7. COST OF MAINTENANCE

7.1 General

Tunnels are normally provided with technically advanced and expensive equipment that, for operation and maintenance, demands a high degree of competence and considerable resource. Professional and structured planning of operation and maintenance activities is necessary if the following demands are to be met:

- the safety of road-users,
- ensuring free traffic flow,
- operational economy.

If the available amount of money for maintenance is not sufficient, there will be an adverse influence on both service levels and safety.

7.1.1 Objectives of Maintenance

The overall aim of operational maintenance is to maintain a specified level of safety, with an optimal level of expenditure and without adverse environmental effect.

This means that maintenance shall be planned and executed in such a way that the operational assumptions made at the design stage remain validated throughout the operational period. Similarly, attention must also be paid to the technical assumptions upon which decisions were based in the planning and construction of the tunnel.

Objectives can be achieved by:

- maintaining the planned functions that have been built into the tunnel,
- maintaining the functional requirements, or modifying them to meet current requirements,
- maintaining the functional safety, or modifying to meet current requirements,

- ensuring that safety equipment meets the requirements, at all times,
- ensuring that safety procedures meet the requirements, at all times,
- aiming at a uniform standard for similar installations, especially tunnels on the same road section, with similar traffic flows.

As a consequence of these objectives, requirements shall be documented regarding the functioning of each installation, and how those functions shall be maintained in the event of interruptions or irregularities in operation.

7.2 Maintenance Cost

Operation and maintenance includes all activities necessary for a tunnel to meet all its functional requirements throughout the service life. Different countries have different definitions of maintenance and operation.

For this report, the working group has defined maintenance to include the following:

- washing and cleaning,
- functional supervision and maintenance of technical equipment,
- renewal and repair of structural components, road surfacing, painting of technical equipment,
- emergency activities such as removal of objects dropped on the road, fixing any components that have worked loose, adjusting incorrect positioning of technical equipment, removal of ice, etc.

7.2.1 Other Factors with an Impact on Maintenance Costs

In addition to the structural elements and technical equipment provided, the following factors have an influence on the maintenance cost:

- the maintenance level,
- organization,
- extent of specialist contractor involvement,
- amount of technical equipment,
- choice of technical solutions,
- requirements concerning the environment and working conditions,
- management system and method,
- tunnel location,
- tunnel operation (one or two-way traffic directions),
- legislation of the country,
- types of contract,
- ease of access to the equipment,
- ease of tunnel closure for maintenance.

7.2.2 Systems requiring Maintenance with Level of Impact on Maintenance Costs

The table below shows to what degree the different technical cost elements influence total maintenance costs:

Technical equipment system	**Influence**
Incoming power supplies	low
Internal power distribution	low
Standby generation	moderate
UPS systems	moderate
Lighting	high
Ventilation	low
Drainage	moderate
Fire fighting	moderate
Communications	moderate
Traffic management	low
Traffic monitoring	low
Building services	low
Plant monitoring and control equipment	moderate

7.3 Technical Systems influencing Maintenance Costs, System by System

7.3.1 Lighting

Lighting factor	**Influence**
Number of luminaries	high
Re-lamping philosophy	moderate
Ease of access	moderate
Ease of de-mounting and replacement	moderate
Cleanliness of tunnel	low
Length of closures	low

7.3.2 Ventilation

Ventilation factor	**Influence**
Number of fans	moderate
Method used (longitudinal, full or semi-transverse)	moderate
Ease of access	low
Ease of de-mounting and replacement	low
Length of closures (if needed)	low

7.3.3 Building Services

Building services factor	**Influence**
Buildings manned or unmanned	moderate
Number, size and location of buildings	high

7.4 Design Requirements

The PIARC report "Classification of tunnels" (1995) contains the following statement: “There is growing interest in the use of classification systems for establishing consistent, safe and economic standards for equipping, operating, maintaining and refurbishing road tunnels.”

Tunnels have been classified (see Chapter 4) according to:

- tunnel length,
- traffic flow.

Other factors need to be taken into account, such as:

- uni-directional or two-directional traffic,
- urban or rural zone,
- over or under water,
- service level (class of road).

The above factors, together with the tunnel’s spatial provision, i.e.:

- emergency lane,
- lay-by,
- turning space,
- safety barrier,
- emergency lane pavement,

and geometry,

- gradient,
- curvature of the tunnel,
- tunnel entrance and exit,

form the basis for the choice of technical equipment, which can include:

Supervision and alarm equipment:

- SCADA
- CCTV
- IDS (incident detection system)
- emergency telephones
- fire alarms
- automatic fire detectors
- instruments for measuring visibility
- instruments for measuring gas concentrations
- sensors for doors, alarm boxes, fire extinguishers
- devices for detecting vehicle height.

Escape routes and communication:

- emergency doors
- radio transmission
- communication equipment
- loudspeakers
- escape route signs
- smoke-free escape routes
- emergency lighting
- variable message signs

Fire fighting and anti-pollution equipment:

- hand-operated fire extinguishers
- fire hydrants
- water reservoir
- fire-hose coil with supply
- sprinkler (if used)
- closed drainage system
- explosion-proof pumps
- air purification (if used)
- incident and Emergency plans
- fire engines (if owned).

Other requirements and equipment:

- functional safety (safety against failure)
- uninterrupted power supply (UPS)
- tunnel lighting
- reversible ventilation
- wall panels (surface and strength)
- fire protection
- traffic control installations
- queue warning
- access equipment.

Aspects of maintenance that have a cost significance include:

- the installed equipment must not be so specialised that it is not practical to change its maintenance contractor,
- the equipment should be selected so that the number of specialist contractors is minimised,
- speed and ease of access to equipment for maintenance purposes,
- external location of equipment, e.g. by placing in a service gallery outside of the trafficked area or remote, co-located heating element measurement and control for signals, instead of the increased maintenance demands of placing control equipment in each unit.

Many factors are decided in its planning and design phase that will have an effect upon future tunnel maintenance. The selected standards and solutions will invariably affect future operation routines and maintenance needs. In specifying the tunnel, it is necessary to understand which factors affect operation and maintenance.

At design stage, a safety plan should have been prepared. Safety equipment, escape routes, rescue routes, staff and emergency services turnout time and intervention possibilities should have been analysed, in combination with risk analysis. Overall safety levels will be documented and acceptable.

The safety plan, to be regularly updated throughout the service life of the tunnel, is of key importance for decisions concerning operation and maintenance expenditure.

New technology can make savings possible but also create new demands on tunnel operation. E.g. the use of in-car mobile telephones by road users (contacting the wrong service) instead of using the tunnel emergency telephone system could result in undetected accidents in the tunnel with a risk of further accidents due to lack of preventive measures (warnings, speed limits, closing of traffic lane etc). This may then create an additional need for an automatic incident detection (IDS).

Installation of IDS may then make it possible to reduce the number of emergency telephones, fire sensors, gas and smoke detectors.

Slow-moving or stationary vehicles can be detected by means of induction coils set into the road surfacing. If image analysis via CCTV is used instead, a further saving in maintenance work could be achieved.

7.5 Service Life Considerations

The various components of a tunnel have very different service lives. The structure itself is expected to have a life of over 100 years. Technical solutions that result in small but regular annual rises in operation and maintenance costs will ultimately create a considerable, additional cost.

Most technical equipment has a shorter life, often 10 - 20 years. Monitoring and other electronic equipment has an economic lifetime of 5 - 10 years. It is important to take initial investment, future operation and maintenance, as well as reinvestment costs into consideration when alternative solutions are evaluated at design stage (See Appendix 3 for tables of expected service life based on experience from Norway and UK.)

To obtain a better evaluation of life-cycle costs, it is important that those responsible for the operation and maintenance of tunnels share their experience at the planning and design stages and take a full part in the choice of systems.

In the process industry it was claimed some years ago that persons who had neither knowledge of nor interest in maintenance determined 80% of the maintenance costs. This situation should not be tolerated for road tunnels.

Considerable savings can be made by fully utilising available maintenance experience - several national highway authorities are doing so to an increasing extent.

Even though one tries to select optimum technical/ cost solutions, situations may arise during the service life of a tunnel that can involve increased maintenance costs. For example, in older tunnels, where there once was little traffic, maintenance work could be carried out in the daytime. A steadily increasing amount of traffic has made it necessary to carry out such work at night.

Rising traffic flow can also result in a need for upgrading and thereby for more technical equipment and resulting increased maintenance costs. In the Netherlands, upgrading was required due to the policy to issue permits for the transport of dangerous goods.

Increasingly strict environmental demands, for which national legislation is the governing factor, chiefly concern restrictions on dust, toxic gases, noise and waste water. These demands may require tunnel modification or the installation of additional technical equipment.

Stricter health and safety demands for the working environment can make compliance more difficult to obtain permission to work in a tunnel with traffic, draughts, noise, dust and atmospheric pollution.

7.6 Systematic Maintenance - Maintenance Methods

There are several common forms of maintenance. Maintenance problems are general whether it is machines in a workshop, an oil rig, a dairy, or a road tunnel.

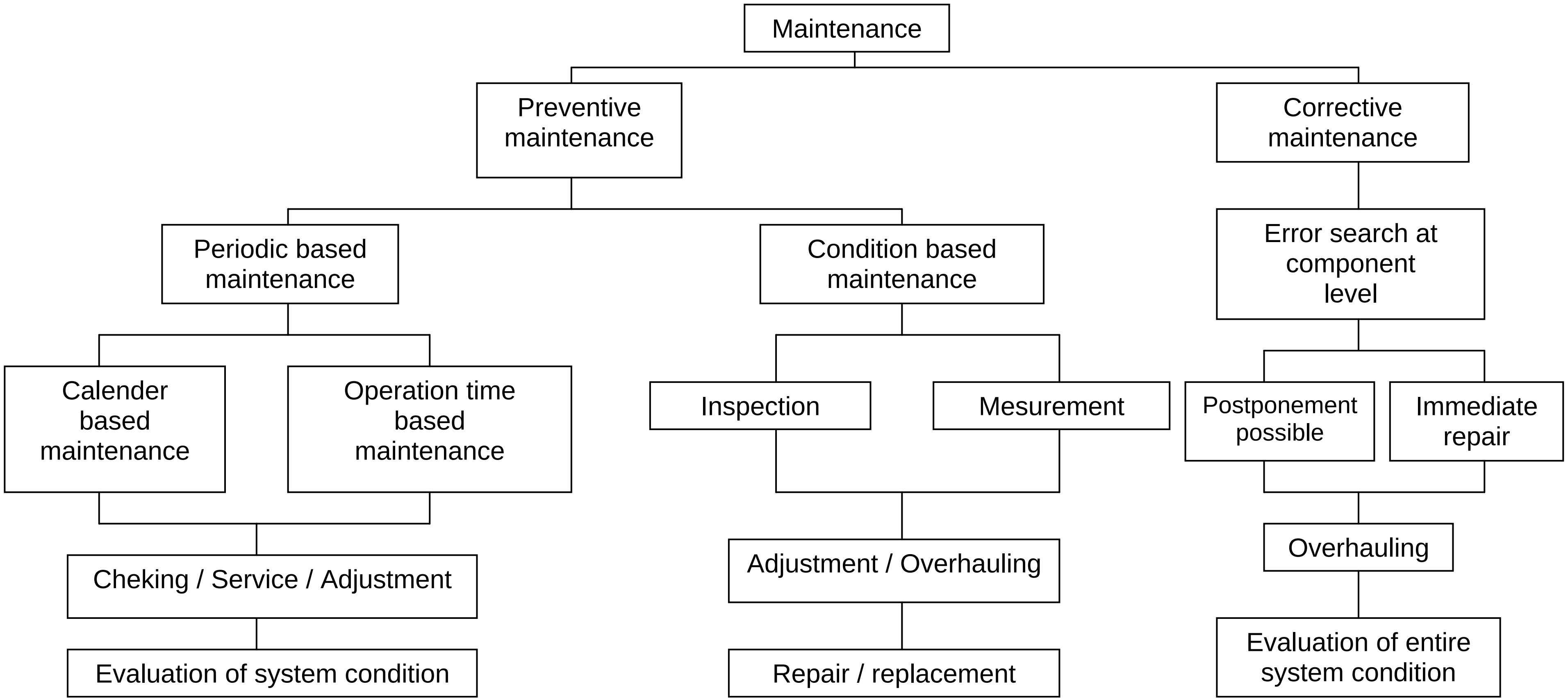
Some systems are well thought-out and contribute to operating a tunnel that is safe for all that use it. Other haphazard forms of maintenance, based on unco-ordinated activities, do not provide the levels of safety needed.

Planned maintenance

Tunnel maintenance should be planned maintenance. A planned maintenance system consists of preventive maintenance, which can be periodic or equipment condition-based, but will always include an element of corrective/ unexpected maintenance, which it is neither possible nor economically reasonable to try to eliminate.

The figure below illustrates the different types of planned maintenance that may be used:

Planned maintenance



7.6.1 Main Groups

It is customary to divide planned maintenance into two main groups:

- preventive maintenance,
- corrective maintenance.

7.6.2 Preventive Maintenance

Preventive maintenance is aimed at preventing an operational breakdown.

Experience shows that maintenance based on preventing damage to components and systems is safer, more effective and more economic than maintenance based on repairing faults or damage. Insofar as the maintenance system is systematic and well planned, one will obtain what is known as systematic preventive maintenance.

The basis for preventive tunnel maintenance (as for the maintenance of buildings, machines and equipment) is the instructions from the designers and suppliers, and the guidelines that the tunnel owner has incorporated into operational instructions.

If there are many types of equipment and several suppliers or manufacturers, the resulting differences in maintenance guidelines will make it difficult to carry out maintenance in a consistent way. Each guideline should be reviewed and if possible be amended/ rejected to suit better the overall maintenance system requirements. Equipment is to suit the needs of the operator (customer) not the supplier.

Systematic preventive maintenance is frequently of help in keeping the cost of maintenance at an acceptable level. The system must be based on experience and averaged expectations – the latter can sometimes result in too much or too little maintenance. The environment in the tunnel is an example of a factor that will have considerable influence. A tunnel that is dusty and humid, with a high salt content, will have more adverse effect on equipment than a dry, well-ventilated tunnel.

There are two types of preventive maintenance:

- Periodic
- Condition based.

7.6.3 Periodic Maintenance

Preventive maintenance is carried out before damage has occurred, and periodic maintenance routines (i.e. after predetermined time periods) are used in this type of maintenance. The length of the periods is normally determined as:

- Calendar based
- Operation time based.

Checking, service and adjustment
In all types of periodic maintenance, the condition and functioning of components is checked and any necessary supplementary work carried either immediately or subsequently.

Condition evaluation
It is a part of a periodic maintenance system that inspections are carried out in which both components and their entire systems are evaluated in order to determine when and to what extent major interventions, such as replacements, are necessary.

7.6.4 Calendar Based Maintenance

The simplest form of calendar based maintenance is the use of standardized checklists based on tunnel (not equipment) operational time or calendar time. The time intervals could be, say, 125, 250, 500 or 1000 hours, or weekly, monthly, quarterly, etc. The selected interval for particular equipment components depends on the average elapsed times between maintenance needs.

The checklist also indicates the type of work to be carried out, and has space to record execution of each job. The person responsible for ensuring that the maintenance has been carried out correctly signs for the list.

Calendar based maintenance is a good starting point particularly for new operators not accustomed to routines, and contributes to systematic maintenance. There will probably be insufficient new information to justify continually changing the intervals to obtain the absolute optimum maintenance regime. Calendar based maintenance is therefore recommended in situations where the introduction of systematic maintenance is important; it can be used as a start before progressing to more active systems.

7.6.5 Operation Time Based Maintenance

Operation time based maintenance refers to the actual operating time of the individual items of equipment. Operation time is registered by means of automatic counters, although manual registration is also a possibility. Maintenance documentation gives the number of hours that shall elapse between the various types of maintenance and servicing.

7.6.6 Condition Based Maintenance

It is important to be aware of the extent to which the costs of preventive maintenance can be reduced. Condition based maintenance makes this possible. By using condition-checking methods, the correct time for maintenance can be determined, so that intervention is neither too early nor too late.

The aim of introducing condition-checking methods is to reduce the extent of preventive maintenance and render it more effective, increase the service intervals and obtain a better overview of the condition of the tunnel and its equipment.

Inspection
The simplest form of condition checking is visual/aural inspection, which means that one searches for leakage, cuts, cracks, arcing, loose components and malfunctions, listens for unusual sounds, etc.

Condition measurement
Equipment condition can be evaluated by carrying out measurements on the equipment during operation. More advanced methods are based on fixed sensors or indicators such as temperature measurements, measurements of electrical parameters, vibration analyses, etc. Operational monitoring systems for lighting, ventilation and pumping makes it easier to also introduce automatic condition checking. Automatic indicators and sensors in preventive tunnel maintenance are used to a very limited extent in the Nordic countries today, but it is technically possible to increase their use greatly. However, the costs must be examined in relation to the benefits that can be expected from such instruments.

7.6.7 Corrective Maintenance

Corrective maintenance involves carrying out maintenance measures after an operational breakdown or an accident has occurred. This type of maintenance greatly reduces operational safety, as it is based on the assumption that components will continue to operate fully until a malfunction arises. It is not possible to plan or budget properly for the required maintenance measures. This type of maintenance is also called breakdown-based maintenance.

Although preventive maintenance is generally preferable, parts of the installation may be maintained on the basis of corrective maintenance. This means that the parts in question are not maintained, but replaced when a defect arises.

For “planned” corrective maintenance, it has to be decided in advance which components are to be included and how rapidly they are to be replaced. In other words, corrective measures are envisaged, but it is impossible to predict when. This is defensible only if the safety of road users will not be affected. If road user safety is affected, redundancy of components may be necessary to ensure continuity of tunnel operation.

Even with preventive maintenance, it must be accepted that components will be subject to malfunction or damage from vehicle impact. When this happens, it must be decided whether the defect needs to be remedied immediately or work can be postponed to a more convenient time.

7.7 Management Tools

A computer based maintenance data processing tool can help to increase the efficiency and reduce the costs of maintenance. Appropriate computer software can simplify the processing of information.

It must be made a simple matter for the user to enter changes and additions to operation manuals and procedures, feed-back from inspections, functional supervision, maintenance and repair records, information from the tunnel SCADA-system, decisions made at meetings etc. It must also be simple to retrieve information and make alterations.

The system can give the user an overview of current outstanding maintenance tasks, so that resources can be effectively utilised.

The tool can also give the user access to all relevant information on the tunnel, work documents, drawings and specifications by means of information technology (IT). This technology also makes it possible to have many points of access to a given information item.

The tool helps to improve quality assurance. Each item of information, drawing, procedure, etc is stored and updated at only one point, so that all who have access to the system will always find the correct and current version of the item looked for.

A number of commercial software maintenance systems are available, all of which to some degree meet the needs of tunnel management. However, developments are extremely rapid, and it can be expected that the use of computer technology will result in rationalisation and centralisation of tunnel management.

7.8 Level of Maintenance

The level of maintenance depends upon national standards and the available funding. If the amount of money available is too low, the level of maintenance will be too low and the service life of the installed equipment stands a high risk of being shortened. Reduced service and safety levels may result and eventual tunnel closure may need to be invoked. Regular and sufficient expenditure levels, with no surprises, are the easiest to handle by both funders and operators.

7.9 Organization of Maintenance

The tunnel owner, or authority responsible for operation and maintenance, must establish an organizational structure for technical maintenance, fire and rescue procedures, as well as traffic operation.

The operational organization is responsible for updating procedures, manuals, specifications, etc. to deal with:

- acute problems, both traffic accidents and technical problems that affect safety or traffic flow,
- service and maintenance, including the regular correction of technical errors that do not need immediate attention,
- awareness and planning for major repairs and replacements.

The structure of the organization depends on several factors, of which the most important are:

- type and extent of technical equipment in the tunnel,
- extent of automatic surveillance and alarms,
- traffic flows,
- geographical location,
- magnitude of the tasks to be carried out.

How the structure is organized will depend on the capabilities it needs in each of the following fields:

Surveillance tasks
These involve surveillance for events that normally result in the alerting of police, fire or rescue services. In some countries it is the tunnel personnel, in others the police or an alarm centre that deals with these tasks.

Operational tasks
The tunnel personnel or a contractor carries out these tasks. To some extent, the tasks can be planned in advance (e.g. cleaning, washing, sweeping).

Preventive maintenance
These tasks are carried out by the tunnel personnel or a contractor, and can be planned, in detail, in advance.

Corrective maintenance/ repair of damage

These tasks cannot be planned in advance. However, the procedures to be followed in the event of failure or damage must be planned for. There are two strategies for dealing with such situations:

- surveillance personnel who can prevent damage from spreading, and call in the necessary specialists. This is relatively expensive because wages must be paid to persons who are on duty in shifts, in case an accident or irregularity happens. The solution can only be recommended when such events are so frequent that they keep a person occupied most of the time or other duties can be included,

- electronic surveillance, with an alarm connection to search and locate others on duty or stand-by. The type and location of the accident or irregularity is indicated by a code. One person on duty must decide whether the matter needs immediate attention or can wait until a convenient time. To facilitate such decisions, alarms are frequently grouped on the basis of importance and how quickly intervention is needed (e.g. A, B and C alarms).

The interface between areas of responsibility of the police, local traffic supervision centre and tunnel management varies from country to country. In each case, an analysis of traffic preparedness and technical operation tasks should be carried out, in order to evaluate the total work load and necessary resource.

Once the areas of responsibility, competency levels and activities list (with extent, frequency, duration etc.) have been defined, there is a basis for deciding between a surveillance centre, manned 24 hours per day, or connecting the tunnel to an existing surveillance centre or other organization.

In several national highway administrations there is an ongoing discussion on the extent to which tunnel works can or should be carried out by government employees or whether they can be contracted to private firms.

A substantial portion of operation and maintenance tasks could, with advantage, be put out to tender. Works carried out by private firms provides a flexible arrangement, as a price for many activities can be agreed (or rates scheduled in advance) each time work is to be carried out - the extent and frequency of such works can then be optimized without carrying non-productive staff over quiet periods.

The effective use of consultants for planning and supervision can also lead to staff reductions in the organization of the tunnel owner.

However, the advantages and disadvantages should be considered before deciding on the tasks to be given to consultants and contractors. Consultants and contractors with the necessary experience for effective road tunnels work are relatively few. Unless the client retains a certain amount of know-how, there is a risk of consultants and contractors eventually attaining a monopoly position that will lead to rapidly rising fees and costs. An “intelligent client” also knows what is wanted, why, and whether it is being supplied.

7.10 Types of Contract

In many countries there is political discussion about authority operated or private contracting (and funding) of public works. The working group should not take part in this discussion. However, it is important that the organization decided upon has a clear interface, as far as cost is concerned, between authority work and the work that can be subjected to contracting. This will enable the authority manager to make use of benchmarking and a best practice judgement for a contracting strategy to lower maintenance costs.

7.11 Selection of Equipment and Selection of Technical Solution

Selection of tunnel equipment and technical solution are factors that probably influence maintenance costs the most. This is a planning matter that regrettably may not be directly connected to operation. However, the working group point out (see Chapters 8 and 9) some basic rules that should apply particularly as equipment is subject to periodic renewal and technical solutions can be changed if they generate unacceptably high operational or maintenance costs.

7.11.1 Selection of Equipment

Selection of equipment is very often selected on the basis of initial investment cost. It is important that the selections will become based on a life cycle cost (LCC) analysis where maintenance schedules and operational methods are taken into account. The PIARC working group on maintenance, management and operation presented, in 1989, a report on the subject “Time of Life and Time of Redemption of Road Tunnel Equipment.” This report gives guidance as to what to expect of equipment and shows that there is a large range between the shortest and the longest life to expect of installed equipment, which should certainly influence decisions and the need to reduce maintenance cost.

7.11.2 Selection of Technical Solutions

To reduce maintenance cost it is important to:

- make the tunnel aerodynamically streamlined, to prevent dust collecting in corners,
- omit horizontal areas, outside the pavement and curb, where dust will be collected,
- assure ease of man and maintenance machine access to all areas that have to be maintained,
- make provision that maintenance work can be done in a simple way and in a minimum of time,
- choose equipment, materials and surfaces that require less, less frequent and simpler maintenance.

7.12 Environmental Factors

Studded tires

In some countries, with severe winter conditions, the authorities allow the use of studded tires. Studded tires produce large quantities of debris and dust from the wear of the exposed asphalt road surface. A car with studded tires produces about 20g/km. A truck about 5 times as much. For tunnels, the dust is a very costly maintenance problem, particularly in tunnels with two-way traffic. The development of non-studded winter tires has reached a level that studded tires are not necessary. Banning studded winter tires can considerably reduce cleaning and road maintenance costs over the winter season.

Disposal of dust and dirt from the tunnel

Dust and dirt from the road and emissions from vehicles will eventually end up at the roadside, over equipment, on the walls and in the drainage system. Many of these elements are toxic and must be treated as such, (PAH, PCBs and lead are examples).

Waste from the tunnel must therefore be treated according to the national laws for disposal of toxic/ dangerous waste. Cleaning of the air before it is released from the tunnel may be necessary and this will tend to increase the maintenance cost.

If national laws allow it, frequent cleaning of the tunnel may reduce the amount of particles in the air and also the need for air filtering. This will also reduce the exposure of workers in the tunnel to toxic dusts.

7.13 Conclusion and Recommendation

There is a general interest in the PIARC Tunnel Committee for reducing maintenance costs. However, where existing tunnels are being upgraded with additional and more complex safety equipment, with stricter environmental demands and more regulated working environment, there is a tendency for maintenance expenditure to increase. Nevertheless, savings are still possible:

- By careful preparation of the safety plan one can find a solution that has a reasonable balance between the geometrical form of the tunnel and the necessary and sufficient technical equipment

- A maintenance system should be established based on preventive maintenance, as a dynamic process in which the extent and frequency of interventions are continuously adjusted according to the condition of the equipment

- Flexibility and savings can be achieved by the effective use of private consultants and putting a number of maintenance tasks out to tender by contractors

- Maintenance experience should be incorporated into tunnel project design and planning and the replacement of equipment – all to be based on life cycle costs.

- The use of new technology and an EDP[7]/ IT-based management system improves the efficiency of maintenance.

The conclusion is that although there are factors that make tunnel maintenance more expensive, there are still possibilities for achieving considerable savings. Highway administrations should take all of the factors described into consideration in order to make more effective use of their road budgets.

[7] EDP = Electronic data processor / IT= Information technology