

Some costs vary widely from country to country, partly because the regulatory requirements are different. It is for this reason that operating costs don't include the cost for periodic exercises and inspections, public information campaigns, training of personnel, and the cost of remaining informed on the latest innovations and improvements,

The present guide does not take into account reinvestment costs and we can therefore divide operating costs as follows:

- Energy;
- Maintenance;
- Staff.

**Energy**
Almost all of the equipment installed in a tunnel requires electrical energy which is usually bought from a supplier. Depending on the power required to guarantee the smooth running of equipment, power supply may be high-voltage or low-voltage. Generally, it is high-voltage if the tunnel is equipped with a ventilation system.

For a tunnel operator, energy expenses are directly related to two parameters: the power required for each family of equipment and the duration of functioning of each family of equipment.

Maintenance
The aim of tunnel maintenance is to ensure safe driving conditions for users by keeping the tunnel at the designed technical standard.

All maintenance tasks should be performed as preventive and/or corrective maintenance. As mentioned in a previous PIARC Report [2], these are defined as:

- Preventive maintenance, which keeps the systems in a good and safe condition. Preventive maintenance is justified on the grounds that without it, the systems could become unsafe and/or could only be brought back to a safe condition at high cost. This maintenance has the advantages of ensuring safe and optimum performance of the facility, limiting surprise failures and can be easily planned. The disadvantage is that parts of the facility will be prone to premature replacement.
- Corrective maintenance and/or replacement carried out after systems have become critical or failed. This has the advantage of achieving a maximum lifespan for components of the facility. The disadvantages are that planning is difficult, unsafe situations can arise due to failure and extra costs can be incurred in the event of damage resulting from the failure.

To both types of maintenance defined above, it is now very frequent to associate two other domains:

- The recycling of the various devices used in a tunnel when these devices reach the end of their life cycle;
- The treatment of effluents before their disposal outside the tunnel.

**Staff**
In broad terms, the operating staff can be classified into three categories:

- Operating personnel (control staff and maintenance staff), dealing with traffic management and technical management;
- Administrative and logistical support personnel (administration, finance, staff, management, etc.);
- Incident first response staff. There may be external emergency rescue teams. If the tunnel organization has enough resources they may have their own first response staff.

### 4.3.2 Respective impact of operating costs

The main energy-consuming devices in a tunnel during normal operation are:

- Lighting;
- Sanitary ventilation;
- Safety devices (signalling, closed circuit television CCTV, etc.);
- Pumping (in subsea tunnels or when there is water seepage.

The respective share of each of these energy-consuming systems varies greatly, depending on the specific characteristics of the tunnel: length, gradient, water ingress, etc. Let us consider, for example, the case of a short tunnel: it will not be ventilated (therefore the ventilation element is removed), but it will be lit with entrance zones covering almost its entire length and, due to its shortness; lighting will be a major energy-consumption factor. In contrast, for very long tunnels, the energy-consumption of lighting will be low compared with the energy-consumption of the ventilation system.

In terms of optimization, ventilation and lighting systems are very attractive because the potential gains can be high.

The table below summarizes the impact of broad families of equipment (with the exception of smoke extraction in case of fire) in terms of electrical consumption, according to the length and type of structure (unidirectional or bidirectional). The information provided should be considered as a general trend as the specific characteristics of a particular structure may lead to different findings.

**TABLE 6. POSSIBLE INITIATIVES FOR A TUNNEL MANAGER OR TUNNEL OPERATOR**

| | L ≤ 500 M | 500 M < L ≤ 3 000 M | | L > 3000 M | |
|---|---|---|---|---|---|
| | uni and bidirectional | uni | bidirectional | uni | bidirectional |
| **Lighting** | Very major | Major | Average | Average | Minor |
| **Ventilation*** | No impact | Very minor | Average | Minor | Major |
| **Safety equipment** | Very minor | Minor | Minor | Average | Average |
| **Auxiliaries and miscellaneous losses** | Very minor | Minor | Minor | Average | Average |
| **Pumping** | Minor | Minor | Minor | Minor | Minor |

Note: The information above only has comparative value within the same column (for instance, electrical energy consumed by lighting is greater when the length of the tunnel increases, but its relative share within the total consumption decreases).

* This includes the continuous ventilation of escape facilities and shelters. However, environmental ventilation (air exhaust to avoid portal pollution) is not considered in this table..

Finally, it must be noted that optimization for energy consumption has to be done not only during design and building phases but during all the tunnel life.

**Maintenance**

The maintenance share is difficult to assess as it is largely dependent on the maintenance policy in place.

If maintenance is mainly carried out by the operator's staff then the cost is relatively low, but as the number of personnel increases, staffing costs are greater. In contrast, if maintenance is completely outsourced, associated costs will be greater but the share for staffing costs will be less.

Generally, the operator has internal teams to carry out a significant amount of the maintenance work and will outsource the rest to subcontractors.

**Staff**

Regarding control staff, a legal framework exists in many countries. Some requirements are compulsory, while others are only recommendations. For example, if regulations demand the presence of a supervisor at the control centre 24 hours a day, then this requirement must be met. Similarly, if regulations require patrols (at given intervals) or the presence of first response teams, it would be difficult to reduce the number of personnel on site.

According to the proportion of subcontracted maintenance, the size of the maintenance staff will vary. The use of subcontractors is strongly linked to the maintenance staff (number and competence) which the tunnel operating body can practically and economically fully employ. It also depends on the complexity and the nature of the installed equipment and the specialist skills required.

### 4.3.3 How to reduce tunnel operating costs

It is recommended to use a kind of benchmarking to evaluate the difference between different tunnels, regions, countries (e.g. energy consumption, staff hours…). Some practices are defined in a previous PIARC reports [1] and [2], (for example: optimization of resources and implementation of an operating strategy in compliance with approved safety concept).

**Energy**
In relation to energy expenditure, the first thing that an operator can do, for any given energy requirement is to play competitors off against each other by consulting several suppliers that provide the kind of electricity to be used (renewable energy). This approach assumes that the installation is optimized in terms of the power installed and the operating times of the various pieces of equipment.
In effect, we have seen that energy expenditure is closely linked to two factors: the power installed per family of equipment and each family of equipment's operating time.

For each family of equipment, the installed power is assessed during the study phase and is fixed during the implementation phase. Once the structure is operational, the power can mainly be changed during renovation. At this time, it may be decreased if the regulations haven't changed and if the energy performance of the replacement equipment has improved. It may be increased if regulations have become stricter (for example: greater smoke extraction capacities).

Basically, outside of renovations, if an operator wants to reduce its expenditure on electricity, it can only do so by optimizing the operating times of the installed equipment and by monitoring peak hours.

**Maintenance**
The nature and number of maintenance tasks to be carried out of course depend on the number and characteristics of the installed equipment, but also depend on the level of traffic and the working conditions on the road and in the technical facilities. That said, for any given structure, the operator may optimise its maintenance by focusing primarily on the planning of the tasks to be carried out.

It is important to consider not only maintenance costs but also the social impact of the closure of the tunnel (availability of the tunnel).

To do this the operator may:

- Develop its maintenance plan based on feedback;
- Use a computer-assisted maintenance management system;
- As far as possible, group tasks to reduce road marking costs;
- Establish internal monitoring indicators.

**Staff**
As we have already said, potential gains in terms of workforce optimization often depend on according regulatory requirements.

A greater degree of optimization is possible in relation to monitoring and maintenance methods. For monitoring, it is advisable to group the operation of several tunnels together.
For maintenance, it is preferable to call upon external companies for highly technical tasks if there are not a lot of equipment units.

## 4.4. ACTIONS THAT REFLECT A MORE SUSTAINABLE APPROACH

This section presents a few innovative ideas or studies that have been conducted or are currently being conducted in different fields and in various countries, and which reflect a more sustainable approach (non-exhaustive list):

- Escape gallery for users;
- Lighting;
- Ventilation;
- Air filtering;
- Treatment of effluents;
- Recycling;
- Maintenance;
- Staff and partnerships.

Some of the above-mentioned initiatives have actually been implemented (creation of an escape gallery in an urban context, remotely controlled lighting, more efficient jet fans and filtering of exhaust air).

These initiatives have been assessed (advantages and drawbacks) with regard to their possible economic, social and environmental impacts.

More detailed descriptions of the different actions recorded are provided in *appendix E* (Implementation of an escape gallery in an urban context, light transition arch, remotely controlled light sources, new jet fans, air filtering, optimization of transformers, solar energy).

### 4.4.1. Escape gallery for users

Depending on the regulations of each country and tunnel characteristics, certain road tunnels must be equipped in such a way that they enable users to reach a place of safety (emergency exits, cross-passages between tubes, escape gallery, shelters…). These safety facilities are quite costly to implement, but fortunately seldom need to be used.

**Case study: evaluation of an escape gallery used for additional purposes**
In order to upgrade its safety standards, plans were made to link the Croix-Rousse tunnel (France) to an escape gallery via cross-passages every 150metres, thereby enabling the evacuation of users.

The tunnel owner wished to give additional functions to this escape gallery by allowing its use by public transport, pedestrians and cyclists. This "*tube*" (as the gallery is called) has:

- a bus lane, 3.40 metres in width (in the other direction, the bus travels through the road tunnel)
- a footpath measuring 1.70 metres in width,
- a two-way cycle lane measuring three metres in width in total.

This is an interesting example of the sustainable use of infrastructure for purposes other than those which was initially intended for.

The impact of the multifunctional use of an escape gallery on the three pillars of sustainable development are shown in the table below.

TABLE 7. IMPACT OF THE MULTIFUNCTIONAL USE OF AN ESCAPE GALLERY ON THE THREE PILLARS OF SUSTAINABLE DEVELOPMENT

| Pillar | Positive aspects | Negative aspects |
|---|---|---|
| Economic | Using an investment originally dedicated to safety for urban transport purposes. | Higher construction and operating costs than for a standard escape gallery. |
| Social | The new gallery creates a link between two districts of Lyon.<br>It promotes green transport modes.<br>It provides pedestrians and cyclists with the same service as that previously reserved to motorists.<br>Daily use of a normally empty space that could have turned into a squat. | |
| Environmental | The new gallery helps to promote green transport modes such as cycling and walking. | Permanent lighting. |

### 4.4.2. Energy

For the reduction of energy consumption a benchmarking system may be helpful. It is possible to compare different tunnels of the same type with their energy consumption per annum and km (Kw.h/a*km). Target values could be defined and used as benchmark during design and major refurbishments in order to optimize consumption.

### 4.4.3. Lighting

Lighting is currently one of the installations that is subject to the most innovation, in terms of the size of installations, the use of innovative lighting sources and the recycling of these same lighting sources. In all cases an economic assessment has to be conducted (e.g. return on investment, net present value).

In concrete terms, a lighting installation consists of:

- An entrance zone. This heavily lit zone, spanning a few hundred meters, prevents the black hole phenomenon for users entering the tunnel. The lighting levels used are very high, as is the associated electrical power;
- An interior lighting zone. This zone is lit to a much lower level than the entrance zone, but it covers the entire length of the structure;
- For some tunnels, an exit zone with reinforced lighting could be implemented.

The actions taken are primarily designed to better define the lighting requirements in the entrance zone in accordance with national regulations. With this in mind, systems have been studied to:

- Provide light sources other than through lighting devices;
- Vary the level of lighting provided by devices to adapt it as much as possible to requirements linked to external light conditions;
- Adapt the level of lighting in the entrance zone to the average speed of traffic (e.g. in case of traffic jams) or to the variable speed limit of the traffic;
- Use more efficient dimming systems (e.g. LEDs, which allow a total and quick variation of light);
- Use new lighting technologies, like LEDs sources;
- Use of sunlight to enlighten a tunnel entrance zone.

Other efforts are underway to optimize interior zone lighting. At the moment, most experiments, and in some cases test sites, involve the use of LEDs (light emitting diode) sources.

The economic case for installing LED lighting is compelling with an important saving on energy.

*Illustration 5 - Picture of a lighting installation with LED*

In Spain, for instance, a new national road tunnel lighting standard is being developed. It includes a methodology for assessing a lighting project and deciding what the best lighting solutions are in terms of profitability throughout their lifecycles.

In France, several studies, aiming to contribute to a further optimization of lighting design and an improvement of its use are currently foreseen.

**Case study: Evaluation of remotely controlled light sources**
In order to reduce power consumption, whilst maintaining a sufficient level of safety, a system enabling 9,000 light sources to be remotely controlled was installed in tunnels on the A14-A86 in the Paris region (a 15km underground network in the district known as "*La Défense*").

Reductions in power consumption are achieved in two ways:

- When the lamp is new, the light flow is at a fixed level (between 70% and 90% of its nominal level), in order to adapt lighting to requirements. This solution limits over-lighting at the beginning of a lamp's life-cycle;
- In nocturnal mode: the lighting level is lowered according to the traffic in the tunnel at night.

In addition, maintenance tasks can be facilitated by:

- Optimizing the lifespan of the system by adapting lighting levels to the state of each lamp;
- Predictive maintenance, thanks to data acquisition for each lamp: wattage, voltage, intensity;
- Optimizing maintenance by a remote fault diagnosis.

The impact of this control system on the three pillars of sustainable development is shown in the table below.

TABLE 8. IMPACT OF CONTROL SYSTEM ON THE THREE PILLARS OF SUSTAINABLE DEVELOPMENT

| Pillar | Positive aspects | Negative aspects |
|---|---|---|
| Economic | Reduction of energy costs<br>Improvement of life expectancy for lamps | Initial investment<br>Maintenance of added equipment or construction |
| Social | User safety and comfort | |
| Environmental | Reduction of energy consumption (reduction of $CO_2$ emission and preservation of resources)' | More material use |

### 4.4.4. Ventilation

The term "*ventilation*" combines several functions: sanitary ventilation, smoke extraction, and sometimes ventilation for environmental protection purposes. See PIARC Report [4].

Sanitary ventilation aims, in normal operating conditions, to maintain the air quality inside the tunnel in accordance with country-specific requirements[4]. In the event of fire, smoke extraction is designed to extract and/or control the smoke to enable users to get to safety and to allow emergency services to fight the fire.

The smoke extraction system meets very strict regulatory requirements and thankfully is very rarely used. Therefore, it is not subject to efforts to optimize its operation.

[4] If there are no national regulations PIARC Recommendations could be used

The requirements imposed in terms of air quality are often determined in relation to the permitted concentrations for different pollutants (CO, NOx) and for opacity values (particles). Vehicle exhaust emissions have significantly reduced over recent years, but the type of pollutants taken into account has changed. As such, sanitary ventilation is still very frequently used. As the thresholds to adhere to are set by regulations and as airflow requirements are assessed, innovation can only address the systems which produce this airflow. This is why improvements have been made to the efficiency of air ducts on fans installed in the station (for transversal or semi-transversal ventilation) or on jet fans installed in spaces where traffic is moving (for longitudinal ventilation).

Sometimes the vitiated air is treated before being discharged to the outside. The next section provides explanations on this subject by presenting air cleaning systems.

Optimization of the ventilation process can be done:

- By controlling ventilation based on real time traffic data;
- By considering the natural ventilation (pressure difference between portals);
- By using the existing by-passes located not too far from the portal[5];
- By monitoring the quality of information given by pollution sensors and temperature sensors.

Due to the recent emergence of vehicles using alternative fuels, the operational risks in tunnels may change because of the different characteristics of these vehicle emissions and the impact of these fuels in an emergency situation.

**Case study: evaluation of the installation of new jet fans**
It is noted that when a jet fan is installed in a tunnel, a considerable decrease in thrust occurs when the unit is very close to the vault of the tunnel or in a niche. This decrease can even be as much as 30%.

Equipping jet fans with inclined outlets has enabled a significant improvement in the in-tunnel thrust to be obtained.

In general, the absorbed power by a single jet fan may slightly increase and consequently can marginally impact the final results, but the total installed power decreases because the required quantity of new jet fans is lower than for conventional jet fans.

*Illustration 6 - Picture of jet fans with inclined outlets.*

[5] When there are two tubes, this allows a short circuit for fresh air in the entrance of one tube and the exit of the second one.

The impact of this new type of jet fan on the three pillars of sustainable development can be seen in the table below.

| TABLE 9. IMPACT OF NEW JET FAN ON THE THREE PILLARS OF SUSTAINABLE DEVELOPMENT | | |
|---|---|---|
| **Pillar** | **Positive aspects** | **Negative aspects** |
| Economic | Reduction of operating costs (energy and maintenance)*<br>Lower initial investment (less jet fans)<br>Higher availability of the tunnel for traffic | Cost of new jet fans |
| Social | (No significant impact) | |
| Environmental | Reduction of energy consumption (reduction of CO2 emission and preservation of resources)' | |
| *Depending on the solution retained | | |

### 4.4.5. Air cleaning

We must remember that a road tunnel used by any given vehicle does not lead to more pollution than a journey by the same vehicle in the open air. However, this pollution is concentrated at certain points (each end of the tunnel and/or vitiated air extraction systems). This is why studies of a tunnel's extracted vitiated air are always very detailed, especially when a tunnel is located in a highly urbanized area.

In some countries, vitiated air treatment systems have been put in place, (a non-exhaustive list of examples follows).

**In Spain:** Since the M30 motorway to Madrid runs through a highly dense urban pattern, efforts have been made in order to avoid air pollutants that could eventually reach the population. Thus, several filtering stations are deployed at ventilation shafts along the tunnels. There are two different types of filters; on the one hand electrostatic particle precipitator filters, and on the other hand NO2 active carbon filters.

**In Japan,** some long tunnels in urban areas have been equipped with noise suppressors, electrostatic precipitators and low-concentration nitrogen dioxide (NO2) removal systems in order to minimize the influence on the surrounding environment.

**In Italy,** In Sottopasso di Monza (2.000m long twin-tube tunnel ) that runs between Milano and Monza on a highly dense urban road, in Cesena (central Italy) and in Pozzano (south Italy) tunnel electrostatic precipitators have been installed on the exhaust air extraction system in order to minimize the polluted air impact on the urban environment.

**In France,** the French portal of the Mont-Blanc tunnel is equipped with electrostatic precipitators for particles in the exhaust air.

**In Norway,** there are a total of 8 tunnels with electrostatic precipitators:

- The environmental requirements for particle cleaning, both inside and outside Norwegian road tunnels, have to a high degree been politically motivated.
- With the exception of two tunnels (Strømsås and Lærdal) the precipitators initially used were first generation and were in operation over the period 1989 - 2012. The precipitators were ceiling mounted, by-pass mounted and one of them shaft-mounted.

- From a practical, environmental and economic point of view the Norwegian investigations and measurements of the first generation filter plants indicated that the electrostatic precipitators' efficiency (under certain conditions) is questionable.
- The last precipitator was closed down in 2013, due to low efficiency and high operational costs.
- As for the use of high-efficiency cleaning plants, one prior assumption ought to be that the benefits are reasonably proportionate to the total investment and operating costs of the plant. However such benefits have not been experienced.
- The precipitators are energy-consuming with high operating costs and have all been closed down due to these main factors.

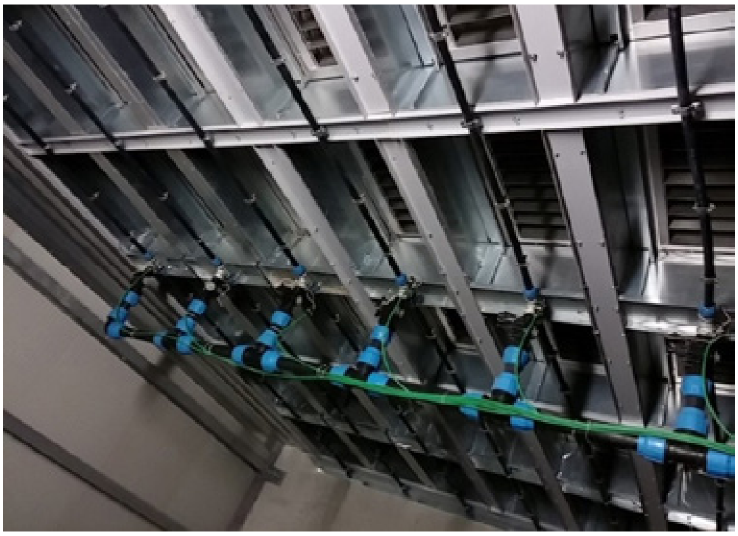


*Illustration 7 - Picture of electrostatic filters of an Air Cleaning System*

As a conclusion, regarding air cleaning, the results are different from one country to another.

An overall balance has to be established between actual efficiency and investment costs, then energy and maintenance costs. The use of air cleaning in road tunnels is relatively new and the number of these installations is very limited. The decision to use such systems therefore has to be carefully analyzed, taking into account several criteria (investment costs, efficiency, maintenance, etc.).

**Case study: Evaluation of an NO and $NO_2$ suppression system**

The M5 East, (Sydney, Australia) completed in December 2001, is a 10-kilometre freeway carrying an average of 100,000 vehicles per day.

In 2007, the construction of a filtration plant was launched in order to test the efficiency of filters over an 18-month period in the west-bound tunnel of the M5 East.

The results of the experiment showed that the system tested was neither very efficient, nor cost-effective, but a more efficient system could potentially be developed. In 2014, the filtration plant was closed down.

This experiment is particularly interesting in that its aim was to improve the air quality in the tunnel and consequently the health of users (social pillar and environmental pillar).

The impact of this type of the filtration plant on the three pillars of sustainable development can be seen in the table below.

**TABLE 10. IMPACT OF FILTRATION PLANT ON THE THREE PILLARS OF SUSTAINABLE DEVELOPMENT**

| Pillar | Positive aspects | Negative aspects |
|---|---|---|
| Economic | | Investment, maintenance and operation costs |
| Social | Human health (limited impact) | |
| Environmental | Good for the environment but no real $NO_2$ removal efficiency | |

### 4.4.6. Effluent treatment

The effluents that are produced by a highway tunnel are either from the underground water table, collected by the tunnel drainage system, or tunnel road surface liquids (cleaning water, rainwater or thawing snow inflowing from tunnel portals or from vehicle tyres, transported liquid goods leakages, or fuel leakages) which are collected by the waste water collection system of the tunnel.

Usually underground water from the tunnel drainage system can be used without any treatment for fire-fighting purposes, for cleaning and for irrigation, or can be channelled directly to the final receiver.

Effluents from tunnel road surface liquids coming into the waste water collection system contain chemical pollutants of different and various levels of toxicity, and flammability i.e. components in a solid or dissolved state, including organic matter as well as minerals, metals, hydrocarbons, solvents, polymers, oil, grease and de-icing salt. The disposal of these liquids must not violate environmental regulations. Depending on the country and regulatory framework in force, these effluents undergo more or less complete treatment before being dumped into the waste water or sewage collection system, outside the tunnel.

For the tunnel road surface liquids collection system it is very important to avoid fire in case of spillage, by installing appropriate devices like firetraps. In order to facilitate the use of clear underground water and to avoid treatment of needless quantities of wastewater (mixture of clear water and road surface liquids), generally the system for drainage of underground water from surrounding rock mass is completely separate and independent from the system for the collection and disposal of road surface liquids.

### 4.4.7. Recycling

Certain parts or components from equipment used in underground construction works have to be regularly replaced. Consequently, during normal operation a tunnel produces waste (lighting elements, batteries from Uninterruptible Power Supply (UPS) units, filters from pollution collection systems, asphalt from pavements, etc.). When recycling that waste, the objective is to completely or partially re-use the different elements when manufacturing new products.

Therefore, recycling is an important topic in environmental policy insofar as it contributes to conserving natural resources, since recycled materials will be used instead of materials that would otherwise have been taken from nature.

#### 4.4.8. Maintenance

Beyond cost-reduction considerations, maintenance can have an impact on the economic and societal pillars of operation policies.

Impacts on the social pillar can be seen through long-term improvements in living conditions, obtained thanks to tunnel construction. Having said that, the initial improvement in traffic conditions obtained has to be conserved, meaning that closures for maintenance work should be as few as possible.

Impacts on the economic pillar occur through seeking to maintain high-level economic attractiveness, which has been generated by the tunnel.

These two cases particularly concern urban tunnels. However, there are also cases where tunnels serve the needs of isolated regions.

Maintaining the performance of infrastructure can only be achieved through a quality maintenance programme, while innovation in this field is more a matter of improvement in methods used (cf. §4.3.3) than of innovation in particular. On the other hand, the objective of reducing the duration of closures can be achieved through the use of so-called "*plug-and-play devices*" (which can be switched off for maintenance). This concept can also reduce workers' exposure time to traffic risks.

Regular monitoring of tunnel equipment (ventilation and lighting), including measuring instruments, is essential to check that this equipment is functioning correctly and that the data they provide is valid. This is especially important for measuring pollution in tunnels. Indeed, a locally excessive measurement would force airflows (in a complex system) to high values, resulting in a very rapid increase in energy consumption. Full servicing in association with a review of all the recorded data will quickly identify any malfunction of sensors or fans which are often not locally detectable.

It is possible to save energy by early detection of malfunctions and other defects. Experience with large power supplies shows that technical defects sometimes generate excessive energy consumption. Energy is also saved because of the lower cost of properly maintained equipment, and a lower depreciation rate due to the extended viability of the equipment.

#### 4.4.9. Staff and partnerships

Mutualizing human resources is one avenue of improvement for overall efficiency in highway tunnel management, whether the goal is to establish a single control centre for several tunnels or to foster a high level of skills that might be shared by several tunnels. Whatever the goal, before going down the path of so-called "*mutualization,*" there has to be careful thought about how to structure the work and how to set reasonable objectives (e.g., how many tunnels can be supervised by the same control centre).

Gains can also be envisaged, thanks to grouped purchases (e.g., consumables for lighting), or by managing shared stores for certain (i.e. expensive) spare parts.

Integrated Traffic and Plant Management Systems (ITPMS) can be developed to enable the operator to centrally manage, control and monitor multiple short road tunnels at various locations from a single main Operation Control Centre (OCC). The implementation of ITPMS can achieve significant savings in both investment and operating costs.

#### 4.4.10. Others

Cost reductions through standardization
Standardization can lead to lower transaction costs in the economy as a whole, as well as to savings for individual businesses. Standardization enables a reduction in the stock of spare parts. In addition, reducing the number of different equipment items leads to improved knowledge of the latter. Finally, it is easier to train maintenance staff when equipment belonging to the same family is identical (fans, circuit breakers, programmable logic controllers,....).

Effects on standards on the client / supplier relationship
Standards have a positive effect on the buying power of companies. Standards can help businesses avoid dependence on a single supplier because the availability of standards opens up the market. The result is a broader choice for businesses and increased competition among suppliers.

## 5. RECOMMENDATIONS

Based on existing policies in each country, the concept of sustainable development may be applied to different fields or sectors, including road tunnels, in particular for the operation of this type of infrastructure.

**Recommendation 1**: At the moment, the main recommendation is to have a general approach in terms of sustainable development.

Many methods of implementation of the sustainability concept exist, but in many cases they do not apply directly to tunnels. They usually apply to building projects, road projects or infrastructure construction projects. However, they can be very useful in the field of tunnels.

**Recommendation 2**: In each country, apply existing sustainable development rules and methodologies to road tunnels. Chapter 3 in this report could serve as a starting point for this.

If tunnel owners or tunnel managers wish to take sustainability aspects into account throughout the whole life of the tunnel (including tunnel planning, design, building and refurbishment) they should develop a sustainability policy and implement it on all levels.

**Recommendation 3**: A sustainability policy must be applied to studies and projects that are performed by planners, designers, constructors and/or contractors etc.

The choices that we need to make in the field of sustainability are the results of a sound balancing of the three pillars.

**Recommendation 4**: It is important to evaluate the weight of each pillar regarding the two others. On top of that, as tunnel managers we also have to take cost effectiveness into account. The outlines of a general approach to balance these aspects were presented in section 1.4.5.

**Recommendation 5**: For each specific country or tunnel operator, this general approach should be tailored to the applicable national regulations and to the policy of the tunnel operator on sustainability.

The impact of the upstream phases, i.e. the planning phase, design phase and, to a lesser extent, the build phase, is considerable.

**Recommendation 6**: The concept of sustainable development must be applied not only to the road tunnel operation, but also to the upstream phases, in particular the design phase.

**Recommendation 7**: It is also recommended to perform a life cycle cost (LCC) analysis. See PIARC Report [6].

**Recommendation 8**: Although results will be less marked, even in existing tunnels it is nevertheless possible to adopt a sustainable approach (both in operation and refurbishment periods).

**Recommendation 9**: It is recommended to focus on energy saving techniques and it is sometimes necessary to go down to component level. In the same way, the use of available technologies (e.g. Intelligent Transports Systems to avoid congestion) has to be encouraged.

## 6. CONCLUSION

A holistic approach to sustainable development must involve all sectors and parameters. It must provide an acceptable and appropriate balance between economic, social and environmental objectives

Sustainability of the world road network and, more particularly tunnels, requires commitment to coordinated planning and design among all stakeholders, in order to reduce the footprint of tunnel operation.

So far, PIARC, the World Road Association has not issued any recommendations regarding sustainable road tunnel operation. This report is a first step to make up for this lack of recommendations. This initial approach constitutes a basis for further consideration of sustainability in the field of road tunnels.

This preliminary stage has enabled certain facts to be established. Firstly, although we cannot speak of an established holistic approach in terms of sustainable development, the work undertaken has highlighted that this concept is well known within the world of road transport. Its practical implementation is increasingly spreading throughout developed countries, based on a regulatory context that differs somewhat from one country to another.

For road tunnels in particular, the situation varies significantly: certain countries which have general regulations have no specific texts for tunnels; conversely, other countries, which may not have general regulations, have set requirements for tunnels (regulatory texts, recommendations, etc.).

The report also shows that several countries have established project assessment methodologies from a sustainable development perspective. A comparison of these various methodologies remains difficult and none of them have really gained ground outside their country of origin.

Now that this report, which constitutes the first steps towards a sustainable road tunnel operations, has been completed, work must continue. This could involve assessing the advantages/drawbacks of existing implementation methodologies and by establishing feedback from projects undertaken within a sustainable development approach.

# 7. BIBLIOGRAPHY / REFERENCES


[1] BRUNDTLAND, G. "*Our common future", **United Nations World Commission on Environment and Development*** (WCED), *1986.*

[2] PIARC COMMITTEE ON ROAD TUNNEL OPERATIONS. *"Good practice for the operation and maintenance of road tunnels",* reference 05.13.B, PIARC, Paris, 2005.

[3] PIARC COMMITTEE ON ROAD TUNNELS. *"Reduction of operational cost of road tunnels",* reference 05.06.B, PIARC, 1999.

[4] PIARC COMMITTEE ON ROAD TUNNELS OPERATIONS. *"Guide for organizing, recruiting and training road tunnel operating staff",* reference 2007R04, PIARC, Paris, 2007

[5] PIARC COMMITTEE ON ROAD TUNNELS OPERATIONS. *"Road tunnels: vehicle emissions and air demand for ventilation",* reference 2012RO5EN, PIARC, December 2012

[6] PIARC COMMITTEE ON ROAD TUNNELS OPERATIONS. *"Best practice for life cycle analysis, both for new and existing tunnels",* reference 2012R14EN, PIARC, 2015.

# GLOSSARY

| TERM | DEFINITION |
|---|---|
| Concept of sustainable development | Kind of development that meets the needs for the present without compromising the ability for future generations to meet their own needs |
| Sustainable road tunnel operation | Application of the concept of sustainable development to road tunnel operation |
| Economic pillar | Creating wealth and improving living standards |
| Social pillar | Meeting needs in terms of health, education, housing, employment, etc. |
| Environmental pillar | Preserving species, natural resources and energy resources. |
| Recycling | Recycling is a process to change waste materials into new products |
| Tunnel Operating body | The organization responsible for the operation of the tunnel. May be the Tunnel Owner or a subcontractor of the Tunnel Owner. |
| Control centre operator | Employee of the Tunnel Operating body in charge of all or part of the operation of the tunnel at a given moment (may be several persons with separate responsibilities, for example traffic operation and technical operation). The tunnel operator can ensure only traffic management (in this case he is the traffic operator and there is a separate technical operator) or traffic and equipment management (he is the unique tunnel operator). |

# APPENDICES

## 1. APPENDIX A: QUESTIONNAIRE

Questionnaire on Sustainable Road Tunnel Operations

**Goal of the Questionnaire**

The goal of this questionnaire is to make an inventory of sustainable road tunnel operation policies (and practices) worldwide: what goals are pursued, what kinds of methods or approaches are used to meet the goals, and how the results are monitored and/or measured.

The results of the questionnaire will be used to collect best practices and make recommendations in the field of sustainable road tunnel operations, as part of a study by PIARC TC3.3 WG1. The results of the study will be made available through a report.

**Definition of road tunnel operations**

The management and maintenance of the tunnel, including all the connected operational activities, in order to support the use of the tunnel in a normal traffic situation, as well as to support the controlled handling of incidents and calamities in the tunnel.

**Definition of sustainable road tunnel operations**

Road tunnel operation practices that are aimed (to a certain degree) at limiting or reducing possible negative impacts on the economy, society and the environment, in order to support long term prosperity. According to this definition, sustainable road tunnel operations are focused on 3 areas. Each area contains several aspects that a sustainability policy can focus on, see table:

TABLE 11. ASPECTS OF A SUSTAINABILE ROAD TUNNEL POLICY PER AREA

| Area | Aspects (example) |
|---|---|
| Economic | • Choice between tunnel and other solutions<br>• Tunnel cost reductions (cost of operations, life cycle costs)<br>• Cost effectiveness of tunnel facilities and organizational measures (e.g. to enhance safety or other sustainability aspects) |
| Social | • Safety of road tunnel users (internal safety)<br>• Safety of people in the vicinity of the tunnel (external safety)<br>• Availability of tunnel to traffic (e.g. design and maintenance concept aimed at reducing the downtime of the tunnel for maintenance and repair, while maintaining the required safety level)<br>• Reduction of travelling time<br>• Multiple use of space |
| Environmental | • Energy use reduction<br>• Carbon footprint reduction<br>• Reduction of emissions / pollution<br>• Reduction of use of materials, natural sources (e.g. recycling)<br>• Noise reduction<br>• Recycling |

**Instructions for filling out the questionnaire**

Please take a few moments to answer the following questions, making use of your own experience. It is not necessary to draw a complete picture of the situation in your country. Neither is it necessary to elaborate on the various subjects, but we would appreciate it if you could provide a reference to an internet link, document or other source for further information on the various goals, approaches, methods and monitoring practices.

Please send the filled out questionnaire to:
jean-claude.martin@developpement-durable.gouv.fr

As a token of our appreciation, all results of our enquiry will be sent to all those who return the completed questionnaire.

Thank you in advance!

## GENERAL QUESTIONS

Your name: ..................................................

Your organization: ..................................................

Your country: ..................................................

Your e-mail: ..................................................

*In what way are you and/or your organization involved in road tunnel operations:*

- ☐ Tunnel Manager
- ☐ Maintenance contractor
- ☐ Consultant
- ☐ Designer/Engineer
- ☐ Other, namely:

*Sustainability questions*

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

Explanation:

- The first question is focused on whether you have taken action in the field of sustainable road tunnels operations.
- If the answer is “*No*”, it is not necessary to answer questions 2 to 8.
- If the answer is “*Yes*”, the next questions focus on further information regarding the goals you have decided to aim for.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

Question 1

*Are there, in your line of work and experience, any sustainability goals or requirements applicable to road tunnel design or road tunnel operations?*

(several answers are possible)

- ☐ Yes: economic aspects, like costs, cost reduction or cost effectiveness
- ☐ Yes: societal aspects, like safety, tunnel availability, travel time reduction or multiple use of space
- ☐ Yes: environmental aspects, like reduction of energy use, carbon footprint, emissions/ pollution, use of materials, natural sources or noise
- ☐ No

Question 2

*Can you please specify the sustainability goals or requirements that are applicable, including, if possible, a quantification of the required results?*

(if you can answer the question by giving a reference to an internet link, document or other available source, feel free to do so!)

Goal / requirement 1

Goal / requirement 2

Goal / requirement 3

Goal / requirement 4

Question 3

*Are the goals/requirements prescribed by national or international legislation, or are they the result of own policy? If applicable, could you please give further details of the legislation?*

(if you can answer the question by giving a reference to an internet link, document or other available source, feel free to do so!)

Goal / requirement 1

Goal / requirement 2

Goal / requirement 3

Goal / requirement 4

Question 4

*What methods are used to meet the goals or requirements, and in what phase (planning phase, design phase, building phase or operation phase of the tunnel)?*

(if you can answer the question by giving a reference to an internet link, document or other available source, feel free to do so!)

Goal / requirement 1

Goal / requirement 2

Goal / requirement 3

Goal / requirement 4

Question 5

*What methods are used to measure/monitor the results or performance of road tunnel operations in relationship with the goals or requirements, and in what phase (planning phase, design phase, building phase or operation phase of the tunnel)?*

(if you can answer the question by giving a reference to an internet link, document or other available source, feel free to do so!)

Goal / requirement 1

Goal / requirement 2

Goal / requirement 3

Goal / requirement 4

Question 6

*How "solid" are the goals or requirements: do you take all the necessary measures to comply, or do you take cost effectiveness into account?*

(if you can answer the question by giving a reference to an internet link, document or other available source, feel free to do so!)

Goal / requirement 1

Goal / requirement 2

Goal / requirement 3

Goal / requirement 4

Question 7

*What is your experience with the sustainability policy on road tunnel operations as you described above (the overall set of goals, demands, methods and results); what are the successes and what are the possibilities for improvement?*

(if you can answer the question by giving a reference to an internet link, document or other available source, feel free to do so!)

Question 8

*Do you have any further remarks, observations or recommendations?*

(if you can answer the question by giving a reference to an internet link, document or other available source, feel free to do so!)

## 2. APPENDIX B: SUMMARY OF THE ANSWERS TO A SPECIFIC QUESTIONNAIRE ADAPTED TO FRENCH SPEAKING ROAD TUNNEL OPERATORS

| | |
|---|---|
| ***French speaking operators*** | 12 |
| ***Tunnel (s)*** | Cross border, urban, interurban, motorway |

*1 – Have you implemented actions for sustainable road tunnel operation (economical aspects, societal aspects and environmental aspects)?*

- Yes: 9
- No: 2
- Other: ISO 14001 process: 2

.............................................................................................................................................

*2 – Which and since when?*

- LED lighting: 2
- Relighting and relamping optimization: 1
- Optimization (reduction) of lighting levels: 1
- Power consumption control: 1
- Power supply optimization: 2
- Selective sorting: 2
- Collection of ground water effluents and analysis of run-off water: 2
- Mutualization (sharing) of maintenance actions: 2
- Maintenance plan and experience feedback: 1

.............................................................................................................................................

*3 – Can you explain the results with quantification if possible?*

- Reduction of power costs: 4 (- 15 % for 2 of them)
- Better waste treatment (lights and muds): 1
- Reduction of traffic jams/ disruptions (- 50 %): 1
- Safety improvements for road personnel: 1

.............................................................................................................................................

*4 – What methods are used to measure the results of the action implemented?*

- Analysis of the electricity consumption for each function (entrance and exit zone lighting, interior zone lighting, ventilation): 2
- Analysis of electricity consumption invoices: 1
- Illumination measurements of: 1
- Lane/direction closure counts: 1
- Analysis of rejections: 1

.............................................................................................................................................

*5 – Are other sustainable actions planned soon?*

- Monitoring of the electricity consumption for other tunnels: 1
- Prioritizing of the cheapest power providers of both countries of a cross-border tunnel: 1
- Light coloured pavement: 1
- Treatment of effluents and run-off water: 1
- Predictive maintenance: 1
- Revision of operation instructions: 1

## 3. 3. APPENDIX C: FLOW DIAGRAM FOR DECISION MAKING

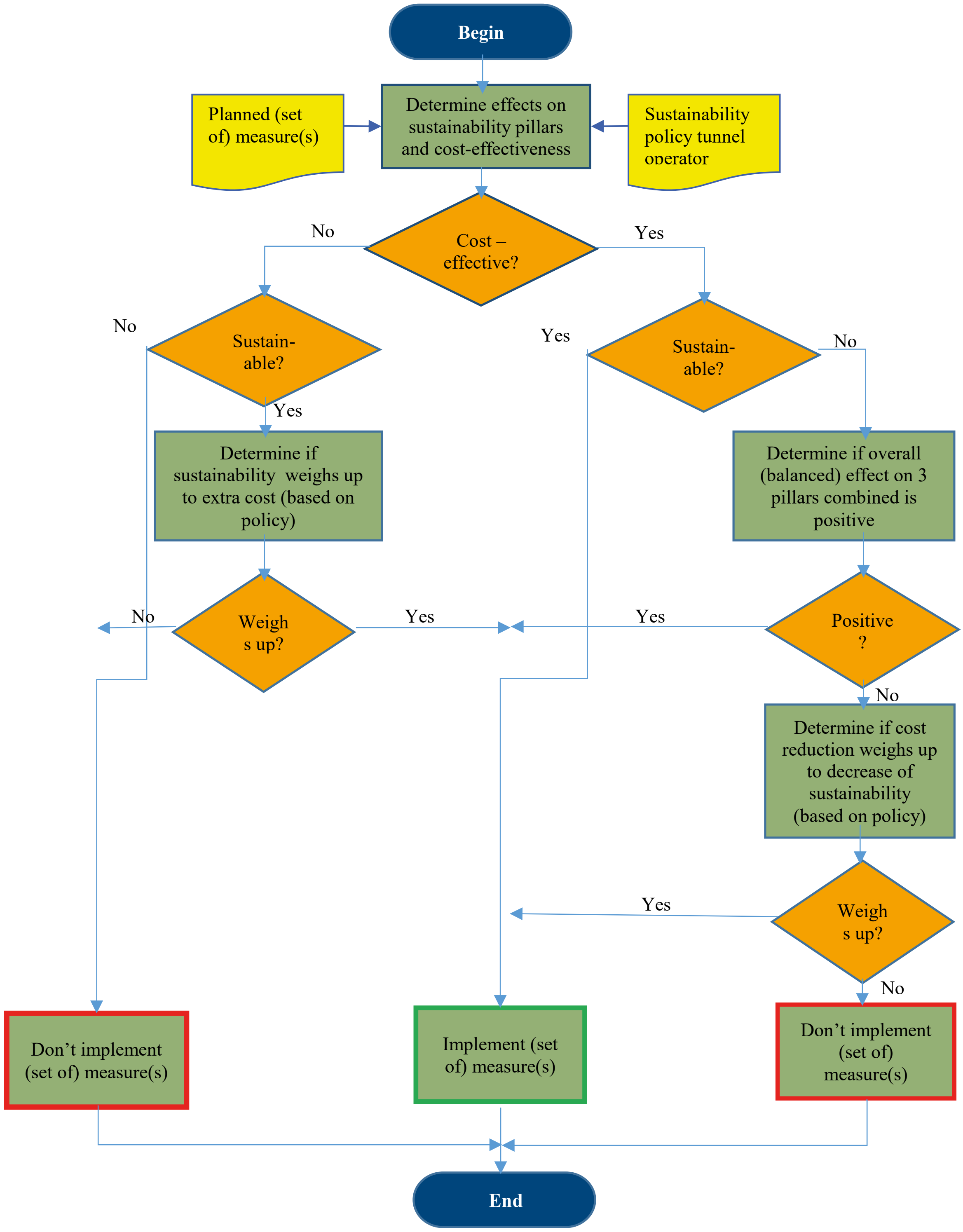



*Illustration 8 - Flow diagram for decision-making*

# 4. APPENDIX D: EXAMPLE OF SOCIAL CONTRACT CLAUSES

a. The contractor agrees, whether it is in his own right or through a subcontractor, to employ the staff presented to him by the Contracting Authority or by the designated framing organization on the jobsite without reservations, in compliance with the present administrative clauses and under the conditions mentioned in the *appendix* hereafter, in the framework of a labor contract, in accordance with the legal provisions in force and the collective employment agreements applicable to the services to be performed on the aforementioned jobsite.

b. The Contracting Authority will call on a supervisory body in order to ensure the supervision of the selected tenderer's compliance during the realization of the mission with the social contract clause referred to under point "*a*", as well as in the *appendix* of the present special specifications.
The supervisory body is the Brussels Regional Employment Office, referred to hereafter as ACTIRIS, with its headquarters at 65, Boulevard Anspach in 1000, Brussels.
For this contract, ACTIRIS will be represented by its general manager or any other member of its staff appointed by him.
In order to fulfill their mission, and as is the case for the representatives of the Contracting Authority, ACTIRIS' authorized delegates will be considered responsible for the supervision of the compliance with the public contract as referred to in article 1 and 2 of the General Conditions; consequently, they may access the jobsite at their own risk in order to supervise the jobsite and provide the necessary monitoring, without any possibility for the contractor to deny them access.
When visiting the jobsite, they must, in any case, inform the general foreman of their presence upon arrival and observe the safety regulations prescribed by the contractor, in accordance with article 30 of the present special specifications. They must inform the Contracting Authority of any act of negligence observed, if any.

c. The Contracting Authority may consider any failure to comply with the commitments made by the contractor for himself or his subcontractors, regarding the employment on the jobsite of the staff as referred to under point "a" of the present administrative clauses, under the conditions provided in the *appendix* to the present special specifications, observed during the realization of this mission, either by the legal project leader or any other authorized person and especially by the ACTIRIS delegate, as a breach of contract as referred to in article 20, § 1 of the General Conditions.
In such cases, the Contracting Authority will apply article 20, § 2 of the General Conditions.
Any breach observed under these conditions can make the tenderer selected subject to one or more of the measures provided under § 4 and 6 of the aforementioned article 20, as well as under article 48, § 3 of the general conditions.

# 5. APPENDIX E: CASE STUDIES

## 5.1. URBAN INTEGRATION OF A SAFETY GALLERY – (FRANCE)

The Croix-Rousse tunnel is in Lyon (France). It goes right through the Croix-Rousse Massif. It allows the connection between the districts bordering the Rhône and the neighboring area bordering the Saône. The Croix-Rousse tunnel is a single-tube tunnel, 1,750 m long. The tunnel is bidirectional with two lanes for each direction. Every day about 50,000 vehicles pass through it.

Since the tunnel opening in 1952, refurbishment works have been carried out without reaching a satisfactory level of safety. For this reason the safety programme undertaken by the Greater Lyon council in 2008 particularly aimed to:

- connect the tunnel to a safety gallery by cross passages every 150 meters allowing the evacuation of users;
- completely renew the ventilation system;
- equip the tunnel with modern monitoring systems such as Automatic Incident Detection (AID).

The Greater Lyon councilors wished to give this safety gallery a truly urban function by allowing access to public transport, pedestrians and cyclists. This "*tube*" (this is how the gallery is named) consists of:

- a one-way, 3.40 meter-wide bus lane (in the other direction buses pass through the road tunnel,
- A 1.70 meter-wide walkway.
- A two-way lane for cyclists, 3 meters wide in total.

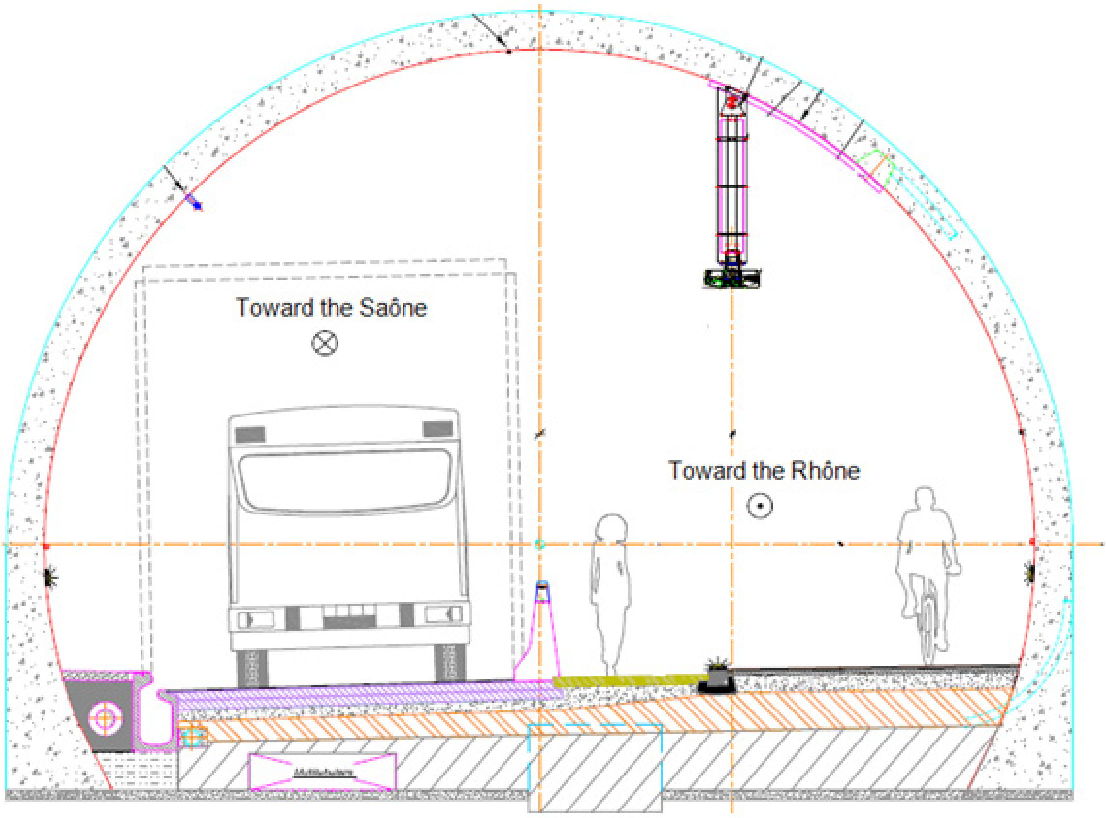



*Illustration 9 - Cross-section of the Croix-Rousse tunnel safety gallery*

*Illustration 10 - Inner section of the Croix-Rousse safety gallery*

In addition, the two portals have been fitted out in a welcoming manner.

This is an interesting example of sustainable development using an infrastructure for other purposes than the ones originally intended.

The table below represents an assessment of all contributions to the 3 pillars of sustainable development provided by this specific construction.

TABLE 12. ASSESSMENT OF THE CONTRIBUTIONS OF THE CROIX ROUSSE SAFETY GALLERY TO THE THREE PILLARS OF SUSTAINABLE DEVELOPMENT

| PILLAR | + | - |
|---|---|---|
| Economic | Using an investment originally dedicated to safety for urban purposes. | Higher operating costs than for a more typical safety gallery |
| Social | The new gallery creates a link between two districts of Lyon.<br>It promotes green transport modes.<br>It provides pedestrians and cyclists with the same service as that previously reserved to motorists.<br>Daily use of a normally empty space that could have turned into a squat. | |
| Environmental | The new gallery helps to promote green transport modes such as cycling and walking. | Permanent lighting. |

## 5.2. LIGHTING OPTIMIZATION

With the exception of ventilation, lighting constitutes the biggest expense in numerous tunnels. When looking into cost cuts, which are a major preoccupation of all operators, the issue of lighting (entrance zones and interior zone) can therefore not be ignored.

**Current reflections (France)**
In simple terms, road tunnel lighting comprises two zones:

- An entry zone where lighting levels are reinforced and gradually decrease as one moves further into the tunnel,
- An interior zone which corresponds to the rest of the tunnel with constant and much lower lighting levels.

Although it does not function constantly, entrance zone lighting is very strong, and cost cuts made through its optimization can therefore often be significant. For this reason, numerous studies aim to cut costs on tunnel entrance zone lighting, either by focusing on lighting design, or by taking into account the advent of new technologies, or by improving equipment control.

More specifically, the current reflections at the Tunnels Study Centre concern the following subjects:

- Lighting design: calculation of the reinforced lighting requirements by the variable spacing method instead of the gradual method (use of computerized calculation methods, for example the CETU's "*Eclair tunnel*" software).
- Carriageway characteristics: studies on carriageway luminance with surface treatment experiments to improve luminance.
- Equipment control: experimentation on luminaire dimming (from 100% to 20% of the luminous flux in high pressure sodium luminaires).
- "*Real time*" monitoring of traffic speed: adaptation of reinforced lighting to the real speed of users about to enter the tunnel.
- Design and control of equipment in remote tunnels: study on how to improve the visibility and safety of cyclists in mountain tunnels whilst at the same time reducing energy consumption (electrical supply by solar panel or wind turbine).
- Performance assessment: experimentation and comparison of luminance by means of a luminance meter, photometer and high output measurements.

- Technology monitoring in terms of new luminaire types or modifications to existing luminaires: performance, life-span and consumption.

**Light transition arch in Spain**

Road tunnels are singular stretches of the road where surrounding lighting conditions change very abruptly. Especially on sunny days, drivers make great efforts to adapt their vision in a few seconds from the outside of the tunnel, brightly lit by sunlight, to the interior which is much darker.

Quantitatively, luminance outside the tunnel on a sunny day can reach very high values, say 4,000 cd/m², while inside the tunnel, the luminance level is usually as low as 3 cd/m².

Tunnel lighting installations aim to diminish the risk of an accident caused by a dazzled driver. A lighting level reduction in accordance with human eye's speed of reaction to light changes is generated with an appropriate pattern of luminaries.

However, this installation requires a lot of electricity, typically 50-95% of the whole tunnel's power consumption.

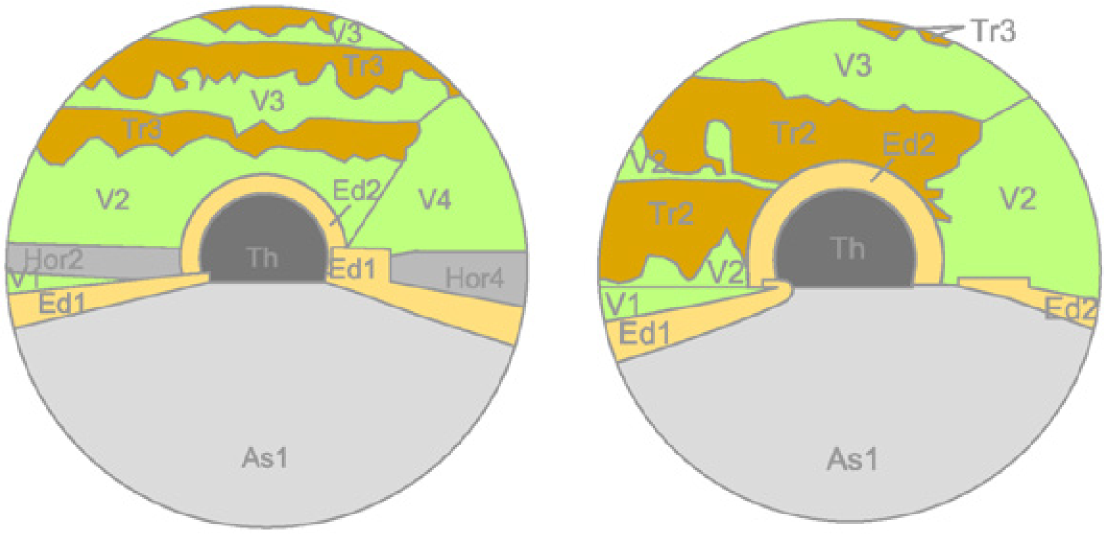
Concerned by this problem, the Spanish Ministry of Public Works at Murcia (Spain), along with Murcia University undertook an R&D project with the goal of reducing this power consumption. The idea was to take advantage of sunlight to light the tunnel, thus decreasing electrical power needs.

A new methodology for lighting studies has been developed in Spain, mainly based on the draft for the new Spanish standard for tunnel lighting.

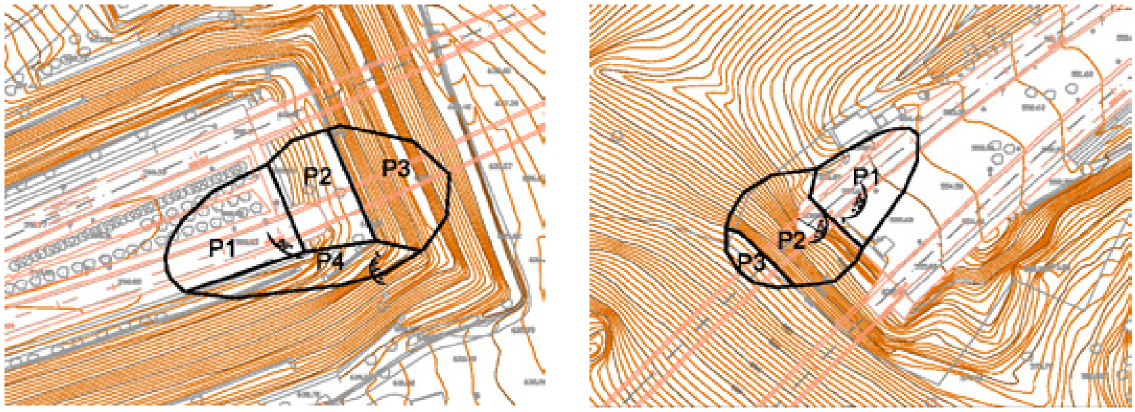
The main aim of the methodology is to develop an accurate lighting study, which enables a technical but also an economical approach to the decision of which lighting technology is the most suitable for each case.

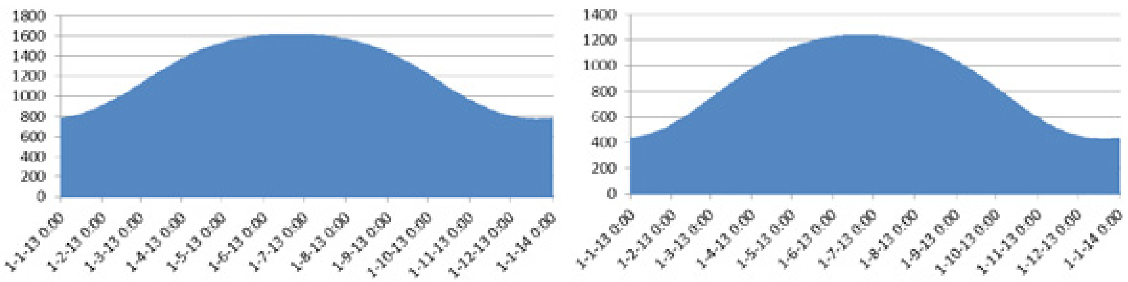
The main phases of this methodology are:

1. Compilation of technical data about the tunnel: drawings, calculations, etc.
2. Visit of the tunnel (if possible): photos, electrical tests, etc.
3. Accurate estimation of traffic intensity: hourly rate estimate with actual tunnel traffic data
4. Accurate estimation of L20: by studying the luminancemeter's actual measures and backups .
5. Evaluation of the current lighting system (if it exists): verifying the current luminance level, and current electrical consumption.
6. Evaluation of feasible technical solutions: HPSV, LED, Fluorescent, mixed solutions, etc.
7. Lighting study, considering several technical options: central, bilateral, etc.
8. Economic analyses for all the alternatives: it is needed an accurate estimation of actual electrical consumption for the existing installation, prognosis of number of working hours for each circuit (based on weather data), prognosis of electrical consumption of the new installation, estimation of the maintenance costs for each installation.
9. Budget of the new installation: it is strongly recommended to have real budget proposals in order to ensure the accuracy of the study.
10. Cost-benefit analysis: internal rate of return (IRR) or, net present value (NPV)




SOUTH PORTAL NORTH PORTAL




SOUTH PORTAL LUMINANCE NORTH PORTAL LUMINANCE

*Illustrations 11 - Accurate estimation of the luminance of each portal*

After studying several possibilities, the research focused on developing a fixed metallic arch placed before the entrance of the tunnel. The arch is formed by metallic frames which hold metallic sheets. This structure gradually reduces the entry of sunlight by an equivalent reduction in the percentage of holes in its coating. Thereby, light levels set by the CIE curve or current regulations, are faithfully reproduced in the threshold zone of the tunnel.

The length of the metal structure is the same as that of the threshold zone of the tunnel (equal to the safety distance calculated for perception and reaction times of 1 second).

The metal mesh, which forms the cover, is punched with holes of the same size, the spacing of which increases along the tunnel in order to reduce the internal luminance according to the proportions determined by the CIE curve.

This theoretical approach has been verified by building a 6:1 prototype model. Measurements made with a luminancemeter inside the model showed that the luminance results inside the tunnel, in each of the different sections, correspond to those set in the CIE curve. Moreover, the projection onto the road surface of the sunlight filtering through the outer holes is not perceived as 'polka-dots' on the road surface, so there isn't any flicker effect. Also, this device enables a natural lighting control inside the tunnel.

*Illustration 12 - Pictures of a 1/6 scale model built to simulate the light transition arch (Murcia, Spain)*

Research shows that this arch is technically and economically feasible, and additional funds have been awarded to build one in a tunnel in Spain.

**TABLE 13. CONTRIBUTION OF THE TRANSITION ARCH TO THE THREE PILLARS OF SUSTAINABLE DEVELOPMENT**

| PILLAR | + | - |
|---|---|---|
| Economic | Reduction of energy cost | Initial investment<br>Maintenance of added equipment or construction |
| Social | Safety (reduction of black hole effect for users) | |
| Environmental | Reduction of energy consumption (reduction of $CO_2$ emission and preservation of resources)' | More material use |

**Remote control of light sources in the A14-A86 road tunnels (France)**

In order to reduce energy consumption whilst maintaining an adequate level of safety, it would be appropriate to vary tunnel light levels during low traffic periods. It is not always possible to reduce the number of lit lamps because of deterioration in the longitudinal uniformity. Therefore, a monitoring system could be used to control and to monitor each luminaire of the underground network.

The solution implemented on the A14-A86 road tunnels (15 km of underground networks in La Défense area of Paris) during refurbishment (2011-2012) allows intelligent lighting management by enabling remote control of the voltage of each light. This system also automatically provides access to an operational and financial intelligence dash-board. The system is based on PLC technology (Power Line Communication). A hub located in the main switchboard communicates with an "*Endpoint*" module connected to each of the 9000 light points. Communication is made by existing power cables.

Energy is thus saved on two levels:

- When the lamp is new, the light flow is limited to a fixed level (between 70% and 90% of its nominal flow) in order to adapt lighting to requirements. This solution reduces the over-illumination at the start of the lamp life cycle;
- During night mode: the level of illumination is reduced depending on the traffic in the tunnel overnight.

In both case, the voltage reduction leads to an energy saving from 10 to 30%.

In addition, maintenance tasks can be facilitated by:

- Optimizing device life expectancy by adapting power to the state of each lamp;
- Allowing predictive maintenance by data acquisition for each lamp: power, voltage, intensity;
- Optimizing maintenance by remote failure diagnosis.

Finally, some difficulties have been experienced:

- The type of power supply (UPS for instance);
- The implementation on existing lighting installation in a refurbishment context: different types of wiring depending on existing light devices.

TABLE 14. CONTRIBUTION OF THE REMOTE CONTROL OF LIGHT SOURCES IN THE A14-A86 TUNNEL TO THE THREE PILLARS OF SUSTAINABLE DEVELOPMENT

| PILLAR | + | - |
|---|---|---|
| Economic | Reduction of energy costs<br>Improvement of life expectancy for lamps | Initial investment<br>Maintenance of added equipment or construction |
| Social | User safety and comfort | |
| Environmental | Reduction of energy consumption (reduction of $CO_2$ emission and preservation of resources)’ | More material use |

## 5.3. VENTILATION

**New jet fan installation**
It is noted that when a jet fan is installed into a tunnel a considerable decrease in the thrust occurs when the unit is very close to the vault of the tunnel or in a niche. This decrease could be even 30%.

It is recommended to use additional technical devices in order to maximize the installation factor. An example is to use deflectors, inclined metal sheets, inclined silencers or nozzles.

In 2013, a study carried out by Graz University, involving a full scale test, noted an increase of the installation factor of 11% when jet fans with nozzles are used.

In general, the absorbed power by a single jet fan increases and consequently can influence final results, whereas the total installed power decreases because the required quantity of new jet fans is lower than for standard jet fans.

| TABLE 15. CONTRIBUTION OF NEW JET FANS TO THE THREE PILLARS OF SUSTAINABLE DEVELOPMENT | | |
|---|---|---|
| **PILLAR** | + | - |
| Economic | Reduction of operating costs (energy and maintenance)*<br>Lower initial investment (less jet fans)<br>Higher availability of the tunnel for traffic | Augmentation des coûts liés aux nouveaux accélérateurs |
| Social | (pas d'impact significatif) | |
| Environmental | Réduction de la consommation d'énergie (réduction des émissions de CO2 et préservation des ressources). | |
| * Depending on the solution retained | | |

**Longitudinal ventilation using "** ***Jet fans plus Inverters*****"**
For complex road tunnel networks, where jet fans are used as part of a more complex ventilation system, the combination of a jet fan plus inverter improves ventilation control and power absorption. Such combined use should be encouraged where possible since it also provides additional maintenance benefits and in some cases better ventilation response in the event of fire.

Installation of inverters must be in the electrics room and technical aspects need to be considered from the design stage, taking into account current best practices (i.e. electric impedance, resonance frequency, etc.), maintenance procedures, costs and installation layout according to inverter producer installation manuals.

For example, in Singapore, inverters are proposed for new road tunnels to deliver the required amount of airflow based on sensor feedback, optimizing the operation of the tunnel ventilation system.

| TABLE 16. CONTRIBUTION OF THE USE OF JET FANS PLUS INVERTERS TO THE THREE PILLARS OF SUSTANABLE DEVELOPMENT | | |
|---|---|---|
| **PILLAR** | + | - |
| Economic | | |
| Social | (No significant impact) | |
| Environmental | Reduction of energy consumption (reduction of $CO_2$ emission and preservation of resources)' | |

**Air cleaning experimentation in Australia (M5 tunnel East Sydney)**
The M5 East, completed in December 2001, is a 10-kilometre freeway carrying an average of 100,000 vehicles per day.

<u>The Air Filtration Project on M5 East</u>
In 2006, the New South Wales Government announced an air quality improvement plan for the M5 East tunnel. The plan was designed to analyse, investigate and improve air quality levels within the tunnel.

In 2007, the Minister for Planning granted approval for the RTA to construct and operate a filtration plant to trial how effective the filters are in the M5 East westbound tunnel.

It was decided that over an 18-month period, the RTA would test the Air Filtration Plant (AFP), to see how best to operate this equipment and evaluate its benefits and costs.

The Final Report (from CSIRO) and the Evaluation Program (by AMOG) are presented below.

A - Final Report (November 2011 - prepared for NSW RTA by CSIRO)

**Conclusion:**
CSIRO has undertaken a comprehensive investigation into the DeNOx technology (denitrification) that is installed within the AFP of the M5 tunnel. The primary objective of this study was to determine the NO2 and NO removal efficiencies of the DeNOx system. The NO2 and NO removal efficiencies have been determined by both CAPS and CM instrumentation and the most reliable measured NO2 removal efficiency is 55% a standard deviation of 4%. Hence, the NO2 removal efficiency is reported as 55% ± 8% with a 95% confidence limit. The most reliable measured NO removal efficiency is 12% with a standard deviation of the order of 5%. The NO removal efficiency is reported as 12% ± 10% with a 95% confidence limit.

A range of additional measurements have been undertaken during these efficiency determinations. These extra measurements have revealed that the activated carbon has the potential for nearly 100% removal of NO2 from a gas stream for the NO2 concentrations measured in this study (20ppm). The NO removal efficiency for new activated carbon was measured to be much less than the NO2 with a removal efficiency of 56%.

The most likely origin of the apparent reduced NO2 and NO removal efficiency of the DeNOx system compared to "*used*" activated carbon is from air leakage around and through the activated carbon filled modules. This study has shown that the NOx mitigation chemistry of activated carbon is complex and much more research is required to fully understand the mechanisms and limitations of this technology within the AFP environment.

**Recommendations:**
CAPS instruments were delivered towards the end of this study and as such the performance of these instruments has not been fully evaluated. It is recommended that further research using the CAPS instruments be undertaken to more accurately evaluate the removal efficiency of the DeNOx system.

The NO2 removal efficiency of activated carbon has been shown to be much greater than the measured NO removal efficiency of the DeNOx system. To increase the NO removal efficiency of the DeNOx system it is suggested that alternative systems be investigated for containing the activated carbon.

B - Evaluation Program (review of Operational Performance in Feb 2012 by AMOG)

**Conclusion :**
The DeNOx system is not effective or cost effective as configured but there may be potential to develop an effective system.

The ESP (Electro-Static Precipitator) was unable to effectively or cost effectively remove PM (Particulate Matter) as configured and its operation was unreliable. Improving the performance of the ESP would require greater space and the addition of more equipment which would further reduce its cost effectiveness and add to its complexity which could further reduce reliability.

The knowledge gained regarding PM behaviour and measurement may provide a foundation for investigations into an alternative design of a lower cost and more efficient system for PM removal.

Based on the outcomes of the trial and the observations stated above, the following recommendations should be considered:

- That the operation of the air filtration plant should cease in its current form; and
- That alternative methods for reducing NO2 and PM be investigated further including consideration of other components of the AQIP for the benefit of both the East tunnel and for future tunnel designs.

**Cost effectiveness:**
The cost of NO2 and PM removal by filtration is significant when compared with other methods of removal. For example, the Department of Environment, Climate Change and Water (DECCW) NSW issued cost estimates for alternative particle removal methods in the range of $130,000 to $300,000 per ton particles removed. The AFP operating Costs (excluding installation), with constant elevated particle concentrations at the inlet for 12 hours per day would still be of the order of $2,000,000 per ton particles removed.

It is also important to note that the benefit of more general pollutant reduction measures such as higher emission standards and retrofitting are gained outside the road tunnel. The AFP only improved visibility in the last 0.4km of the westbound M5 East tunnel. Motorists would pass through this section of tunnel in less than one minute even in congested traffic conditions. The improvement was 29% between the AFP inlet and outlet, and about 6% at the westbound exit, and a corresponding very low improvement in the eastbound tunnel. In Comparison, the benefits of pollution reduction measures such as vehicle emissions management are gained everywhere in the road network.
In 2014n the Air Filtration Plant has been decommissioned.

This study has shown that the NO2 and NOx mitigation chemistry is complex and much more research is required.

TABLE 17. CONTRIBUTION OF THE AIR CLEANING EXPERIMENTATION IN THE M5 TUNNEL EAST SYDNEY TO THE THREE PILLARS OF SUSTAINABLE DEVELOPMENT

| PILLAR | + | - |
|---|---|---|
| Economic | | Investment, maintenance and operation costs |
| Social | Human health (limited impact) | |
| Environmental | Good for the environment but no real NO2 removal efficiency | |

## 5.4. ENERGY

**Current reflections in France regarding the use of transformers**

Savings can be made with power transformer redundancy. When a redundant power transformer is installed, there is less power dissipation and loss when all the equipment is connected to the same power transformer than when they are equally distributed on both of them.

An efficient operating mode for example would be to switch from one transformer to another on a weekly basis to ensure that both transformers are fully operational and rapidly available in case of failure of the other transformer. Upgrading this operating mode with redundancy transformers is neither complex nor expensive, even if the electrical power distribution has not been designed and built in such a way. This therefore allows energy and cost savings.

**Photo-voltaic power plan**

Another interesting approach, undertook mainly in Latin America, is to take advantage of solar radiation with a photovoltaic power plant which supplies the tunnel with electrical power. There are already at least two installations, such as the Pedro Galleguillos Tunnel, in Chile and the Santa Rosa Tunnel, Risaralda, in Colombia. Both tunnels have an LED lighting system.

*World Road Association (PIARC)*
*Tour Pascal - 19e étage*
*92055 La Défense CEDEX, FRANCE*

*International Standard Book Number: 978-2-84060-470-9*
*Frontcover © PIARC Technical Committee C3.3 Road Tunnel Operations*