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RECOMMENDATIONS ON MANAGEMENT OF MAINTENANCE AND TECHNICAL INSPECTION OF ROAD TUNNELS

PIARC Technical Commitee C.4
Road Tunnel Operations

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 2008 – 2011 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 organizations or agencies.

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CONTENTS

SUMMARY

The scope of this document is to provide recommendations for the maintenance of road tunnels, essentially in the domain of equipment. Aspects relating to civil engineering like emergency exits, drainage system and pavement are also listed.

This document gives information about the general principles of maintenance and technical inspections. It explains clearly the differences between technical inspection and safety inspection. However safety inspections are not described in it.

INTRODUCTION

Scope

Whenever exceeding the length of a few hundreds of metres, road tunnels are provided with equipment for ensuring the safety of users under normal conditions or in case of disturbances to normal operation. Depending on the nature of the structure (length, traffic load, uni or bi-directional traffic, etc.), one can find in a road tunnel a large variety of equipment, ranging from electromechanical systems (lighting, ventilation, power supply, etc.) to communication systems and operational devices (SCADA[1] system, remote surveillance, radio-retransmission, etc.).

Some of these systems, namely the power supply system and the SCADA system, are very important in the sense that they have links with all equipment of the tunnel.

Because of their involvement in the global safety chain, the equipment and installations must be selected and designed with great care, with regard to maintenance, inspection and refurbishment.

The great diversity of equipment brings about the participation of a large number of manufacturers. Because each of them specifies particular types of maintenance and interventions on a system composed of several sub-assemblies of varying origins, maintenance can be complicated.

It is also necessary to consider the constraints related to the conditions of these interventions: whether or not the closure of all or part of the structure is required, the frequency and duration of interventions and the safety of maintenance personnel.

Objective

The purpose of this report is intended to assist operator or operating body. This report is about good practice in the field of maintenance.

Therefore, this document proposes recommendations for the management of maintenance, essentially in the domain of equipment. The aspects relating to light civil engineering (emergency exits, drainage system, and pavement surface, etc.) are listed and described only very briefly.

It is also regarding the controls that have to be implemented for verifying that the maintenance actions performed allow the proper achievement of defined objectives at economical costs. These controls are defined in the form of technical inspections and their aim on the one hand is to make sure that the maintenance actions carried out allow the equipment to function in a satisfactory manner and on the other

[1] Supervision Control And Data Acquisition

hand, that the frequency of maintenance actions is adequate (neither too high because it will lead to unnecessary expenditure nor too low because the life cycle of certain equipment may get reduced).

After a brief reminder of the most common definitions, the document will describe first the problem of maintenance and then the technical inspection in particular.

Limitations of the study

The information and recommendations contained in this report are the result of individual written contributions as well as suggestions made during working group meetings.

In addition, questionnaires were sent out to all the member countries of the technical committee and the responses provided by many countries have allowed a larger vision regarding practices in terms of maintenance.

The recommendations in this report were therefore discussed in detail in the working group. They were also presented and discussed in the technical committee Road Tunnel Operations on several occasions (before being validated by the technical committee).

1. GENERAL PRINCIPLES

1.1. DEFINITION OF MAINTENANCE

The term *"maintenance"* may have different significances from one country to another and covers more or less wide domains. In certain countries, the tests and trials on equipment are considered to be a part of the operational domain and not the maintenance domain; in others, the complete overhauling of an equipment is a maintenance action; for yet others, the scheduled interventions are operational tasks. For an operator, depending on the country where the tunnel is located, the activities for which the operator is responsible may or may not belong to the maintenance domain.

A good illustration of this diversity may be seen in the responses to a survey on maintenance. To the question regarding the definition of the scope of maintenance, the responses obtained from 31 members representing 19 different countries are given in *table 1*. Within a same country, the practices may be different.

TABLE 1 - ACTIVITIES BELONGING TO OPERATION OR MAINTENANCE DOMAINS

Activities	Operation	Maintenance
Management of traffic	29 out of 31	2 out of 31
Management of equipment	21 out of 31	10 out of 31
Power consumption	19 out of 30	11 out of 30
Cleaning the walls	3 out of 30	27 out of 30
Cleaning of equipment	4 out of 31	27 out of 31
Tests/verifications/measurements	7 out of 29	22 out of 29
Planned interventions	9 out of 29	20 out of 29
Unplanned interventions	13 out of 29	16 out of 29
Refurbishment	5 out of 30	25 out of 30

The activities that the operators consider without hesitation as belonging to the maintenance domain are therefore: cleaning of walls and equipment, tests/verifications/measurements, planned interventions and refurbishment. For unplanned interventions, the responses are less clear on whether this type of actions belong to the maintenance domain.

As we just saw, the scope of maintenance does not at all cover the same activities from one country to another. It is nevertheless necessary to retain a single definition and from this point of view, the most relevant and most consensual definition of maintenance seems to be the one that appears in the Guide to good practices for road tunnel maintenance [1]. It defines maintenance in terms of objectives and states that *"the objective of tunnel maintenance is to ensure the traffic of users in total freedom, while maintaining the specified level of safety. It is however necessary to add that this objective should be achieved without causing danger to the neighbouring residents or to maintenance operatives or needless reduction of the capital invested."*

This definition is very close to that used in several countries of Europe: *"maintenance is the set of actions allowing to maintain or restore a property in a specified state or in measure to provide a determined service"* or the definition from Canada (province of Québec): *"the maintenance actions have the objective of guaranteeing to users the level of regulatory safety with which the tunnel was designed"*.

The maintenance operations may be divided into two groups:

- **the preventive interventions** that are carried out at predetermined intervals and are meant for preserving the equipment in good operational condition. The preventive maintenance offers the advantage of preventing unforeseen failures to the maximum extent and being easy to plan. It can however lead to high levels of expenditure if the interventions are too frequent: this type of maintenance therefore needs to be optimised;
- **the corrective interventions** that are carried out when a system or part of a system is malfunctioning or when hazardous events which may affect the safety resources of the tunnel (fires, water submersion of equipment, large accidents, etc.). The corrective maintenance limits the number of interventions, but it has the disadvantage of not using a system to the maximum extent of its theoretical life cycle. It cannot be planned, therefore sometimes results in carrying out emergency interventions with considerable additional costs and possibly, disturbances to the traffic flow in the tunnel.

The preventive maintenance can be subdivided into:

- **systematic maintenance:** The interventions are made according to a schedule established based on time (every week, every month, etc.) or according to operational periods;
- **conditional maintenance:** The interventions are subordinated to measurements (measurement of performance, measurement of wear, etc.).

1.2. DEFINITION OF TECHNICAL INSPECTIONS

A road tunnel is operated during very long periods of time and among the persons who participated in its design and construction, very few would be capable of sharing their knowledge with the persons responsible for its management and operation. It is therefore extremely important to be able to benefit from a maximum of information on the structure and its equipment before it is opened for traffic. One of the means allowing to respond to this requirement is the initial detailed technical inspection to be made when the whole equipment set of the tunnel is installed.

This **initial detailed inspection** must be conducted by the tunnel manager before he starts out the operation of his structure or before he hands it over to the operator. The objective of this initial inspection is on the one hand to verify the quality and the performance of installations and on the other hand, to ensure that the structure and its equipment comply fully with the provisions imposed by regulatory texts relating to the safety.

This inspection that allows establishing a reference point on the condition and the performance of the tunnel during its commissioning should be followed by other inspections throughout the life of the tunnel. These inspections should be carried out periodically at intervals that may vary from one country to another but is most often in the range of several years.

These **periodic inspections** should have the same objectives as the initial detailed inspection; they are however conducted in lesser detail than the initial inspection because with the tunnel being open to traffic, the interventions within the traffic area are more difficult to operate.

It is important to indicate here that the results obtained during a periodic inspection allow verifying that the maintenance programme is appropriate and that the resources invested allow achieving the objectives fixed.

1.3. INTERRELATIONS OF MAINTENANCE, TECHNICAL INSPECTIONS AND SAFETY INSPECTIONS

It may be remembered that all the maintenance actions conducted by the competent party (operator, subcontractors, etc.) have the objective of guarantying to the users the regulatory level of safety for which the tunnel is designed.

The detailed initial inspection allows setting a reference point before the opening of the tunnel for traffic. Then, periodic inspections allow evaluating at regular intervals that the safety level continues to remain satisfactory with regard to the equipment.

Differences found during a periodic inspection can lead to an increase or an improvement in the resources provided for maintenance (financial and human resources or a larger number of repairs); in certain cases, the results may also lead to the replacement of equipment.

A periodic technical inspection may also allow sometimes providing information for a safety inspection. In fact, the technical report *"Tools for the management of safety* *in road tunnel"* [2] indicates that a safety inspection is composed of three main parts:

- infrastructure and systems,
- safety documentation and procedures,
- operations (organisation, training of personnel, quality plan, etc.).

Certain results, notably from functional tests, may be useful for the organisation responsible for conducting a safety inspection with reference to the *"systems"* part.

It must be added that the organisation responsible for conducting a safety inspection of a tunnel does not involve the operating personnel. Therefore, the use of all or part of the results of a periodic technical inspection is left to the discretion of the organisation conducting the safety inspection. It is quite possible that for the purpose of verification, certain tests that are carried out during a periodic technical inspection are repeated during a safety inspection.

2. MAINTENANCE

A road tunnel has a varied range of equipment that may be located in the traffic area (both inside and outside the tunnel) or in the technical rooms or in a control-centre. Submitted to varying load (some are used continuously, others several times every day while others may not be used for several years), they all require high or low frequency interventions so that they can be relied upon when the need arises.

2.1. MAINTENANCE POLICY

2.1.1. Level of maintenance

The actions that have to be carried out as part of a maintenance plan *(see 2.2.2, page 18)* may be classified from the most simple technically to the most complicated. We thus obtain the six following levels:

- cleaning of tunnel structures (walls, roadway, ceiling, etc.),
- cleaning of equipment,
- tests / verifications / measurements / calibrations,
- planned interventions,
- unplanned interventions,
- refurbishment.

The first level concerns the day to day maintenance and does not require a high technical level from the maintenance operatives. The second level may require the assistance of more qualified staff when there are electrical or mechanical risks involved (high and low voltage equipment). The third level requires more substantial technical skills, particularly regarding the measurement and calibration parts. The planned interventions (fourth level) can be conducted only by personnel having sufficient technical skills in the concerned domain of intervention (electricity, electronics, information technology, instrumentation, etc.).

It may be noted that up to the fourth level, all the actions to be undertaken belong to the domain of preventive maintenance. On the other hand, the tasks of the fifth level (unplanned interventions) belong to the domain of corrective maintenance. They include in particular troubleshooting: fault location, repairs and re-commissioning tests.

Refurbishing actions concern equipment that has reached the end of its life cycle or equipment that no longer provides the expected performance, or even in some cases, systems for which spare parts are no longer supplied by the manufacturers.

2.1.2. Choice of maintenance strategy

Maintenance is defined as preventive and/or corrective. So while establishing their maintenance policy, a road tunnel operator must first of all prepare the maintenance strategy to assess the optimum combination of maintenance regime to be followed: preventive or corrective.

It has to be kept in mind, that the ascertainment of an optimal strategy is a matter of a combined consideration of cost benefit and safety evaluation.

In this process, statistical data is used to calculate the average cost per annum based on the average lifetime of each component, the initial investment cost, the expected maintenance costs during service and traffic costs related to each intervention. Based on these calculations different maintenance strategies can be prepared and assessed to identily identify whether preventive or corrective strategies or a combination of the two is the optimum strategy.

If corrective maintenance is the optimum, the operator must accept the potential of a high level of unplanned interventions, because equipment failures may occur in a totally random manner. A problem that arises may require a long time for the repairs, or even a very long time if the spare parts are not available or if the traffic conditions do not allow the opportunity to intervene in the tunnel. The tunnel manager may thus find himself/herself in a degraded situation that may, depending on the nature of malfunctioning equipment, impose restrictions on the operation of the tunnel, or even its closure. A curative type of approach does not allow the planning of tasks. It leads to interventions that have to be made as quickly as possible and these interventions may get complicated by a lack of availability at the time of failure in terms of human and / or material resources.

If the optimum strategy is preventive maintenance, one may not prevent failures but their frequency of occurrence can be reduced to a great extent.

The choice between preventive maintenance and corrective maintenance has to be determined depending on the human and technical resources available and according to the difficulty of maintenance actions to be carried out. A conditional type of approach allows optimising to the largest extent the number of interventions and the stock of spare parts; inversely, it imposes a precise monitoring of equipment in place with in particular checking of performance and periodic tests.

The principles of optimizing the maintenance are illustrated in the report *"Life Cycle Aspects of tunnel Equipment"* [4].

See also reports [2] and [3].

The questionnaire on maintenance, mentioned previously, included a question on the distribution between corrective and preventive maintenance actions: the responses obtained from 28 members belonging to 19 countries are given in *table 2*.

<table>
<tr><th colspan="4">TABLE 2 - DISTRIBUTION BETWEEN CORRECTIVE AND PREVENTIVE MAINTENANCE ACTIONS</th></tr>
<tr><th>Share of corrective</th><th>Share of preventive</th><th>Number of responses</th><th>Cumulated responses</th></tr>
<tr><td>5%</td><td>95%</td><td>1</td><td rowspan="8">16</td></tr>
<tr><td>10%</td><td>90%</td><td>1</td></tr>
<tr><td>15%</td><td>85%</td><td>1</td></tr>
<tr><td>20%</td><td>80%</td><td>3</td></tr>
<tr><td>25%</td><td>75%</td><td>1</td></tr>
<tr><td>30%</td><td>70%</td><td>4</td></tr>
<tr><td>35%</td><td>65%</td><td>2</td></tr>
<tr><td>40%</td><td>60%</td><td>3</td></tr>
<tr><td>50%</td><td>50%</td><td>4</td><td>4</td></tr>
<tr><td>60%</td><td>40%</td><td>3</td><td rowspan="2">4</td></tr>
<tr><td>80%</td><td>20%</td><td>1</td></tr>
<tr><td></td><td></td><td>Total 24</td><td>24</td></tr>
</table>

The number of responses is 24 out of 28 questionnaires returned by the members. Among the 4 who did not respond, 2 of them indicated that for them, the distribution between corrective maintenance and preventive maintenance changed over time depending on the age of the equipment; the other two did not provide any response, this may allow thinking that they do very little maintenance.

The responses show a distribution rather in favour of preventive maintenance (16 out of 24) in the measure that the share of preventive is greater than that of corrective. There is an equal distribution for 4 responses out of 24. The corrective is preferred only in 4 responses out of 24.

Good practice would be to adopt a preventive approach in the range of 70% to 80% for life safety systems. Operating above 80% may result in excessive maintenance costs. And operating below the range of 70% to 80% increasing safety risks.

2.1.3. Using subcontractors

The tunnel operating body is the organisation responsible for the operation of the tunnel. It may be the Tunnel Owner or a Contractor to the tunnel Owner.

The tunnel operating bodies of a road tunnel rarely carry out all the maintenance of equipment present in the structure for which they are responsible. It is common practice to employ sub-contractors to perform maintenance activities.

In terms of sub-contracting, the definition of an operator's strategy does not depend only on the human resources available; it also depends on the number of structures that the operator has to manage and the type of equipment installed. For conducting the maintenance of not very complex equipment in one or more tunnels of modest size, it is often possible to find the necessary skills internally; for maintaining very complex and/or safety equipment (radio-retransmission, supervision and SCADA system, etc.), it is necessary to rely on external contractors specialising in these domains. For instance, the intervention in safety software should be restricted to qualified staff, because its development, verification and validation are more demanding than conventional software. More details are given in appendix for sub-contracting policy.

A choice well adapted to the situation of a particular operator may not perhaps suit another operator. It is therefore difficult to define general rules but we can nevertheless identify practices that are shared by a large number of operators:

- the actions requiring considerable investment on tools (washing of tunnel, for example) are very often sub-contracted unless the operator is responsible for a large number of structures, in which case, it may be cost effective to manage this type of action internally;

- the maintenance of systems requiring an advanced knowledge of electronics and information technology is often sub-contracted because if the operator wishes to handle this internally, maintenance staff must have very advanced technical skills in domains that are often changing very fast.

For systems of lesser technical complexity (power supply, lighting, etc.), the trend is to handle the tests, trials and measurements internally and to entrust the interventions, planned or unplanned, to sub-contractors.

In the questionnaire on maintenance, there were two questions relating to sub-contracting: the first one, on the use (or not) of sub-contractors and the second one on the proportion of maintenance sub-contracted.

The responses provided to the question on the use or not of sub-contractors are given in table 3.

<table>
<tr><th colspan="3">TABLE 3 - WHO HANDLES THE MAINTENANCE ?</th></tr>
<tr><th>Maintenance conducted by</th><th>Number of responses</th><th>Cumulated responses</th></tr>
<tr><td>The owner of the tunnel</td><td>3</td><td rowspan="3">14</td></tr>
<tr><td>The operator</td><td>6</td></tr>
<tr><td>The owner of the tunnel and the operator</td><td>5</td></tr>
<tr><td>The owner of the tunnel and sub-contractors</td><td>4</td><td rowspan="3">17</td></tr>
<tr><td>The operator and sub-contractors</td><td>9</td></tr>
<tr><td>Only the sub-contractors</td><td>4</td></tr>
<tr><td></td><td>Total 31</td><td>31</td></tr>
</table>

We note that a short majority of members responding prefer sub-contracting (17 responses out of 31).

Among the operators who make use of sub-contractors, we note that:

- 17% of them sub-contract a quarter of their maintenance,
- 33% of them sub-contract half of their maintenance,
- 13% of them sub-contract three quarters of their maintenance,
- 37% of them sub-contract almost the totality of their maintenance.

It is, however, necessary to point out that even when the use of sub-contracting is relied on heavily, the operator must have access to some technical skills internally. Firstly for verifying that the work executed by the sub-contractors is satisfactory, but particularly for preserving sufficient knowledge and control over his own equipment. Secondly to have the possibility to control the costs.

In case of outsourced maintenance, the tunnel operator has to keep full control of installations, i.e.:

- make sure that the maintenance is carried out according to the contractual clauses,
- remain the owner of all the data of his installations: drawings, history of the works done, files of the executed works, contractual documents (report of reception, description of works done, invoices, etc.),
- plan regular meetings with the subcontractors.

2.1.4. Requirements for subcontractors

Beyond the legal and commercial aspects of the contract, the technical requirements of a contract may be of three types:

- systematic interventions planned and defined very precisely, including specified response time,
- objectives of availability and/or performance to be respected,
- a combination of the above two possibilities.

The sub-contractor may have to be qualified and certified for certain types of activities (for example, for high voltage and low voltage works, for performing calibrations, for safety software development, etc.)

Commonly, the contract of a sub-contractor includes a description of the tasks to be carried out with a time schedule. Each maintenance action is therefore assigned a frequency (change of filter in a CO analyser every month, for example). With this type of requirements, it is easy for the tunnel operator to verify that the required tasks have been carried out according to the correct frequency.

Other requirements may be defined, particularly those for which the nature and the frequency of maintenance actions are left to the initiative of the sub-contractor. In this case, the sub-contractor has to respect an objective, perhaps relating to the performance (the level of lighting must not drop below 80% of the level during commissioning, for example), or the availability (the annual availability of pollution analysers must be greater than 95%, for example). In this situation, the advantage for the sub-contractor is that interventions can be optimised, thereby reducing maintenance costs. For the operator, the advantage is that equipment does not have to be monitored on a daily basis: the disadvantage is that minimum operating standards must be maintained: neither too high nor too low. If the limits are too high, this will mean that the expenditure is higher than the requirement. If the limits are too low, the tunnel and its equipment will not be maintained properly and the regulatory safety level of the tunnel according to its design specifications will no longer be guaranteed.

2.2. MANAGEMENT SYSTEM

As mentioned in a previous report [1] irrespective of the maintenance strategy retained, there are three requirements to which a tunnel operator has to provide responses:

- **Safety culture.** The safety of tunnel infrastructure, users and employees depends on a strong safety culture, encouraged by the tunnel operator and accepted and shared by all the stakeholders. Risk analyses must be conducted for specifying stringent safety norms and obtaining safe working systems. This includes safety procedures for routine as well as emergency interventions.
- **Availability and responsiveness.** The tunnels operate continuously and are dependent on the constant availability and performance of critical equipment. The response times for repairing or replacing defective equipment must be specified and respected, based on their criticality.
- **Records.** The maintenance manager should create and keep up a complete database of all the equipment and for each of them, a detailed history in terms of interventions, defects and repairs. All the maintenance personnel, including the sub-contractors, have to follow this system, whatever the measures that the tunnel manager considers as most appropriate with regard to their contractual obligations.

2.2.1. Maintenance staff

The role of maintenance personnel is to maintain the technical equipment of tunnel(s), taking into consideration both preventive and corrective aspects, and in some cases, even verify the work of sub-contractors. The normal work concerns planned preventive maintenance operations but the personnel may also be called upon for emergency response to critical faults.

In this type of intervention, the patrols of the operator, the police or the traffic operator may also participate for protecting and enforcing the secure work zones (closing of lanes, road signs, variable message signs, etc.).

Essentially, specialised technical knowledge is required from the operatives [3]. The equipment in a tunnel is extremely varied: power supply, lighting, ventilation, alarms, control-command, surveillance, communications, etc. In addition, there are civil engineering structures. The maintenance requires the skills of varied professions: electricians, electro-mechanical technicians, electronic engineers, network engineers and civil engineering specialists. During recent years, electronic components and sub-assemblies have started occupying an increasing place in tunnel equipment. This is happening to a certain extent at the expense of electromechanical systems and results in a progressive reduction of activities related to electromechanical techniques in favour of new professions (network administrator, industrial IT engineer, etc.). In certain domains, particularly in electronics, the technological advances, new manufacturing processes and costs favour a certain evolution in approach to maintenance interventions, moving away from the concept *"maintain and repair"* to that of *"operate until failure and replace"*. See also reports [2] and [3].

2.2.2. Maintenance plan

The maintenance plan should detail the different tasks to be carried out and must provide all the details necessary for their execution. The plan is generally divided into three parts:

- collection of all the documents and internal or external information concerning the tunnel equipment. This includes all the technical manuals, drawings, dimensioning data and safety documentation, etc.
- list of all the tasks to be carried out with a detailed description of actions to be performed;
- the interventions procedures (location, access conditions, necessary tools, etc.).

The maintenance plan should be generally prepared by the contractor and then must be used by the tunnel operating body (or tunnel owner or tunnel manager) at the start of the structure's life. It should then be revised periodically taking into consideration particularly the elements contributed by feedback on experience.

The feedback on experience allows analysing:

- the functioning of various systems present in the tunnel,
- evaluation of results (tests, inspections and measurements),
- relevance of maintenance actions undertaken,
- annual and refurbishment operational budget.

The maintenance plan therefore has to be a dynamic document evolving over time *(figure 1, following page)*.

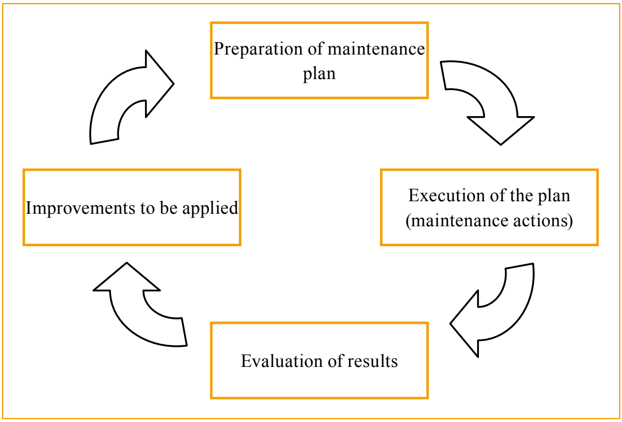

FIGURE 1 - MAINTENANCE PLAN DYNAMICS

2.2.3. Maintenance management system

Road tunnels contain increasing volumes of equipment. It is now common to find devices such as those related to power distribution or lighting; we also find an increasing share of complex systems using highly efficient technologies (high speed data transport networks, automatic incident detection, digital video equipment, etc.). The interventions required on equipment present in the road tunnel as a whole are numerous and of differing natures; they must be conducted at specific intervals. Intervention conditions may be difficult, particularly when it is necessary to intervene inside the tunnel within the traffic area. To all these constraints we must add the necessity of maintaining the traffic capacity of the structure at the highest possible levels.

Maintenance actions, therefore, have to be carefully planned and managed. The results of various inspections made must be preserved and archived so that they are easily accessible. In order to be able to meet all these requirements, the operator therefore has to set up a computerised maintenance management system.

The role of a maintenance management system is to assist the operator in (see report [1]):

- planning the works and the interventions,
- setting up performance monitoring indicators (failure rates, availability rates, etc.),
- management of costs,
- preparation of provisional budgets,
- management of sub-contractors,
- management of maintenance personnel (training, in particular),
- etc.

2.3. EQUIPMENT TO BE MAINTAINED

In terms of maintenance, we can often distinguish between general equipment and management equipment. The first are essentially made up proven materials based on mechanical and/or electromechanical technologies. The second are more sophisticated and reliant on computer and/or electronic technologies.

Among the general equipment we can find (list not exhaustive):

- power supply and distribution,
- lighting,
- ventilation/smoke clearance,
- fixed signposting,
- fire-fighting water supply network,
- evacuation of liquids (collection, pumping and treatment).

The management equipment covers (list not exhaustive):

- supervision Control And Data Acquisition: sensors, PLC devices, data transmission networks, supervision systems, etc.
- remote surveillance and automatic incidents detection.;
- dynamic sign posting (variable message panels);
- emergency call network;
- radio-retransmission;
- fire detection in the tunnel;
- metering/counting;
- other equipment: Access control, internal telephones, fire detection in service rooms, etc.

Average intervals to make preventive maintenance are shown in *table 4, following page,* for the main types of equipment. The figures are coming from previous PIARC reports and from answers given to questionnaires made for this report. They are given as an indication. For each tunnel, the maintenance manager should define the well adapted interval for his own equipment. Then he should regularly evaluate the results of the preventive maintenance to determine if too much or too little maintenance is being carried out on each system.

A lot of safety equipment having the main objective to reduce the risk of occurrence of emergency situations is installed in tunnels, and to ensure maximum possible protection for persons participating in this situation if such an event occurs. Therefore, each maintenance activity must be carefully planned in connection with the global safety level of the tunnel. So *table 4* also gives indication of the importance of the equipment regarding safety.

When planning maintenance activities, each tunnel manager takes into account the required continuity of traffic operation. The first point is to evaluate the impact on the traffic for the different maintenance activities and indications on this impact are given in *table 4*.

TABLE 4 - FREQUENCY, SAFETY LINK AND IMPACT ON TRAFFIC

Type of equipment	Average Maintenance interval	Link with safety	Impact on traffic
Power supply (high voltage)	6 months to 1 year	highest	low[1] or high[2]
Energy distribution (low voltage)	6 months	highest	low
Normal Lighting	2 or 3 months	medium	high
Evacuation Lighting	1 or 2 months	high	high
Normal Ventilation	6 months	medium	low or high
Emergency Ventilation)	6 months	high	Low[3] or high[4]
Fixed signposting	2 or 3 months	high	high
Dynamic signposting (including VMS)	2 or 3 months	high	high
Traffic Barrier gates	4 months	high	high
Fire-fighting water supply network	6 months	high	medium
Evacuation of liquids (collection, pumping and treatment	6 months	medium	low
Control-command system: sensors,	1 or 2 months	high	high
Control-command system: PLC devices, data transmission networks,	4 months	High	Low
Supervision and SCADA systems	2 months	High	Low
Cameras	1 or 2 months	High	High
Video processing and networks including automatic incidents detection	4 months	High	Low
Video monitoring in the control centre	2 months	High	Low
Emergency call network	2 months	High	High
Radio-retransmission	4 or 6 months	High	High
Fire detection in the tunnel	2 months	High	High
Metering/counting	2 months	Low[5]	High
Access control (technical rooms and control centre)	6 months	Low	Low
internal telephones	6 months	Low	Low
fire detection in technical rooms and control centre	6 months	Medium	Low

[1] Low if there is redundancy on the power supply
[2] High if there is not redundancy on the power supply
[3] Low if there are ventilators in technical rooms
[4] High if there are jet fans inside the tube
[5] Can be medium is ventilation regulation is linked to traffic analysis

2.4. DEFINITION OF TASKS

As mentioned earlier *(§ 2.1.1)*, the maintenance actions may be classified into 6 levels. These levels range from the technically simplest tasks to the most complicated and are as follows:

- cleaning of tunnel structures (walls, roadway, ceiling, etc.);
- cleaning of equipment;
- tests/verifications/measurements;
- planned interventions;
- unplanned interventions;
- refurbishment.

The first five levels above are described in greater detail in the following part of this paragraph.

A comprehensive maintenance plan is required to maximise the coordination of multiple maintenance tasks.

2.4.1. Cleaning of tunnel structures (walls, roadway, ceiling, etc.)

In road tunnels, the dirt that is deposited on the walls mostly comes from the exhaust gases, the wearing parts of vehicles (brakes, tyres), oil leakages from vehicles and wear of the pavement. The level of deposits varies with tunnel characteristics (length, slope, etc.), ventilation performance and traffic characteristics (density, percentage of heavy vehicles, vehicles with snow tyres, etc.).

The washing of walls contributes to increased comfort of the user but just as important, it contributes to prevention of corrosion in equipment (cabinets, panels, cables, etc.) installed inside the tunnel and maintenance of luminance levels (because of the restoration of reflectiveness).

The walls are usually washed at the same time as cleaning and sweeping of the pavements, sidewalks and possible garages or service alleys.

The frequency of cleaning in a tunnel is related to its characteristics, to the nature and density of traffic; it also depends significantly on the budget available to the tunnel manager.

The tunnel drainage system should also be regularly cleaned to maintain adequate flow of fluids.

2.4.2. Cleaning of equipment

This concerns the equipment located inside the tunnel (the most exposed) and also those that are located in the service rooms. This type of cleaning also requires to be carried out at regular intervals, covering particularly:

- sweeping of spaces accessible to users (niches and emergency exits),
- sweeping the service rooms and operational halls,
- dusting of cases, cabinets and electrical panels,
- washing of equipment installed in the traffic area (lighting equipment, sign board panels, sign boards indicating the safety niches and emergency exits, lenses of cameras, etc.).

The frequency of cleaning for equipment (or a technical site) depends on the rate of dirtying and also on its function: the panel's signposting the niches and the exits have to be cleaned more often than cabinets placed in the service rooms.

2.4.3. Tests/Verifications/Measurements

The objective of tests is to verify that the functioning or placing in secure configuration of an equipment is possible through local (traffic area, service rooms), or remote (control-command station) command. They may concern in particular:

- starting service of each equipment locally from electrical cabinets as well as remotely from the technical rooms/control centre;
- switching from normal power supply to standby power supply;
- closing of access barriers;
- verification of safety systems (including emergency stop);
- manoeuvring a device including report of status information (opening the doors of safety niches, emergency doors opening, release of extinguishers, manoeuvring of fire hydrants, etc.);
- unitary commands (starting a fan, activation of a variable message signs, etc.) issued from the control-command station.

The verifications are very often made visually. They allow obtaining useful information regarding certain equipment: either directly (appearance, readability, exterior condition), or by comparison with reference values (reading the displayed values). Among the verifications most frequently made in tunnel, we find:

- visual verifications of condition (appearance);
- verifications of displayed values;
- verifications of supports and/or fastenings;
- verifications of connections;

- verifications of readability on luminous panels;
- verifications of the condition of luminous sources;
- verifications of batteries on uninterruptible power supplies;
- etc.

Taking measurements is more complicated than making verifications. In fact, these are more technical interventions that require a certain level of skills and the use of measurement instruments. The principal measurement actions that may be carried out are the following:

- calibration of sensors;
- calibration of sensor activation thresholds;
- electrical measurements (voltage, intensity, power, frequency, amplification gain, etc.);
- photometric measurements (lighting and luminance);
- measurements of fresh air flow or smoke clearance;
- etc.

2.4.4. Planned interventions

They are of varied nature, ranging from the replacement of a lamp on a luminous panel to settings of cameras. The most common interventions are as follows:

- replacement of filters on pollution sensors;
- lubrication of bearings on motors;
- tightening of electrical connections;
- setting of amplifiers;
- replacement of luminous sources (lighting equipment, panels, overhead marker lighting);
- replacement of batteries on uninterruptible power supplies;
- etc.

2.4.5. Unplanned interventions

In spite of conducting a preventive maintenance of very high quality, it will not be possible to avoid some corrective maintenance interventions. These interventions require the presence of personnel with technical skills in the concerned domain. It will be necessary to carry out tests for verifying that the repairs made are satisfactory.

The unplanned interventions are by nature unforeseeable. However, the operator is recommended to set up a process for responding in the most efficacious manner possible to this type of problem. For this, an examination of the following aspects would be necessary:

- skills of personnel with reference to the installed equipment;
- skills and qualification / certification of sub-contractors regarding the tasks entrusted to them;
- acceptable intervention times for the different periods (day and night, week days or week-end);
- composition of consumable stocks (luminous sources, filters, etc.);
- availability of certain components from the manufacturers (electronic cards of PLCs, analysers of automatic incident detection, etc.).

2.5. REFURBISHMENT

2.5.1. Evaluation criteria

The necessity of refurbishing equipment should be evaluated based on several criteria:

- the risk that the equipment may cause to the users or the operating personnel, following degradation;
- a non-repairable fault in the equipment (fire in an electrical transformer, rupture in the turbine of a fan);
- high frequency of failures in the same equipment;
- absence of spare parts that may result in an inability to repair the equipment if it fails;
- degradation of rated performance of a system (ventilation, lighting);
- change of traffic conditions (increase of volume, heavy trucks allowed or forbidden, dangerous goods allowed or not, etc.);
- in some case, to take into account a new national law or new requirements it can be compulsory to change some equipment before the end of the equipments life cycle.

2.5.2. Establishment of forecasts

The total or partial replacement of certain equipment may be very costly, it is therefore prudent for the operator to anticipate as far as possible this type of action, in order to be able to obtain the budgets necessary in good time. Such forecasts should be as precise as possible.

The replacement cannot be anticipated without taking into account the life cycle of the different devices installed. As there are many types of equipment in varying numbers, they have therefore different service lives. They may range from a few years (for electronic or computer equipment) to several decades for electromechanical type of equipment (ventilation, power supply). More information can be found in report [4].

2.5.3. Availability of spare parts

In order to be able to maintain any equipment, it is necessary to have the necessary spare parts readily available or be sure of obtaining them within a reasonable time. When the installations are recent, this does not pose particular difficulties. For installations that have been in place for many years, it is necessary to confirm the availability of spare parts with the manufacturers.

The operator should also consider:

- optimization of spare parts stock (sufficient but not excessive number of spare parts and consumables),
- options for spare parts supply,
- requirements for stockroom,
- logistics (distribution, handling, storage and all other related actions).

If for a certain type of equipment, it is no longer possible to ensure its maintenance or repairs in case of failure, plans must be made for replacing this equipment while it is still in working condition, with a more recent model.

2.5.4. Special Precautions with safety systems

The refurbishment of safety systems of a road tunnel has to be tackled with special care, like what was done for the first design. Thus, the whole iterative process for development, test and commissioning should be performed with high quality control process.

3. TECHNICAL INSPECTIONS

Inspections can be routine (daily, weekly, monthly, annual) or principal. The routine inspections are linked to maintenance.

Before it is opened to the public, a road tunnel should undergo an initial detailed technical inspection. This first detailed inspection should have the objective, on the one hand of verifying the quality and the performance of installations according to the contractual obligations and on the other hand, to make sure that the structure and its equipment fully comply with provisions imposed by mandatory safety regulations.

Throughout the life of the structure, principal periodic detailed inspections should be conducted for obtaining a full and global diagnosis of the condition and the operational character of the equipment. These inspections also allow to verify that the resources employed for conducting the maintenance are not excessive or insufficient.

3.1. AREAS TO BE COVERED

A detailed technical inspection may cover:

- **civil engineering:** the main tunnel, the access structure and heads as well as galleries and other connected structures related to safety or operation (service rooms, ventilation stations, control-command station);
- **pavement:** geometry, surface markings and quality of surfacing;
- **equipment:** lighting, ventilation, power supply, remote surveillance, technical management, etc.
- comprehensive tunnel documentation (as built drawings, maintenance inspection and safety reports, maintenance plan, etc.).

However this chapter gives recommendations only for equipment.

3.2. TECHNICAL INSPECTION METHODOLOGY

3.2.1. Inspectors qualifications

Equipment present in a tunnel are numerous and highly varied.
The team responsible for inspecting the equipment in the tunnel must be competent in all the concerned technologies. This competence may be shared among several persons and in this case, one of them may be named the head of the inspection team.

Over a time, equipment installed in tunnels has become increasingly complex. This situation thus requires that the inspection team should have a high level of competence: an engineer level or equivalent is highly recommended.

Lastly, because of specific requirements of underground structures, it is preferable to entrust the inspections only to experienced persons. Senior engineers with at least three years of experience in the domain of tunnels are recommended in order to carry out inspections.

3.2.2. Required resources

The human resources necessary for carrying out the inspection of tunnel equipment may be found internally among the operator's personnel. However, since the principal objective of technical inspections is to verify that the human and financial resources allocated to tunnel maintenance are adequate, it is recommended not to entrust the inspection to teams that are responsible for the day to day maintenance.

Fot the intervention of external service providers, very precise specifications have to be drafted, including the description of equipment, the definition of tasks and the skills required.

For the intervention itself, it is necessary to:

- define the time limits of interventions,
- define the human resources required internally,
- define the human resources required externally (police, sub-contractors if any),
- define the accesses to be used,
- verify the existing procedures,
- define specific procedures for the inspection plan (see §3.2.3),
- provide the necessary traffic guidance equipment,
- make a list of measurement equipment (anemometer, luxmeter, wattmeter, etc.),
- provide special equipment (cherry picker, fork-lift truck),
- plan possible traffic deviations to be set up.

Careful preparation is required before an inspection so as to minimise the inconvenience that may be caused to the users and for persons living nearby.

First of all, the access conditions must be examined. They may be difficult in tunnel, particularly for very long tunnels or those with dense traffic. It is thus important to identify properly the zones that have to be accessed (space with traffic, technical rooms inside the tunnel, technical rooms accessible from the exterior, control command centre, etc.). In fact, very often, the inspection will not be possible without interrupting the traffic partially or totally. These closures, total or partial, should be limited as far as possible and with the least possible duration.

It is also necessary to examine the timeframe chosen for the inspection. Periods with dense traffic should be excluded as far as possible for interventions in the traffic space.

Lastly, one must take into account the immediate environment of the tunnel so that the nuisances created by the tests (noise, vibrations, etc.) create the least possible inconvenience for persons residing nearby.

In case a route includes several successive tunnels, the planning should not be made for individual tunnels but it should cover globally the entire route for concentrating possible traffic restrictions over a single period.

3.2.3. Inspection plan

The technical inspection plan should detail the different tasks to be carried out and must provide all the details necessary for their execution.

As a rough outline, a technical inspection plan is composed of four phases:

- definition of inspection objectives and content (establishment of technical reference system);
- collection of available archived data (plans, notes, results of previous inspections, etc.);
- effectively conducting the inspection;
- compilation of results (report, summing up note, etc.).

A detailed inspection must therefore be started by preparing a list of equipment and devices in the tunnel (safety equipment, emergency exits, etc.) that are to be inspected. For each system, it is necessary to define the measurements to be taken (ventilation outputs, lighting levels, etc.) and the functional tests to be carried out (local commands, commands from the control centre, automatic sequences servo-controlled by sensors, etc.).

The second stage then consists in collecting the maximum of available data like:

- drawings and diagrams,
- initial characteristics and rated performances,
- operating manuals,
- results of previous inspections.

The intervention itself is the third stage.

After each inspection a complete report must be drafted: this is the fourth stage.

3.2.4. The rating system

The results of measurements can be defined using a rating system.

For the evaluation of results, it is recommended to create a scale that allows qualifying the state of the equipment. This system is absolutely necessary but its application requires making some fundamental choices.

The first choice concerns the scope of application: Is it necessary to assign a score (or assessment) globally for all the tunnel equipment? Or, give a score to each type of equipment? If one chooses not to make a global assessment, then it is necessary to make a classification of equipment. A global assessment of equipment does not really make sense because they have neither the same service life nor role regarding safety offered to the user. On the other hand, an individual assessment of each equipment installed in tunnel will result in giving a multitude of assessments without providing a clear view of the whole. A good solution seems to make an assessment according to large families of equipment (electrical power supply, ventilation, lighting, SCADA, etc.). A difference should be made for the systems which are a basis for other systems like Energy Supply or Communication network. It should be assured that these systems are not valued commonly with systems which are dependent upon them.

The second choice concerns the number and level of the evaluation scale. Some countries think that the greater the number of levels (for example 10) the better the assessment will be precise.

Regarding the evaluation scale, it is necessary to have a well-designed reference system because the score given during an inspection has to be the same whatever is the inspector.
Experience shows that one must not exceed the maximum of 10 levels without going below four levels (very good, good, bad, very bad). Avoid if possible having an odd number of levels because this leads to creating an 'average' level that one may be tempted to use too often.

In order to give values like *"very good", "good"*, etc. there is a need for comparable criteria like age, safety factor and further the criteria *"availability"* as a key value. Most electronic systems behave in a way that they have a *"up-time"* and *"down-time"*, and the interesting point is to know the chance of failure. But this value is a probabilistic value, which is not easily available. Some suppliers provide for experience values given for a certain life span like the Mean Time Between Failure (MTBF). It is important that these criteria are independent from each other in order to avoid aggregated evaluation results, which are not usable.

When it is well designed, that is, when it is constructed with a precise reference system, a scoring method offers a double advantage. Firstly, it will lead to an evaluation that will be identical irrespective of the entity making the inspection. Secondly, it will allow monitoring over a period the performance of a given tunnel or comparing the performance a group of tunnels presenting very similar characteristics (length, traffic, type of equipment, etc.).

3.2.5. Inspection reports

The results and data collected during an inspection must be analysed for making a very precise assessment of the state of the inspected tunnel equipment. These elements can also allow monitoring the same equipment over a period and thus to anticipate refurbishment actions. These two objectives can be achieved only is the results and the data obtained from the equipment are compiled in a structured format and saved in a tool allowing their processing as desired.

The sheets in which the results of tests are noted and verifications must be pre-printed with pre-defined headings; in addition, they must be identical from one inspection to another. Each sheet should be as complete as possible; it should contain notably details like:

- Name of the tunnel,
- Location of the tunnel,
- Date and time of inspection,
- Name(s) of inspector(s),
- Nature of equipment inspected,
- Description of the equipment,
- Location of the equipment inspected,
- Measurements taken (including characteristics of the measuring apparatus),
- Measurement results,
- Immediate actions to be taken, relating to safety,
- Assessment based on the results,
- Pictures or photos (if required),
- Remarks (if required),
- Date for next inspection,
- Type of the next inspection (if required).

The report itself will include the list of all equipment and sites inspected, a reminder of the objectives and content of the inspection, in addition to a detailed description of the inspection. It should cover the following points:

- a detailed analysis of results (summary, comparison with previous inspections and placing in perspective);
- a global evaluation;
- a list of points to be dealt with in priority;
- recommendations if any.

Photos can be put in the annexes of the report. They can be helpful for comparisons with photos of the same conditions or defects taken during previous inspections, so that the rate of deterioration can be evaluated.

3.3. INITIAL DETAILED TECHNICAL INSPECTION

3.3.1. Principles

It is recommended to conduct an initial detailed technical inspection before commissioning the road tunnel. This detailed inspection must be conducted by the tunnel manager before he starts out the operation of his structure or before he hands it over to the operator.

The principal inspections and tests to be carried out may be divided into four groups:

- check of good design of structure and equipment with regard to regulatory requirements;
- verification that the quality of materials and equipment used corresponds to the technical requirements of the specifications, with particular reference to aspects of fire résistance, waterproofing of formwork and means used for protecting the equipment against corrosion (painting, galvanisation, anodisation, etc.);
- measurement of performance of installations (ventilation, lighting, control-command, radio-re-broadcast, etc.);
- functional tests that may cover:
  - individual functioning of each sub-system,
  - individual functioning of each system,
  - particular safety sequences associating several systems with one another.

The last point is the most important because the test of safety sequences is crucial to have a good functioning of the whole system. These tests are widely known under the expression *"integrated tests"*. They refer to system chains starting by a detection system (e.g. fire alarm system) and ending as at an alarm on the operative's screen in the control centre and additionally in several actions of other systems as the ventilation and lighting systems. The tests should be based on a defined and approved *"interaction chart"*, which shows all interdependencies of technical systems.

3.3.2. Detailed inspection according to type of equipment

3.3.2.1 Quality of design

Verification that the design of tunnel with all its equipment is accurate should be made essentially keeping in mind the safety aspects. This verification has taken place several times during the upstream phases of the project and this should be the final inspection before commissioning the project.
It is thus necessary to verify that there are no unsuitable systems or systems not responding perfectly to the rules of safety.

3.3.2.2 Quality of materials used

For all the equipment, it is also necessary to check the quality of materials and products used, particularly for the reaction and resistance to fire as well as water tightness and corrosion resistance. Criteria of sustainable development have to be taken into account.

3.3.2.3 Performance

The measurements of performance concern essentially the major characteristics of the equipment like volumes of air, levels of lighting, battery autonomy, quality of video images and data transmission speed.

The details of performance to be verified for the different families of equipment are given in *table 5* (list not exhaustive). The inspection of performance is of course to be adapted for taking into account the regulatory requirements applicable in each country. Measurements of performance other than those indicated in the table may be carried out according to circumstances specific to each structure and the particularities of each equipment.

TABLE 5 - PERFORMANCE MEASUREMENTS

Type of equipment	Measurements
Power supply (high voltage)	• Measurement of time necessary for switching from normal power supply mode to emergency supply mode (and for returning to normal supply) • Measurement of time necessary for switching from one transformer to another
Power distribution (low voltage)	• Measurement of the autonomy of Uninterrutible Power Supplies (UPS) • Measurement of the autonomy of generating units • Measurement of time to start for generating unit, voltage and frequency • Measurement of noise and vibrations levels for generating unit
Lighting	• Measurement, at different operating levels, of luminance or illuminance on the pavement, in the tunnel entrance zone and inside the tunnel • Measurement of lighting levels obtained on the footpaths and on the side walls • Measurement of lighting levels in emergency and/or evacuation conditions

TABLE 5 - PERFORMANCE MEASUREMENTS (continued)	
Type of equipment	**Measurements**
Ventilation / Smoke clearance	**Longitudinal ventilation** • Measurement of air flow speed obtained under different operational regimes • Measurement of the reversibility time of jet fans (when these machines are reversible) • Measurement of volumes of air sucked by smoke exhaust stations (when the tunnel has this type of equipment) • Measurement of noise and vibrations levels **Transversal ventilation** • Measurement of fresh air blown in through the different ventilation ducts • Measurement of volumes extracted from the different ventilation ducts • Checking the proper distribution of air flows along the different ventilation ducts • Measurement of reversibility times (for reversible systems) • Measurement of noise and vibrations levels **Ventilation of emergency exits** • Measurement of air volumes blown in for sanitary ventilation • Measurement of air volumes blown in during fire mode.
Fixed signposting	• Measurement of duration of readability for “photoluminescent” signs
Fire-fighting water supply network	• Measurement of pressure at each fire hydrants • Measurement of flow at each fire hydrants • Measurement of the capacity of the tank
Fixed Fire-fighting system	• Operate pump and measure current • Measurement of pressure at each pump • Measurement of flow rate at each pump
Evacuation of liquids (collection, pumping and treatment)	• Measurement of collection time in case of spill of a given volume on the pavement • Measurement of pressure and flow volume of pumps
Supervision Control And Data Acquisition (SCADA): sensors, Programmable Logic Controllers (PLC) devices, data transmission networks, supervision systems	• Measurement of time for sending back information collected in the tunnel to the supervision control centre • Measurement of transmission time of remote commands from the supervision control center to the terminal equipment
Remote surveillance (CCTV) and automatic incidents detection based on CCTV.	For the different events that the system should detect, it is necessary to measure: • The detection rate • The frequency of false alarms • The rate of false detections

TABLE 5 - PERFORMANCE MEASUREMENTS (continued)	
Type of equipment	**Measurements**
Closing barriers	• Measurement of time for closing
Dynamic sign posting (variable message panels)	• Measurement of display time of different message types • Checking the readability of messages
Emergency call network	• Checking of the audibility of all the emergency phones in the tunnel and near the portals • Checking of the audibility of the emergency phone in the control centre
Radio-retransmission	• Measurement of radio-electric fields inside the tunnel for different frequencies • Measurement of radio-electric fields inside technical rooms and control centre for different frequencies
Fire detection in the tunnel	• Measurement of time for reporting an alarm to the control centre from the different zones of the tunnel • Measurement of the autonomy of fire detection units
Metering/counting	• Measurement of metering data (flow, speed, occupation, etc.) for the different metering sites
Access control (technical rooms and control centre)	• Measurement of time for reporting information to the control centre from the different access points
Internal telephones	• Control of the audibility of internal telephones
Fire detection in technical rooms and control centre	• Measurement of time for reporting alarm for different equipped rooms
Loudspeakers	• Checking of audibility in different places in the tunnel (with and without ventilation)

3.3.2.4. Functional tests

The objective of functional tests is to verify the proper functioning of the different tunnel equipment in accordance to design specifications. The command orders may be passed manually from the Control Centre (CC) or generated automatically by the SCADA system.

These tests may cover:

- The individual functioning (e.g. starting of a fan, including the opening of the damper and the auxiliaries).
- The functional sequences according to each type of equipment, the sequences that may sometimes associate sub-systems from several families (e.g. automatic application of a lighting level: sequence in which intervenes a sensor, a PLC device, the power supply and the luminaires).

For various types of equipment, the details of tests to be performed are given in the *table 6* (list not exhaustive).

TABLE 6 - FUNCTIONAL TESTS	
Type of equipment	**Tests**
Power supply (high voltage)	• Verification of the functioning of high voltage power supply sources • Verification of the switching of transformers • Verification of the starting of generator units (if existing)
Power distribution (low voltage)	• Verification of the functioning of the UPS in case of loss of normal supply • Verification of all the low voltage circuits (on/off)
Lighting	• Verification of the turning (on/off) of the different lighting circuits (manual commands from the control centre) • Verification of the turning (on/off) of the different reinforcement lighting circuits (automatic commands servo-controlled by sensors)
Ventilation/smoke clearance	• Calibration of different pollution sensors and anemometers • Verification of the generation and transmission of pollution alarms to the control centre • Verification of the starting and stopping of different ventilation levels (manual commands from the control centre) • Verification of the starting and stopping of different ventilation regimes (automatic commands servo-controlled by the pollution sensors) • Verification of the triggering from the control centre of smoke clearance systems according to pre-defined scenarios for different fire locations • Verification of the dampers.
Fixed signposting	• Verification of the readability of panels
Fire-fighting water supply network	• Verification of the functioning of each fire hydrant and valves • Verification of the water circuits looping systems • Verification of pumping system (if existing)

TABLE 6 - FUNCTIONAL TESTS (continued)	
Type of equipment	**Tests**
Fixed Fire-fighting sytem	• Visual checking of the pumps room equipments • Visual monitoring of the pipes and the nozzles • Filters checking • Pump start control • Operation control of the deluge valves • Verification of the triggering from fire direction systems for appropriate scenarios • Activation of all spraying zones for spray structure visual control (using proper pressures and flows) • Verification of generation and transmission alarms to the SCADA system • Check and correct pressures gauges are required
Evacuation of liquids (collection, pumping and treatment)	• Verification of the collection of liquid spills (oil, etc.) • Verification of alarm made in case of dangerous goods
Supervision Control And Data Acquisition (SCADA): sensors, Programmable Logic Controllers (PLC) devices, data transmission networks, supervision systems	• Verification of power supply PLCs (inputs/outputs, normal power, emergency supply, restarting) • Verification of lighting PLCs (inputs/outputs, normal power, emergency power, restarting) • Verification of sanitary ventilation PLCs (inputs/outputs, normal power, emergency power, restarting) • Verification of smoke clearance PLCs (inputs/outputs, normal power, emergency power, restarting) • Verification of tunnel closure and traffic management PLCs (inputs/outputs, normal power, emergency power, restarting) Note: sometimes only one or two PLCs are in charge of all the equipment above, depending on the number of inputs and outputs. • Verification of redundancy for PLCs • Verification of individual (or global) remote commands from the control centre • Verification of status information reporting to the control centre • Verification of alarm reporting • Verification of data storage • Verification of redundancy of transmission network • Verification of the proper functioning of supervisory system • Verification of the redundancy of monitors

TABLE 6 - FUNCTIONAL TESTS (continued)	
Type of equipment	**Tests**
Remote surveillance (CCTV) and automatic incidents detection based on CCTV.	• Verification of the good quality of images • Verification of the display cycles • Verification of cameras identification • Verification of remote controlled cameras • Verification of camera switching for different events (open door, using emergency phone, using extinguishers, etc.). • Verification of automatic incident detection for all types of events to be detected (stopping vehicle, pedestrians, lost goods, etc.). • Verification of image storage process • Verification of alarms storage process • Verification of storage capacity
Closing barriers	Verification of the command for: • signalling lamps placed at the tunnel entrance, • closing barriers.
Dynamic sign posting (variable message signs).	Verification of the command for: • variable message signs (including message alternance if existing), • lane control signs.
Emergency call network	• Verification of all emergency phones inside the tunnel and near the portals • Verification of the emergency phone in the control centre
Radio-retransmission	• Identification of pre-recorded messages • Verification of the broadcasting of these messages • Control of the audibility of radios • Control of the audibility of safety messages in general public radios
Fire detection in the tunnel	• Checking the proper transmission of alarms in case fire is detected • Checking the proper activation of automatic sequences in case fire is detected
Metering/counting	• Checking the proper transmission of metering data • Checking the storage of metering data at the control centre
Access control (technical rooms and control centre)	• Checking the proper transmission of alarms in case of detection of intrusion
Internal telephones	• Control of the audibility of internal telephones
Fire detection in technical rooms and control centre	• Checking the proper transmission of alarms in case fire is detected
Loudspeakers	• Identification of pre-recorded messages • Verification of the broadcasting of these messages • Control of the audibility of loudspeakers

3.3.2.5. Particular safety sequences

It is necessary to verify the proper execution for some particular sequences that require the activation of various equipment. These sequences may be generated either automatically or by an order issued by the SCADA operator.

The number and nature of these sequences can vary greatly from one tunnel to another. The following sequences can be mentioned as examples:

- opening the door of a safety recess (initiated on door opening),
- unhooking of an extinguisher (initiated on unhooking),
- opening the door of an emergency exit (initiated on door opening),
- switching on power supply (initiated by the lost of normal power supply),
- emergency closure of a tube or the tunnel (initiated by the operator at the control command station),
- fire scenarios at different locations of fire starting (initiated by the operator at the control centre).

3.3.2.6 Verification of redundant systems

Whenever possible the loss of certain resources should also be tested in order to evaluate their impact on performance and safety, for example, by disconnecting: data transmission networks or fieldbuses to SCADA computers, by disconnecting a radio-retransmission system, by simulating a failure in a luminance meter. Such tests should be conducted in order to make sure that the appropriate actions and/or alarms arise both at the disconnection and at re-connection, as well as the time it takes.

3.4. PERIODIC DETAILED TECHNICAL INSPECTION

Throughout the life of the structure, periodic detailed inspections must be conducted at regular intervals by the operator. The frequency of these inspections varies from one country to another but it is in the range of several years.

The inspections and tests to be made are identical to those recommended for the initial detailed inspection with regard to:

- measuring the performance of installations.
- functional test (individual functioning by sub-systems, functioning by systems and particular safety sequences).

In general, the measurements of performance and individual tests are not all carried out with the same level of detail as during the initial detailed inspection.

3.5. ACTIONS TO BE TAKEN AFTER AN INSPECTION

It should be noted that the principal objectives of a periodic detailed inspection are to verify that the maintenance programme is well adapted and that the budgets allocated are neither too excessive nor too low. The results of a detailed inspection must therefore allow evaluating these two points: quality of the maintenance undertaken and the level of financial resources allocated.

Certain results, more particularly those from the different functional tests conducted may be useful for the organisation conducting the safety inspection *(figure 2)*.

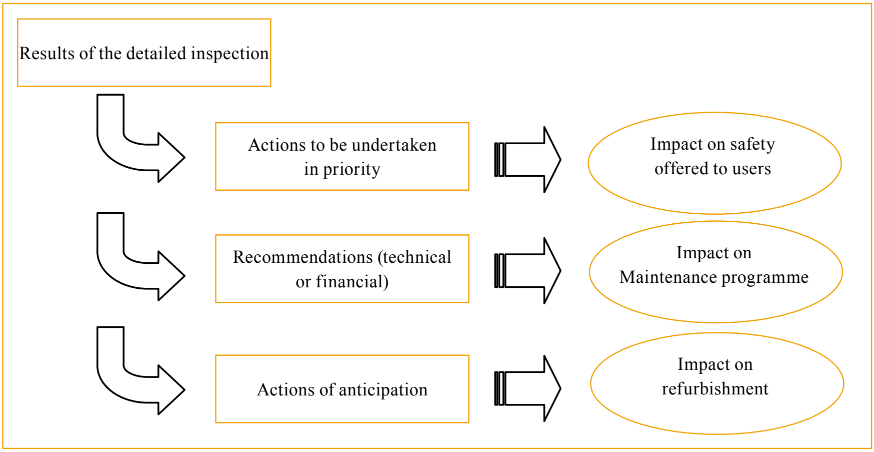

FIGURE 2 - USE OF RESULTS FROM A DETAILED INSPECTION

4. CONCLUSIONS

Where they are quite long and/or located in an urban area, road tunnels are fitted with equipment to provide for safety of users. This has to be maintained regularly in order to function correctly.

Such equipment may be classified into two groups: devices of electromechanical type (lighting, ventilation, power supply, etc.) and communication systems and operational devices (SCADA system remote surveillance, radio-retransmission, centralised technical management, etc.).

The first group of equipment has a life cycle in the range of several decades and sometimes does not require difficult maintenance (with the exception of the emergency generators). The second groupe often has a shorter life cycle and uses more and more complex technologies (electronics and/or software). Nevertheless, both groups require care and technical knowledge.

The presence of equipment thus imposes on a road tunnel operator the carrying out at regular intervals of highly diverse maintenance actions. Several options are available to them: corrective and/or preventive maintenance, use of internal and/or external resources and a percentage of sub-contracted maintenance. Through these different choices available to them, the operator may develop a maintenance strategy with the objective of optimising the resources available to them (personnel and budget) with a minimal operational risk. The results of this policy should be evaluated by carrying out technical inspections at regular intervals.

The aim of these inspections is to make sure on the one hand that the maintenance actions allow obtaining a satisfactory performance and on the other hand, verify that the money invested on maintenance is well adapted to the needs.

5. REFERENCES

[1] PIARC TECHNICAL COMMITTE ON ROAD TUNNELS *"Good practice for the operation and maintenance of road tunnels"*, reference 05.13.B, PIARC, Paris, 2005

[2] PIARC TECHNICAL COMMITTE ON ROAD TUNNELS *"Tools for the tunnel safe management"*, reference 2009R08, PIARC, Paris, 2009

[3] PIARC TECHNICAL COMMITTE ON ROAD TUNNELS *"Guide for the organizing, recruiting and training road tunnel operating staff"*, reference 2007R04, PIARC, Paris, 2007

[4] PIARC TECHNICAL COMMITTE ON ROAD TUNNELS *"Life Cycle Cost of Tunnel Equipment"* reference 2012R, PIARC, Paris, 2012

6. APPENDICES

Several options are available to the operator in terms of sub-contracting policy (following tables can be found in section 6.2 of PIARC report [3]).

- Sub-contract only the interventions of a specific technical level. The operator may thus sub-contract operations that are simple technically but that demand a specific costly tool (washing the walls with special equipment, for example). Inversely, he/she may also entrust to sub-contractors tasks requiring advanced level of technical skills (transformer stations, power electronics converters, automation systems, supervision systems, radio-retransmission equipment, calibration of sensors, etc.);
- Sub-contract all the tasks necessary for the maintenance of one or more families of equipment (power systems and ventilation, automation and remote surveillance, for example).
- When an operator has available sufficient personnel with technical skills covering the domains where interventions are needed (civil engineering structures, electromechanical equipment, electronic equipment, etc.), he may define his strategy based on the following three approaches:
  - For all the equipment, provide for certain levels of maintenance internally and sub-contract the execution of the others levels. Most often, these are the simplest levels in terms of technical complexity such as the cleaning of walls, cleaning of equipment and sometimes, the tests /trials/measurements *(table 7, following page)*.
  - Sub-contract the maintenance of one or more sub-families of equipment *(table 8, following page)*. In this situation, it is quite common to use several sub-contractors, each of them specialising in a well-defined domain.
  - Combine the above two approaches *(table 9, following page)*.

The tasks of refurbishment are not entrusted to sub-contractors, unlike the traditional maintenance actions. An action of completely refurbishing equipment is based on a choice of the operator. A refurbishment will require technical studies allowing the comparison of several possible solutions; these studies are in principle outsourced by the operator to external design offices. Similarly, for the following stages, the installation and commissioning are often carried out by external contractors. A refurbishment of safety systems (involving both hardware and software) in general is a complex and critical task, requiring particular attention up to the verification/test and commissioning phases. Unqualified or precipitate modifications have been in the origin of major failures in safety systems.

TABLE 7 - SUB-CONTRACTING ACCORDING TO LEVELS

	Family of equipment (non exhaustive list)						
	Power distribution	Lighting	Ventilation	SCADA system	Closed Circuit TV	Radio – re-broadcast	Etc.
Cleaning	Operator	Operator	Operator	Operator	Operator	Operator	…
Tests/trials/ measurements	Operator	Operator	Operator	Operator	Operator	Operator	…
Planned interventions	Sub-contractors						
Unplanned interventions	Sub-contractors						

TABLEAU 8 - SUB-CONTRACTING ACCORDING TO EQUIPMENT FAMILY

	Family of equipment (non exhaustive list)						
	Power distribution	Lighting	Ventilation	SCADA system	Closed Circuit TV	Radio – re-broadcast	Etc.
Cleaning	Sub-contractor	Operator	Operator	Operator	Sub-contractor	Sub-contractor	…
Tests/trials/ measurements	Sub-contractor	Operator	Operator	Operator	Sub-contractor	Sub-contractor	…
Planned interventions	Sub-contractor	Operator	Operator	Operator	Sub-contractor	Sub-contractor	…
Unplanned interventions	Sub-contractor	Operator	Operator	Operator	Sub-contractor	Sub-contractor	…

TABLEAU 9 - COMBINED SUB-CONTRACTING

	Family of equipment (non exhaustive list)						
	Power distribution	Lighting	Ventilation	SCADA system	Closed Circuit TV	Radio – re-broadcast	Etc.
Cleaning	Operator	Operator	Operator	Operator	Sub-contractor	Sub-contractor	…
Tests/trials/ measurements	Operator	Operator	Operator	Operator	Sub-contractor	Sub-contractor	…
Planned interventions	Sub-contractor	Operator	Sub-contractor	Sub-contractor	Sub-contractor	Sub-contractor	…
Unplanned interventions	Sub-contractor	Operator	Sub-contractor	Sub-contractor	Sub-contractor	Sub-contractor	…

Very often, the strategies developed by the operators combine an approach based on level with an approach based on equipment family. Many operators manage maintenance tasks them selves that do not require high level technical skills.

An operator may adapt his sub-contracting policy depending on the number of maintenance operatives employed and particularly according to the level and technical skills of those personnel. When the technical skills are available to a sufficient extent, an operator will be less inclined to make use of sub-contractors; inversely, if he has very few maintenance personnel or insufficient technical skills, he will be calling upon sub-contractors to a far greater extent.

GLOSSARY	
Term	**Definition**
Tunnel manager	The public body (national, regional or local government), private body or public/private/partnership or an individual appointed by them, responsible for the management of a tunnel. Note: in many countries the tunnel manager is the owner of the tunnel.
Tunnel-operating body	The organisation responsible for the operation of a tunnel. May be the tunnel owner or a contractor to the tunnel owner.
Operating staff	All employees of a tunnel-operating body
Maintenance staff	All employees in charge of maintaining the technical facilities of a tunnel.
Operations Manager	The individual in charge of the day-to-day operation of a tunnel
Tunnel operational staff	Employees of the Tunnel Operating body in charge at a given time of all or part of the operation of the tunnel. Note: may be several persons with separate responsibilities, e.g., traffic operation and equipment operation. The tunnel operator may oversee 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 only tunnel operator).
Maintenance operative	An employee of the Tunnel Operating body with specific duties and tasks within the tunnel Maintenance team.