Value engineering for tunnel equipment

Prepared for Quality Services, Civil Engineering, Highways Agency

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The purpose of the project is to re-examine the present level of provision of mechanical, electrical, communications, monitoring, traffic control and safety equipment provided in highway tunnels. There is concern about the complexity and reliability of equipment and the effect of its maintenance on traffic flows. Value for money in operation and maintenance of equipment in tunnels is increasingly important, and areas are sought where economies can be made without compromising safety or increasing congestion.

A value engineering review has been undertaken of highway tunnel equipment. This review followed the procedures developed from the Value for Money Manual (Highways Agency 1996a), and comprised a value management and value engineering workshop and subsequent detailed reviews. The review drew heavily on the experiences of the operators of Highways Agency and other UK highway tunnels.

The principles of value engineering are summarised and a specific methodology is proposed for dealing with tunnel equipment. It was found that it was unrealistic to define unique optimum solutions for all tunnel equipment because of the many site specific factors associated with highway tunnels. However, it was possible to identify the areas in which changes were likely to have the most significant impact on value.

For each of the main systems the function, typical maintenance, common problems and possible alternatives associated with the equipment, are discussed. Where adequate information is available options have been costed and a number of detailed value engineering reviews are presented showing the implications of particular alternatives. Over 60 specific areas of possible improvement have been identified and are listed in the report in Section 6.

This report sets out a methodology for conducting site specific value engineering audits of highway tunnel equipment. This methodology is intended to be appropriate both to the initial fit out of a new tunnel and to subsequent refitting during the life of the tunnel. The work described in this report has also contributed to the drafting of the advice note on highway tunnel maintenance (BA 72).

1 Introduction

1.1 Background

The strategic aim of the Highways Agency is to contribute to sustainable development by maintaining, operating and improving the trunk road network in support of integrated transport and land use planning policies. Key objectives include minimising whole life costs, implementing network control to make best use of existing infrastructure, reducing congestion, minimising environmental impact, improving safety, working in partnership with others to promote choice and information and improving its business. These objectives provide the background for this review of tunnel equipment provision, operation and maintenance.

Jones and Fudger (1987) reviewed all aspects of operation and maintenance of road tunnels for the benefit of promoters, designers and future operators. This report builds on the earlier work and deals with the application of value engineering to road tunnel equipment. The required functions and alternative choices are identified and improvements proposed. A value management review of wider issues concerning tunnel procedures is reported separately (Bird *et al.*, 2001), and PIARC (1999) have reported on the reduction of the operational cost of highway tunnels.

1.2 Objectives

There is concern about the complexity and reliability of equipment and the effect of its maintenance on traffic flows. Also value for money in operation and maintenance of equipment in tunnels is increasingly important, and areas are sought where economies can be made without compromising safety or increasing congestion. The primary purpose of this study is therefore to re-examine the present level of provision of mechanical, electrical, communications, monitoring, traffic control and safety equipment provided in highway tunnels and to provide general guidance on these issues. In the course of the work, however, it has become apparent that there are not unique and general solutions to all of these issues. Therefore a secondary purpose of the work reported here has been to develop an appropriate and consistent methodology to address specific cases. Also the guidance extends to identifying systems and possible options which should be addressed in any such reviews to increase the likelihood of an optimum solution being developed.

1.3 Sources of information

The review is based principally on experience of the operators of the following tunnels: Conwy, Penmaenbach and Pen-y-Clip Tunnels (all on the A55), Blackwall Tunnel (A102), Holmesdale and Bell Common Tunnels (both on the M25), Hatfield Tunnel (A1(M)), Saltash Tunnel (A38), the Mersey Tunnels and Southwick Hill Tunnel (A27). This group includes urban, rural, motorway and toll tunnels built over approximately the last 100 years. In addition general experience of tunnel operators reported at the Highways Agency Tunnel Operators' Forums and UK Tunnel Operators' Meetings was taken into account.

1.4 Structure of report

Section 2 describes the methodology which was developed from that given in the Value for Money Manual (VFMM) (Highways Agency, 1996a). Sections 3, 4 and 5 deal with the assessment of function and cost. Section 6 summarises the findings and Section 7 gives conclusions and recommendations for future practice. Detailed assessment results are contained in the Appendices.

2 Value engineering principles and method

2.1 Definitions

Value is defined as function divided by cost. It therefore represents what is often referred to as value for money and is a quantity which should be maximised wherever possible. It is not necessarily achieved through reduction in specification (simple cost cutting). It may be achieved by an increase in function or a reduction in cost, or a combination of the two. Therefore key factors in determining value are the function of the system considered and its cost. Quantification of these elements is considered further in Section 3 and Section 4 below. Value management and value engineering are defined in the VFMM as follows:

Value management

A structured group decision making technique to achieve the essential overall objectives by reviewing and confirming project objectives to deliver the project at the optimum value, consistent with required performance, project timing and quality.

Value engineering

An organised systematic approach to obtaining value for money by enhancing the value of a project by delivering the necessary functions and required quality at lowest whole life cost.

Broadly similar definitions are given by the Institution of Civil Engineers (1996), Connaughton and Green (1996) and BS EN 1325-1: 1997.

In practice value engineering is often considered to be a subset of value management (Hayden and Parsloe, 1996). Chronologically value management normally occurs first and is concerned with overall objectives (Bird *et al.*, 2001).

2.2 Approach used in this study

The methodology used in this review has been developed from the procedures in the VFMM. These procedures are intended for application mainly to new projects and major capital maintenance schemes, although the VFMM suggests they could apply less formally to routine maintenance where a number of Maintaining Agents collectively improve techniques and processes. It is also important to note that the review was undertaken in association with a wider value management study of tunnel procedures.

Setting out the framework for the study was accomplished by means of a value management and value engineering workshop. Participants at this included representatives from tunnel operators, the Highways Agency (Quality Services - Civil Engineering), TRL and a designer. Thus most perspectives on tunnel operation were represented. The workshop was led by an experienced facilitator from the Highways Agency and included functional analysis, brainstorming and evaluation phases.

The functional analysis phase concentrated on identifying and agreeing what the objectives driving the selection of equipment were. At this early stage the key objectives were considered to be maximising safety, minimising traffic delay, protecting the environment and minimising whole life cost. The relative importance (and therefore weighting) to be applied to each of these factors was also considered and it was found that this depended to some extent on the observer's viewpoint.

The brainstorming phase of the workshop was an open discussion in which all were encouraged to contribute any thoughts they had on possible approaches to tunnel equipment. These were recorded by the facilitator resulting in the generation of a register of 100 ideas, listed in Appendix A, which formed a basis for the subsequent stages of the workshop. The nature of brainstorming is such that some ideas seem obscure, for example 'no *brillo* pads', and a few ideas could not be understood later. However these may have served to stimulate other ideas and so should not be regarded as inconsequential.

In the third phase of the workshop the ideas were assigned scores. Each idea was given a score out of ten based for its expected performance in meeting each of the key objectives in turn. These scores were then weighted to take account of the perceived importance of each objective and a mean score derived to describe the idea's overall performance. In this way an overall ranking of the ideas was drawn up. The ideas were then also assigned a recommendation, either: *Retain,* for further development; *Park* for possible later consideration; or *Kill* to remove from further consideration. This was necessary because it was recognised that some suggestions might have met the objectives well but were, for other reasons, unrealistic. (For example limiting tunnels to use by electric cars only scored highly in terms of environmental protection but was not considered a realistic option at present). These initial results are presented for illustration in Appendix A (it may be noted that the scoring used was somewhat different to that now presented as the preferred system, this reflects the evolution of the process). Also at this stage, a subjective evaluation of Whole Life Cost was included as one of the objectives. However, in later stages, when actual cost data are available, cost is dealt with separately from the other objectives. Further discussion on the processes for effective value workshops has been given by Bird *et al.,* (2001).

After the workshop process was completed, subsequent investigation concentrated on the items identified as being likely to bring the greatest benefits. These were investigated and analysed in greater detail using a combination of examination of case history data from operators and information from designers and suppliers. For each of the main systems that function, typical maintenance, common problems and alternatives associated with the equipment are discussed in Appendix D to Appendix U. Where adequate information is available options have been costed and a number of detailed value engineering reviews are included following the methodology described in Section 3.3. The methodology may also be understood by examining one of the worked value engineering reviews, for example see Table D1. Detailed analyses were carried out by the authors and scores developed by consensus.

The review results were observed to be highly dependent on site specific factors and so must be regarded as being indicative only, although they illustrate how the VFMM principles may be applied to an individual tunnel. The process should be repeated on an individual basis to assess the likely benefits of a particular system for a particular tunnel. The differing weightings proposed by the participants (discussed further in Section 3), illustrate the necessity of re-evaluation of objectives and weightings to take account of differing local circumstances and priorities.

As part of the present study the generic processes of the VFMM and the experiences of the workshop and reviews have been used to develop a tunnel equipment specific process of value engineering review. This process is recommended for future value engineering reviews of tunnel equipment. The process is illustrated in Figure 1 and the key parts of the methodology are described in more detail in Sections 3 to 5.

3 Function assessment process

3.1 Objectives and function

In the context of value engineering the function of a system is to provide the means to meet a specific objective or objectives. These objectives are generally physical in nature. Cost is not included among the specific objectives because cost issues influence the approach to each objective and cost minimisation is considered in a separate part of the value engineering process.

The objectives, and therefore the functions, for a particular system may be established using the techniques of functional analysis. Using the methods described in the VFMM a generic functional analysis system technique (FAST) diagram for highway tunnel equipment was prepared and presented at the workshop. This aimed to illustrate the relation between equipment function and the high level objectives of tunnel operation. It was subsequently further developed and the final form is presented in Figure 2.

If a number of objectives are identified for a system it becomes necessary to compare the relative importance of each. To do this the objectives must be quantifiable in common terms and this is dealt with in detail in Section 3.2. It may also be necessary to weight the objectives to give appropriate emphasis to more important issues. To assist both the current review and subsequent analyses the workshop process was used to develop a list of what were judged to be the key objectives of tunnel operation, weighted from different perspectives. The perceived relative importance of the different objectives will vary

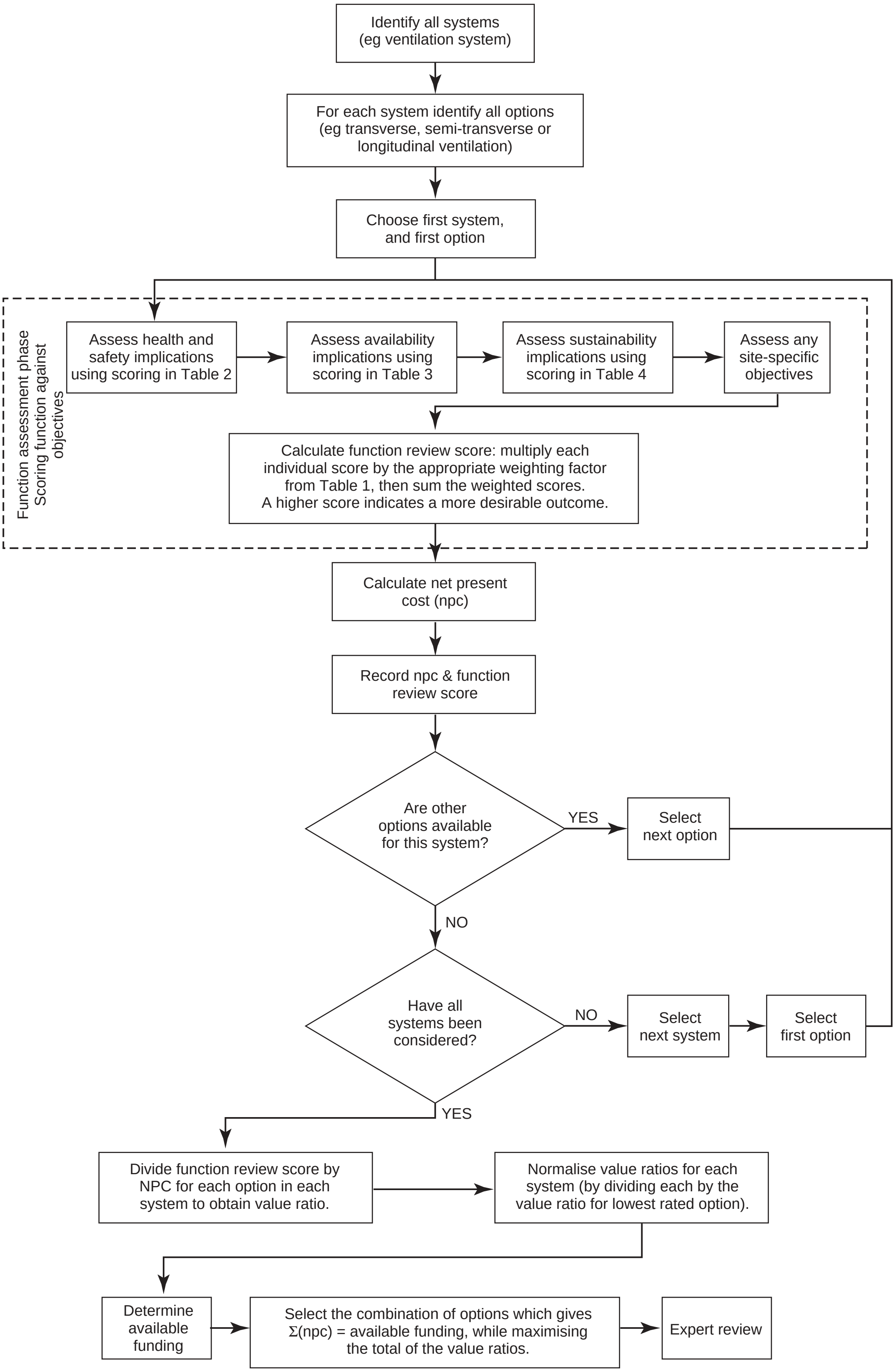

Figure 1 Value engineering review process

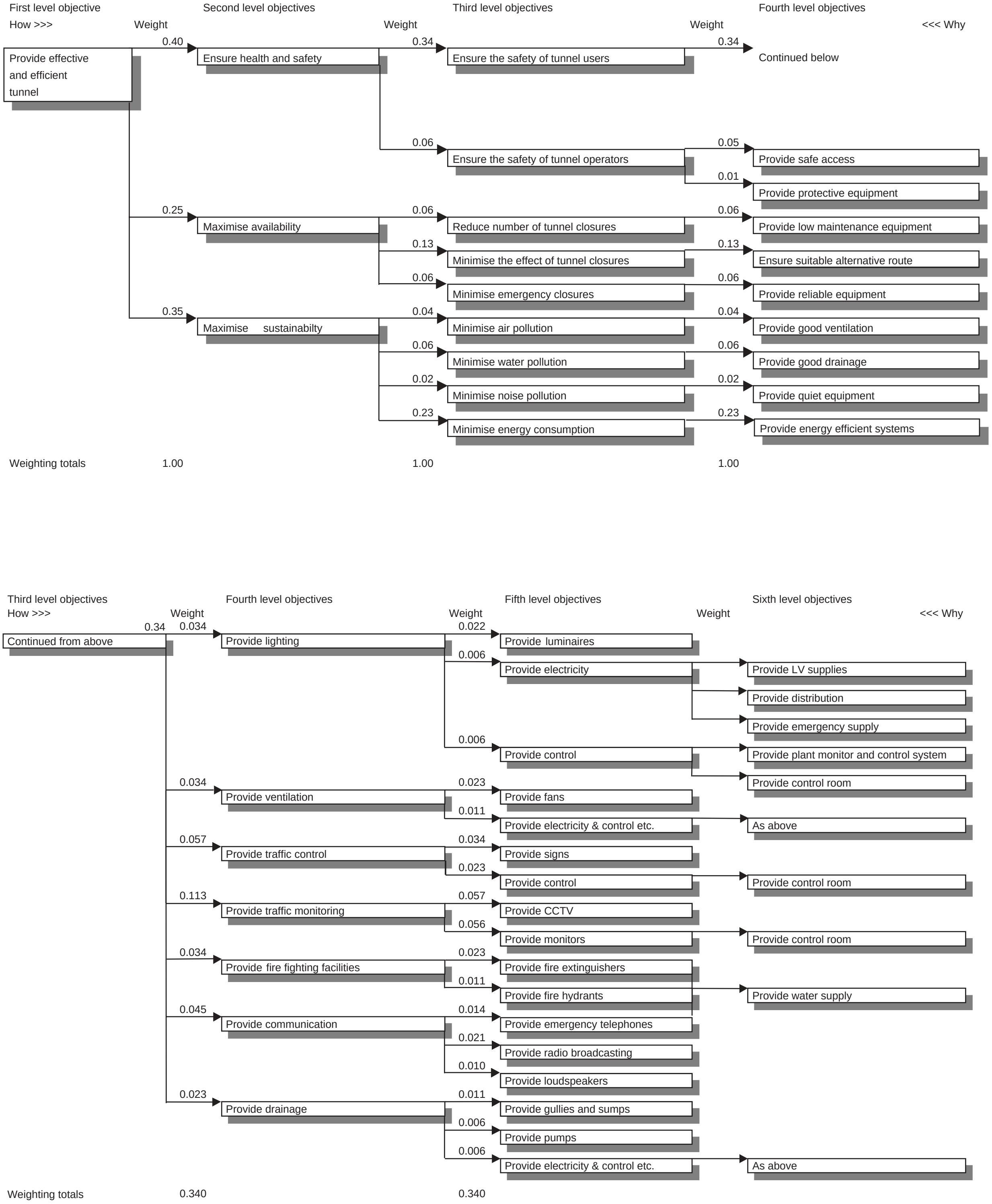

Figure 2 FAST diagram for highway tunnel equipment

according to the viewpoint of the observer. This is illustrated in Table 1 for the second level objectives for operating a tunnel with ratings being suggested from the viewpoints of the owner, the operator and the road user. These ratings were developed from discussion at the workshop which contained representatives of all three groups. The remainder of the discussion in this report is weighted from the owner's perspective and these weightings are included in the FAST diagram and subsequent value engineering calculations. In the case of a Value Engineering review of a particular tunnel, it will be necessary to re-evaluate the weighting of these objectives, and add any site-specific objectives, for example local integration with park and ride scheme.

Table 1 Relative weighting of objectives

Viewpoint	*Owner*	*Operator*	*User*
Health and safety	0.40	0.45	0.2
Availability	0.25	0.35	0.45
Sustainability	0.35	0.20	0.35
Total	1	1	1

3.2 Identifying options for systems

Once the objectives for the system have been defined, possible options for equipment to meet the objectives must be identified. This may also be achieved in the workshop environment. However, it is important that the discussion is seeded with ideas to ensure that full use is made of existing knowledge. The Appendices to this report will provide assistance in this respect. The discussion should address each detailed objective identified in the FAST diagram. Current practice and possible alternatives should be identified and listed in a register of ideas which may subsequently be used for scoring the ideas.

3.3 Scoring function for each option

Once a list of options for a system has been identified the next stage in the process is to score each option in relation to how well it meets the various objectives. To permit comparisons to be made a standardised scoring system has been developed which contains an element relating to each main objective. It was also found necessary to introduce a standardised definition for each objective. The scoring system and the definitions are presented in Table 2 to Table 4. Individual scores should be established by consensus amongst informed observers in a workshop environment. It is also important to note that small variations in individual scores rarely have a significant impact on the overall result so lengthy discussion of minor points of detail is unlikely to be very beneficial in this process.

A minimum score of unity is used in Table 2 to Table 4, rather than zero, to remove the risk of a mathematical singularity occurring. The distortion produced by this is unlikely to be of any significance.

Once a given suggestion has been scored for each of the three main objectives an overall function review score may be obtained. To do this the individual objective scores are multiplied by the appropriate weightings from Table 1, and any site-specific objectives, and the products are summed. The resulting score may be used to rank possible alternatives for different systems to establish their relative merits in terms of function (but without consideration in cost terms). A higher score represents an option which offers better function.

Table 5 illustrates the typical results format for a review comparing two options. In this case option 2 is seen to offer considerably enhanced function when compared with option 1. Whether option 2 also offers better value is a separate question which requires the additional consideration of cost.

4 Cost assessment process

4.1 Costing terminology and method

Once function has been quantified it is necessary to determine a cost element associated with each option being considered. Only once function and cost have been quantified can value be quantified. In most cases it will also be appropriate to consider the whole life cost rather than the capital cost alone when making assessment of best value.

The whole life costing of present equipment and alternatives in this review was carried out in accordance with the procedures set out by the Institution of Civil Engineers (1996). Definitions of the key terms are given below. Calculations for specific equipment options are presented in worked examples in the various Appendices to this report. These are based on a dual two lane tunnel of 1km length and 120km/hr design speed. The cost of traffic delays are calculated from the tables in the Trunk Road Maintenance Manual (Highways Agency, 1996b) which show the daily user costs applicable under various conditions in lane rental schemes.

Net present value (NPV) or *net present cost* (NPC) is the sum of money that needs to be invested today to meet all future financial requirements as they arise throughout the life of the investment. Dale (1993)

Present cost (PC) *factor* is multiplied by the unit cost to obtain the total NPC, for example if a lamp currently costing £50 requires to be replaced every 5 years for 50 years, the present cost factor is 2.06, at a discount rate of 8%. The total NPV of the cost of replacement of a lamp at 5, 10, 15…45 years is £50 x 2.06 = £103.

Value ratio is the total weighted score from a function review divided by the total NPC for each alternative. To compare options for a given system a *normalised value ratio* may be calculated by dividing each derived value ratio by the lowest value ratio in the group.

In the present calculations the discount rate has been taken as 6% in accordance with current guidelines.

4.2 Factors that influence costs

PIARC (1999) has listed the general influence of the various systems on the overall energy and maintenance costs for a highway tunnel. Table 6 summarises the

Table 2 Health and safety scoring

Health and Safety: the extent to which the option being considered will provide safe and healthy conditions for those using the tunnel or working in and around it.

100	Provides an environment free of any health and safety risks.
75	Health and safety risks judged to be minor relative to other risks associated with the highway. Risks also judged to be substantially below the limit of tolerability.
50	Health and safety risks judged to be similar to those associated with other established highway infrastructure.
25	Health and safety risks judged to be major relative to other risks associated with the highway. Risks approaching the limit of tolerability.
1	Fatal.

Table 3 Availability scoring

Availability: the extent to which the option being considered will permit the facility to be available for normal use. In the context of a highway tunnel this will generally be a measure of the lane and/or bore closure requirement associated with the option.

100	Full availability at all times (no closures required).
75	Has the potential to be operated and maintained with substantially less closures than the normally accepted level.
50	Requires the maximum currently accepted level of closures.
25	Requires substantially more than the maximum currently accepted level of closures.
1	Nil availability.

Table 4 Sustainability scoring

Sustainability: the extent to which the option being considered protects the resources and the environment for future generations. Thus options which involve high consumption of energy and primary resources or which generate high levels of pollution would be rated as having low sustainability.

100	Sustainable. Imposes no limitations on future generations.
75	Substantial benefit in terms of sustainability, for example the option may substantially reduce energy and resource consumption and/or substantially reduce pollution.
50	Similar to other currently accepted options in terms of resource consumption and pollution.
25	Substantial disadvantage in terms of sustainability, for example the option may substantially increase energy and resource consumption and/or substantially increase pollution.
1	Unsustainable.

Table 5 Example function review table

		Option 1	*Option 2*
Objective	Importance rating	Rating (1-100)	Rating (1-100)
Availability	0.25	50	75
Sustainability	0.35	50	75
Health and safety	0.40	50	60
Total weighted score		50	69

Table 6 Influence of system on energy and maintenance costs in UK

	Cost influence		
System	*Capital*	*Energy*	*Maintenance*
Choice of power supply tariff	Low	**High**[1]	Low
Internal power distribution	**High**	Low	Moderate
Service building equipment	Moderate	Low	Moderate
Emergency power supplies	Low	Low	Moderate
Lighting	**High**	**High**	**High**
Ventilation	Moderate	Moderate	**High**
Drainage (tunnel with sump)	Moderate	**High**	Moderate
Drainage (no sumps)	Low	Low	Low
Communications	Low	Low	Moderate
Traffic monitoring	Low	Low	Moderate
Traffic control	Low	Low	Low
Plant monitoring and control equipment	Moderate	Low	Low

[1] Tariff may be dependent on factors such as peak lopping.

influence of various systems on the overall capital, energy and maintenance costs for a UK tunnel. This table is derived from available cost information but it should be noted that the influences may vary significantly from tunnel to tunnel. Particular emphasis in any value engineering review should be placed on the high cost items. Thus, for example, it may be seen from Table 6 that lighting contributes significantly to capital and running costs and therefore the lighting system should be a particular focus of value review.

4.3 Cost data

Cost data for use in the value review process was sought from a range of sources. The PIARC Technical Committee on Road Tunnels (PIARC, 1999) have studied the reduction of operational cost. It assembled earlier studies and existing cost data from tunnels across Europe. It also recognised the benefit of making cost comparisons between tunnels of similar form and operating conditions, but deriving trends through statistical analysis has proved unsuccessful, largely because of inadequacies in the available data. In an attempt to remedy this situation a theoretical unit cost model is being developed for the HA by TRL. Such a model provides an indication of cost trends based on a few key parameters, for example length, number of lanes, bi-directional or un-directional, gradient and orientation. In such a model costs are based typically on overall costs using current best practice, but could not accommodate the choice between, for example, alternative types of corrosion protection of luminaires. The model also requires calibration with current costs.

PIARC (1987) also showed that operational costs on average divide approximately equally into energy, staff and maintenance costs (Table 7).

Table 7 Operational costs for 1984 (PIARC 1987)

Average percentage breakdown of total annual operational cost

		Maintenance		
Staff	*Energy*	*Civil engineering*	*Equipment*	*Number of tunnels*
36%	33%	31%		112
		11% (0. 15% of civil engineering capital cost)	20% (1.75% of equipment capital cost)	81

Despite extensive efforts collection of comprehensive historical cost data relating to UK tunnel equipment has proved problematic. This was due to a combination of factors including commercial sensitivities and differences in the ways in which such expenditure has been recorded. Notwithstanding these difficulties recent capital and maintenance cost data covering most systems have been assembled for a number of UK tunnels. These summaries are tabulated in Appendix C with comparable overseas data. Other, more detailed, cost data relating to specific equipment are included in the Appendices dealing with specific systems.

Consideration was given to normalising the cost data, for example maintenance cost per fan. However this was thought to be unsatisfactory because:

i Unit rates within maintenance contracts or cost centres used by tunnel operators may not be consistent. For example: one subcontract may cover various items of equipment; maintenance cost centres do not necessarily correspond to capital cost items; or administrative costs may or may not be included.

ii Because of practical problems with data collection the data were largely based on a limited set of tunnels.

In view of the limitations of current information and statistical or theoretical approaches to cost prediction, consideration was given to the means of introducing cost into the value engineering review. The approach adopted follows the VFMM principles and combines the qualitative and quantitative consideration of cost. The reviews, at the workshop and subsequently, included qualitative assessments of the impact of ideas on whole life cost. Where quantitative analysis was reasonable, value engineering reviews were conducted incorporating a whole life cost comparison of alternatives.

Like the function review this approach to cost is of a generalised nature and can only be applied with caution to a specific case. However, the data do serve to illustrate how whole life cost principles may be applied to an individual tunnel and give guidance about alternatives that might be considered in an individual design. Detailed and accurate costing is only possible after detailed design for a specific tunnel, nonetheless, the current costs assembled in the Appendices will be a source of data for designers.

Life expectancy of equipment in the reviews was based on guidance provided in BD 78/99 (DMRB 2.2.9) unless other information was available, for example from a manufacturer of specific equipment or from the direct experience of operators. However, it should be noted that, because of discounting, costs after about 20 to 30 years have little influence on whole life cost.

5 Review and decision phase

Once the function and cost assessment phases of the value engineering process have been completed and the results recorded the final stages of the process involve review of the findings and their use in decision making (as shown in Figure 1).

To achieve this the results should be tabulated and ranked according to the value ratio scores. Thus the option which gives the greatest expected value benefit will appear at the top of the list. Once a final form of the ranked list has been agreed the ideas showing the best gain in value for the systems should be selected for implementation. In practice this implementation may be influenced by financial constraints and so it may be necessary to restrict works to a subset of the proposals. If this is the case the ranked results may be used to select a combination of measures which gives the highest return (in added value terms) for the available capital expenditure. Alternative strategies, such as maximising function, could also be chosen and may be applicable in some situations.

At this stage someone with a good working knowledge of tunnel equipment and the site under consideration should review the findings to identify any 'rogue' results or options which can be seen to be inappropriate for a particular case despite scoring highly in the workshop process. This peer review should be seen as an integral part of the value engineering process and may have a significant impact on the outcome.

6 Summary of findings

The value review process undertaken in this study has demonstrated that there are a large number of possible developments and refinements for tunnel equipment which would result in either improved function, lower whole life cost or both. Some of these developments will only be applicable to new build, others may be relevant to the ongoing operation or refurbishment of existing tunnels.

The benefits may be of various types. Some benefits are directly quantifiable in cost terms through potentially reduced capital cost or lower whole life cost due to reduced maintenance and lower energy consumption. A second group of benefits are those which may bring improvements in function such as: better safety, better availability, reduced environmental impact or optimised maintenance regimes. Other benefits may arise through simple changes which would enhance durability of equipment to overcome problems commonly observed in existing tunnel equipment.

It is also clear from the review process that the optimum solution for one tunnel may not apply to another. Indeed prescription of a universal set of detailed recommendations for all highway tunnels appears most unlikely to represent best value. Therefore, it is important that a systematic review methodology is available to identify the best options for any given tunnel. Ideally this should be undertaken within a wider value management based approach to tunnel operation such as that described by Bird *et al.*, (2001).

The key findings for each type of tunnel system are summarised in Table 8 to Table 18 as recommendations. In many cases these are not absolute but rather suggestions that a specific option should be considered (reflecting the site specific variations in what constitutes best practice). The full findings and supporting discussion are presented in Appendix B to Appendix U (and cross-referenced in the tables below). These Appendices include detailed descriptions of systems, system maintenance, typical costs (where available), common issues and problems, possible alternatives and illustrative value engineering review calculations.

7 Recommendations

To obtain improved value it is recommended that the value engineering review procedures described in this report should be applied in the following situations:

i design of a new highway tunnel and its equipment;

ii design of systems and equipment for highway tunnel refurbishment;

iii when there are major changes in technology available in the market place;

iv periodically during the operational life of a tunnel to ensure that best value is achieved in ongoing operation. (It may for example be useful to conduct value review processes at the time of principal inspections.)

When a value engineering study is conducted for a particular tunnel it should include both functional analysis (to identify the required systems) and a system-specific review of options. The functional analysis stage may be seeded with ideas from the analysis presented in Figure 2. For reviews of options for particular systems the process should be seeded with ideas from the relevant Appendices of this report. However, it is expected that the most beneficial options will be found to be amongst those listed in Section 6.

8 Acknowledgements

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Table 8 General issues (Appendix B)

Recommendation	*Nature of likely benefit*
Design teams should include representatives with experience of operation and maintenance.	Ease and efficiency of maintenance.
Mechanical, electrical and civil engineering design should not be prepared in isolation from one another.	Widespread benefits, e.g. Whole life costs, safety, ease of maintenance.
Common standards for software and interfaces would simplify future upgrades of plant monitoring and environmental control systems, thus reducing upgrade costs.	Whole life cost.
Standardisation of common parts or consumables should be sought wherever possible.	Whole life cost, simplified supply chain.
Condition monitoring should be considered in lieu of manual inspections. This may reduce cost but is also desirable for its ability to predict failure more reliably.	Whole life cost, reliability.
Design should aim to minimise the need for lane or bore closures for maintenance.	Safety, availability.
Where safety considerations require a separate escape bore, consideration should be given to locating equipment requiring frequent access in that bore.	Safety, availability.
Design should aim to minimise the need for special skills for maintenance.	Less special skills needed.
An area should be reserved for use as a maintenance contractor's compound.	Ease of maintenance.
Access covers in the carriageway, particularly in the wheel tracks, should be avoided.	Safety, durability.
Specific consideration should be given to protection of electro-mechanical systems from water ingress.	Safety, durability.

Table 9 Ventilation system (Appendix D)

Recommendation	*Nature of likely benefit*
Consider alternatives to manufacturer's recommended maintenance intervals, for example through condition monitoring.	Whole life cost.
Consider the use of reversible motors and bi-directional impellers to avoid maintenance problems associated with variable pitch fans.	Whole life cost.
Consider operator intervention during traffic congestion, such as: 'TURN ENGINE OFF' signs and radio messages, or restricting queuing in the tunnel.	Whole life cost, environment.
Consider whether mechanical ventilation is needed in tunnels less than 575m long.	Whole life cost, capital cost, environment.
Consider the use of fewer, more powerful fans.	Capital cost, reduced maintenance.
Consider the use of electronic soft starters.	Function (faster response).

Table 10 Lighting system (Appendix E)

Recommendation	*Nature of likely benefit*
Consider using threshold lighting in accordance with the method in draft CEN (1996) rather than that in BS5489: Part7: 1992,	Whole life cost (less energy).
On climbing approaches to tunnels consideration should be given to a reduction of SSD.	Whole life cost (less energy).
Experience outside the UK provides a strong case for considering the use of counterbeam lighting installation. Trials may be necessary to prove its appropriateness in UK conditions.	Whole life cost (less energy).
Reduce the luminance of surfaces visible in the access zone and take measures to increase visibility.	Whole life cost (less energy).
Use front access luminaires rather than end access luminaires.	Easier maintenance.
Consider likely in-tunnel corrosion effects in detailed design of luminaires and supports. Avoid contact between dissimilar metals.	Durability.
Consider dimmable control gear for new or refurbished lighting installations.	Whole life cost (less energy).
Optimising lighting switching levels and time delays in design and during maintenance.	Whole life cost (less energy).
Regularly recalibrate photometers and lighting control equipment.	Whole life cost (less energy).
Optimise lamp cleaning and replacement intervals by trials in short sections of the tunnel.	Whole life cost (optimised maintenance).

Table 11 Pumped drainage systems (Appendix F)

Recommendation	*Nature of likely benefit*
Consider dual mid-tunnel sumps, dual outflow pipes and dry wells for tunnel sumps.	Safety, availability, ease of maintenance.
Consider the use of soft starters or variable speed controllers for pump control.	Durability.
Consider alternatives to manufacturer's recommended maintenance intervals, for example through condition monitoring.	Whole life cost.
Consider whether the assurance provided by condition monitoring is sufficient to reduce the number of pumps in the system.	Capital cost.
Consider low maintenance level detection and duty cycling controls.	Whole life cost (less energy).

Table 12 Fire protection systems (Appendix G)

Recommendation	*Nature of likely benefit*
Consider AFFF extinguishers rather than dry powder to avoid the dangers posed by inappropriate use.	Avoid visibility problems.
Establish reliable procedures with the local water company for advanced notification of planned maintenance to fire hydrants and water mains and put appropriate contingencies in place to allow the tunnel to continue to operate.	Availability.
Site nitrogen bottles used within nitrogen-foam flooding systems at locations not susceptible to vehicular impact damage.	Reduce damage risk.

Table 13 Communications and traffic control systems (Appendix H to Appendix K)

Recommendation	*Nature of likely benefit*
Advanced testing facilities to be built in to all new and replacement tunnel emergency telephone systems.	Ease of maintenance.
New telephone systems should, whenever possible, be based on existing proprietary equipment.	Ease of maintenance, simple supply chain.
The necessity of maintaining smoke control and internal telephone systems, where alternative means of communication exist, should be reviewed.	Avoid duplication of equipment.
Include text transmission facilities in radio relay systems.	Aid to maintenance staff.
Consider replacing some pan, tilt and zoom CCTV cameras with increased numbers of fixed CCD cameras.	Capital cost.
Consider digital CCTV cameras.	Enhanced function.
Base tunnel signing control systems on generic designs (for example NMCS2).	Simplified supply chain.
Base all new internally illuminated tunnel signs on LED technology.	Durability, whole life cost (less energy).
Consider enhanced message signs using LEDs with integral battery support and battery management in preference to rotating prism signs.	Reduced maintenance.

Table 14 Environmental control system and plant monitoring (Appendix L)

Recommendation	*Nature of likely benefit*
Provide separate control systems for safety critical items used in emergency control procedures.	Safety, availability.
Give special attention to the robustness of instrumentation located in the tunnel and seek to minimise its maintenance.	Durability, availability.
Advanced computer technology in tunnel ECSs is preferred.	Reliability.
Systems integration, based on the tunnel ECS communications system, should be considered to reduce the number of system components.	Ease of maintenance, reliability.

Table 15 Electrical distribution and protection systems (Appendix M to Appendix R)

Recommendation	*Nature of likely benefit*
Consider use of peak lopping with tunnel generators.	Whole life cost (lower supply tariff).
Consider whether twin generators suitable for peak lopping are an acceptable alternative to providing duplicate HV supply.	Whole life cost.
Use condition monitoring to schedule maintenance for transformers.	Whole life cost, optimised maintenance, reliability.
Check tightness of connections on LV systems during routine maintenance, taking care to avoid over-tightening. Alternatively consider the use of thermography to identify loose connections.	System reliability.
Use LED indicator lights in LV switchboards.	Reliability.
Eliminate tripping and closing units as far as possible in the electrical distribution system.	Reliability.
Where battery tripping and closing units are necessary, combine monitoring of batteries with any other battery system provided.	Avoid duplication of equipment.
Use split earthing systems to allow testing without entirely disconnecting the electrical distribution from a safe earth.	Safety.
Locate panels away from traffic where possible.	Ease of maintenance, reduced risk of damage.
Give special attention to corrosion risk and watertightness of panels.	Durability.

Table 16 Emergency power supplies (Appendix S)

Recommendation	*Nature of likely benefit*
Condition monitoring of UPS batteries should be considered in all new tunnel installations, and UPS replacements.	Whole life cost.
Consider the use of a generator rather than battery power where power interruptions longer than 15 minutes are to be covered.	Whole life cost.

Table 17 Cabling and M&E support systems (Appendix T)

Recommendation	*Nature of likely benefit*
Tunnel service routes should be designed to be as dry as possible.	Durability.
The greater use of appropriate grades of industrial plastics, for tunnel cable trays, conduits and certain supporting systems should be considered.	Durability.

Table 18 Tunnel service buildings (Appendix U)

Recommendation	*Nature of likely benefit*
Consider minimisation of cable runs when choosing service building location.	Capital cost.
Consider integration with portal structures and ventilation structures.	Capital cost.
Provide a single operator interface.	Removes duplication.

Appendix A: Results of internal value engineering workshop

Workshop results				*Internal value engineering review score*				
				Weighting				
				Whole Life Cost (WLC) 0.50 *Environment (E) 0.25* *Traffic Delay (TD) 0.10* *Safety (S) 0.15*				
Idea No.	*Ideas ranked in order of internal review score*	*Description and summary of discussion at workshop and recommendation. Retain unless shown Park (P) or Kill (K)*		*W L C*	*E*	*T D*	*S*	*Total*
29	Higher pay for operators	Means better training and qualification of operators, need to develop standard job descriptions, qualification and continuing training.		9	7	8	8	8.25
16	Condition monitoring	Thought to be an excellent option for new installations.		8	7	7	7	7.5
4	LEDs for tunnel lighting	Technology does not exist at present.	P	8	7	6	7	7.4
97	Design tunnel ‘to’ M&E and not fit around it	Means considering needs of M&E equipment from initial design stages.		8	7	6	7	7.4
87	QA systems for operators	Sensible QA schemes, that avoid needless paperwork, should lead to better quality procedures.		7	7	7	8	7.15
37	Reliability of funding	The then current annual bidding cycle encouraged a short term view, funding over a longer term allows better planning and better choices.		7	6	8	8	7
67	Ensure tunnel is waterproof	Thought to be the preferred option, but difficult to achieve in practice.		7	7	6	7	6.9
84	Use LEDs not bulbs on distribution boards	Bulbs on distribution panels fail frequently. LEDs are more reliable and are available now, so this idea should be implemented.		8	6	5	6	6.9
98	Exclude Civil contractor from M&E equipment - take specialist advice	Means that M&E equipment should not be designed wholly from civils view. Linked with idea 97.		7	7	6	7	6.9
99	Design for maintainability and durability	Means taking a view of Whole Life Costs in design.		7	7	6	7	6.9
83	Replace battery UPS with fuel cells	Technology does not exist at present. Development of technology will be driven by needs wider than those of tunnels.	P	7	7	5	7	6.8
1	Internally illuminated signs	Means substituting more reliable LEDs for bulbs and fibre optics.		7	7	6	6	6.75
47 `	Regional tunnel control centres	Centralisation of control for several tunnels will result in economies.		7	6	7	7	6.75
80	All electric road vehicles	Technology does not exist at present. Development of technology will be driven by needs wider than those of tunnels.	K	7	8	5	5	6.75
95	‘Performance’ maintenance contracts	These should ensure standards maintained, particularly towards end of contract period.		7	7	6	6	6.75
103	Counter beam lighting	Idea added after workshop.		8	7	5	3	6.7
30	Dimming control	Potential energy savings, but possible increase in maintenance cost and shorter lamp life. Technology review required.	P	7	7	5	6	6.65
50	Stainless steel that does not rust	Idea not considered viable.	K	7	6	6	7	6.65
96	Preventative maintenance	Already practised, but use of condition monitoring would improve the technique.		6	7	7	8	6.65
23	Automatic closure barriers	Physical barriers instead of coning. Capital investment required but improves safety of for operator and results in cheaper and faster tunnel closure.		5	8	7	9	6.55

24	Automatic cross-over barriers in central reservation	As idea 23.		6	6	7	9	6.55
15	Simple equipment design	Designers already consider this.		7	6	6	6	6.5
18	No access covers on road surface	Should be possible at design stage to remove requirement for these. Covers on wheel tracks should be avoided.		6	6	8	8	6.5
48	Commonality of spares	Requires standardisation of designs. Many advantages. Disadvantages are obsolescence and reduction of competition.		8	5	5	5	6.5
92	Mandatory permit to access	Utility providers with services in tunnels often enter without notice. Generally thought better to avoid services in tunnels, or ensure agreements with utility providers control of access.		5	8	8	8	6.5
93	'Control' rights of utilities	As idea 92.		5	8	8	8	6.5
79	Prohibit hazardous loads	Topic is widely discussed elsewhere and not within the scope of the workshop.	K	7	4	6	9	6.45
73	Analysis of incident and maintenance reports	Problems of differing standards and unnecessary records. Well planned recording system should result in better feedback and overall improvement of standards.		6	7	6	7	6.4
85	Provide breakdown recovery	This depends on individual tunnels, many have nearby facilities so no need for dedicated staff. Relatively few breakdowns so not thought a cost effective solution.		6	6	7	8	6.4
10	No lighting	Would save energy, but reduce safety. Standards exist for lighting levels. Idea not considered viable.	K	8	8	2	1	6.35
71	Fewer, bigger fans	Reduces capital and maintenance costs, but still need a certain number of fans to provide redundancy when one fan out of operation.	K	7	7	5	4	6.35
21	Mandatory speed control	Speed control during maintenance works, similar to motorway roadwork operations. Recommended.		6	6	7	7	6.25
33	Tube lights	Light distributing pipes offer many advantages for maintenance, but new technology requires investigation.		7	6	5	5	6.25
52	No 'brillo pads'	Means avoiding abrasive brushes for wall cleaning. Idea not considered viable.	K	7	6	5	5	6.25
82	Standard approach to manning, operations and maintenance	Nationally agreed standards might make planning at each tunnel easier and avoid missing important considerations.		6	6	7	7	6.25
86	Eliminate hard shoulders	Reduces capital cost. Depends on wider route considerations.		8	7	2	2	6.25
88	Use lightweight gantries	Lighter cheaper structures now required by HA standards have lower capital but higher maintenance cost.		7	6	5	5	6.25
25	Eliminate cones for closures	See ideas 23 and 24.		5	7	7	8	6.15
51	Standardisation of equipment	See idea 48.		7	5	5	6	6.15
28	Better control of over-height vehicles	Other research suggests road layout should require drivers to choose to drive through tunnel.		6	5	6	8	6.05
3	Self cleaning lights	Non stick coating, e.g. 'Teflon' may reduce need for cleaning. Requires further investigation.		6	6	6	6	6
5	Self cleaning walls	See idea 3.		6	6	6	6	6
6	Self cleaning fans	See idea 3. Particularly applies to fan body.		6	6	6	6	6
13	No duplication of equipment	Means single HV supply may have sufficient reliability, electricity supplies generally becoming more reliable.		7	6	4	4	6
26	Pop-up cones	These might jam and fail, considered impracticable.	K	5	7	7	7	6
38	Heat pumps for service buildings	Increased capital cost, but reduced energy cost. Sound idea.		6	7	5	5	6
40	Generate own power	See idea 35.	K	7	4	6	6	6

42	Sell ‘space’ to utilities	Income of benefit to owner of tunnel, but causes problems in operation, e.g. providing access for maintenance, and possible leakage. Should avoid high energy supplies e.g. HV and high pressure gas.		6	7	5	5	6
46	Reduce lighting when tunnel is congested	Higher capital cost, but lower energy cost. Possible problems of reliability. System would form part of advance lighting control.		6	7	5	5	6
62	Privatise tunnels	Idea not considered viable.	K	7	5	5	5	6
63	On-line maintenance manuals and help facilities	Present systems requires paper manuals and plans. Computer storage allows faster access, particularly in emergencies. Increased capital cost and need to consider back up.		6	6	6	6	6
64	Expert systems	See idea 63.		6	6	6	6	6
65	Relational databases	See idea 63.		6	6	6	6	6
66	Use Virtual Reality models	See idea 63.		6	6	6	6	6
91	Reduce number of operators	Consistency of approach would offer savings. Longer response times. Overload in event of incident. Tunnels in UK are widely spaced, so fewer operators would each cover a wide area.		6	6	6	6	6
102	Need for backup HV supplies	Idea added after workshop. See idea 13.		7	6	4	4	6
34	Optical fibres	Light from central lamp distributed by optical fibres. Idea impractical.	K	6	6	5	6	5.9
9	More accessible control panels	Remove panels to service tunnel. Greatly increased capital costs. Need emergency panels to be located in road tunnel.		6	5	6	6	5.75
60	Standard response times	Idea not considered viable.	K	5	6	7	7	5.75
72	Use item 66 for operator training	Use virtual reality for training operators in normal and emergency procedures without entering tunnels therefore cheaper and safer. Requires VR model to exist which should be available for a new tunnel.		5	6	7	7	5.75
8	Better lighting control panels (plastics)	Corrosion is a major problem with existing stainless steel designs. Plastics should be investigated, but offer less impact resistance.		7	5	5	3	5.7
74	Prioritise on high impact incidents	See idea 73.		5	5	6	9	5.7
7	Better lighting supports	Stainless steel supports are complex construction, but no particular alternatives were formulated.		6	5	5	6	5.65
22	Better information for drivers	VMS warnings provide advance information on hazards. Network issue.		5	5	7	8	5.65
57	Simplified Man Machine Interface	Computer control of equipment from control room improves operational control.		6	5	5	6	5.65
75	Standardise recording and reporting	See idea 73.		6	5	5	6	5.65
54	‘Engine-off’ signs automatic	Cutting engines when stopped should reduce emissions and save on ventilation energy costs. In-tunnel matrix signals thought better.		5	6	5	7	5.55
36	Dust extraction	Filters and electrostatic precipitators improve air quality/ avoid need for ventilation ducts. Application limited to very long tunnels.	K	4	7	7	7	5.5
41	Change electricity tariff	Economies by bulk purchase of electricity and at appropriate tariff should reduce energy costs.		6	5	5	5	5.5
49	Disposable light fittings	Idea not considered viable.	K	7	3	5	5	5.5
68	Use tile linings	Easier to clean and good reflectivity, higher capital but lower maintenance costs. May be cheaper ways of achieving same objectives.		4	7	7	7	5.5
76	Report responses and effectiveness of	Idea was not fully recorded at workshop.	K	6	5	5	5	5.5
77	Simplify fund-bidding process	See idea 37.		6	5	5	5	5.5

58	In-tunnel fire protection systems	Idea not developed at workshop because of limited time.		4	6	7	8	5.4
61	Development of statistical techniques	Idea not developed at workshop because of limited time.		5	5	6	7	5.4
45	Active noise suppression for ventilation	Noise cancellation (of fans) would improve safety during emergencies and maintenance. Solutions may exist with passive silencers.		4	7	5	7	5.3
69	Fireproof the roof	Fire resistant coatings would result in less structural damage by fire. Extra capital cost and possibly reduced cost of repair following a fire. Tunnel fires rare therefore idea not considered worthwhile.	K	4	6	6	8	5.3
56	Programmed emergency sequences	Current sequences listed in manual, with computer control of equipment these can be pre-programmed. Could reduce operator overload in emergencies. Backup required. Sequences requires careful thought in application.		4	5	6	9	5.2
12	Provide service tunnels	See idea 9.		4	5	7	8	5.15
35	Emergency generators for rock tunnels	Emergency generators provided where reliance placed on dual HV supplies. See also idea 13.		4	5	7	8	5.15
39	Micro-wave link	Problems with links from tunnel to remote control room. Existing systems are satisfactory if properly engineered.		6	4	5	4	5.1
55	Auto incident detection	Systems to alert operators to an incident. Technology is available and should be introduced as appropriate.		4	5	6	8	5.05
59	Sprinklers	Idea not considered viable at workshop. Further review being undertaken.	K	4	5	6	8	5.05
11	Auto vehicle guidance	Development of technology will be driven by needs wider than those of tunnels.		4	5	7	7	5
14	Remove need to access during normal operation	Remove local control facilities from tunnel, e.g. auto reset. Reduced access to tunnel reduces traffic disruption.		4	4	8	8	5
89	Stagger jet fans	Easier maintenance access to side of fans. Avoids loss of multiple units in fires. But more vehicle movements during maintenance.		5	5	5	5	5
94	Charge utilities for consequent costs	Charge utilities for costs of access. See idea 92.		5	5	5	5	5
43	Intelligent CCTV	Control CCTV based on electronic image processing . See idea 55.		4	5	6	7	4.9
44	No phones	Considered unacceptable.	K	6	5	3	2	4.85
19	Lights on walls	Moving lights to lower level would provide easier access for maintenance, but reduce effectiveness of lighting.	K	5	4	5	5	4.75
78	Continuous catenary lights	Lights on chain that can be pulled out of tunnel for light replacement. Considered practically difficult.		6	3	5	3	4.7
32	Electrostatic precipitators	See idea 36.		3	7	5	6	4.65
27	No 3-lane 2-directional tunnels	Relates to the operational problems at Saltash tunnel.		3	4	7	9	4.55
81	All tunnels to have maintenance vehicles	Contractors normally provide their own vehicles.	K	4	4	5	7	4.55
31	Travelling wave of light	Only applicable in long, low flow tunnels.	K	4	4	6	6	4.5
101	Daylight screens	Idea added after workshop.		5	3	5	5	4.5
2	Fail-safe equipment	Main application for signs. Fans and light failures normally left until next closures. Saves costs and traffic delays resulting from unplanned maintenance, but extra capital cost of duplication.		3	5	6	7	4.4
100	Paint tunnels in pastel colours	Idea not developed at workshop because of limited time.		3	6	5	4	4.1

20	Speed ramps in tunnels	Results in risk of traffic bunching and rear-end collisions.	K	4	4	3	5	4.05
70	Disposable fans	More use of disposable parts, reducing maintenance time. Judged not to save overall costs.	K	4	3	5	5	4
90	No stagger-start - provide override for emergencies	Stagger starts of fans required to avoid circuit overload results in slower emergency response. Modern fans are able to start quickly so this was not viewed as a problem.		3	4	5	6	3.9
53	No washing - of tunnels	Idea not considered viable.	K	4	4	4	2	3.7
17	No maintenance	No planned maintenance, i.e. run equipment to destruction. Likely to increase overall costs.	K	1	1	3	1	1.2

Appendix B: General issues

B.1 Introduction

In the conclusions of their review Jones and Fudger (1987) commented that promoters and designers of new tunnels need to be more aware of the requirements and problems of their operation and maintenance. Discussions with tunnel operators at the value engineering and value management workshop and at other times indicate that this is still true. This appendix draws together general issues, which should be addressed by designers, which are not included in the detailed reviews of individual equipment types.

B.2 Integration of all aspects of design and planning

Designers have reported that insufficient consideration is given to requirements of mechanical and electrical equipment in determining the tunnel cross-section and layout. In the planning stage, topography may be exploited to avoid the need for mechanical ventilation or make construction and escape shafts possible (Haack, 1998). Jones and Fudger (1987) report a common problem of reduction of tunnel cross-section to the minimum which limits cost of construction without due consideration being given to requirements for maintenance of services. The provision of a service tunnel or use of fewer, more powerful fans (discussed in Sections D.5 and M.5 below) provide examples of how aspects of civil, mechanical and electrical design should not be considered in isolation.

B.3 Standardisation between Highways Agency tunnels

Many items of electrical and mechanical equipment are designed and manufactured specifically for each tunnel project, so that there is little or no commonality between equipment installed in one tunnel and another. It has been suggested that greater specification of standardised equipment could lead to cost savings, particularly when purchasing replacement parts. However, it is considered that standardisation would have little impact on installation or operating costs. The main benefits would be seen in greater commonality of some replacement parts, reduction of the risk of obsolescence and possible reductions in stocks of spares. These are normally based on manufacturers' recommendations, and vary so widely that it is not practical to estimate a typical cost benefit. The disadvantages of standardisation are that innovation may be inhibited and choice of supplier limited. Therefore it is considered that on balance the costs of implementing a rigid policy of standardisation would not be justified.

However greater compatibility of software and common standards for interfaces would make future upgrading of plant monitoring and environmental control systems less expensive, by reducing the need for additional software development.

B.4 Standardisation within a tunnel

Provision of equipment of similar type, or from the same manufacturer, may allow scheduling of maintenance by the same organisation or during the same tunnel closure and so reduce mobilisation costs of maintenance. Also the use of common parts or consumables may result in economies in stores and simplification of supply chain management.

B.5 Condition monitoring

The use of condition monitoring allows maintenance intervals to be optimised. Techniques such as vibration analysis, line current spectrum analysis, oil debris analysis and shock pulse monitoring enable the condition of equipment and need for maintenance or repair to be assessed. They can be used to optimise the maintenance regime and quantify any reason for adjusting recommended maintenance intervals specified for individual items of equipment. Particular applications of condition monitoring are discussed in Sections D.5 and F.6 below.

B.6 Access for maintenance

Tunnel operators continue to report difficulties of access for maintenance (see for example Section D.3 describing insufficient space around jet fans). Also an instance is reported of pipework installed without rodding access. Access arrangements have implications for safety as well as for maintenance costs and duration, and should be addressed fully in designs.

Consideration should be given to access that does not require lane or bore closures, or only requires lane closure instead of bore closure, for example through appropriate location of sumps and provision of service tunnels. Such measures reduce disruption to traffic and have the advantage that maintenance may be carried out in normal working hours when work is likely to be to a better quality, at lower cost and more easily checked.

Certain tunnel systems require the use of specified methods of working employing specialised skills. For example, working in confined spaces (such a sumps or cable ducts) requires specific 'Confined Entry' training. Similarly, the operation of a high voltage network requires personnel to be 'Authorised Persons'. During the design phase for the tunnel it may be possible to arrange the design such that the requirement for the operator to maintain certain specialised skills is reduced or eliminated. This expedient will reduce the overall maintenance costs.

Consideration should be given to making available an area of land for use as a contractor's compound for major maintenance works. This could be accomplished by simple planning restrictions.

Instances have been reported of passing vehicles 'lifting' access covers. Wherever possible these should be located away from the carriageway. If this is not possible they should be positioned outside wheel tracks.

B.7 Water ingress

Damage caused by water ingress through the tunnel structure has required extensive refurbishment and replacement of tunnel equipment in recent years. Management of water to protect equipment should be considered explicitly at the design stage. In addition to avoiding any drips from the tunnel crown attention should be given to the water tightness in hidden locations such as chambers, tunnel panels and ducts.

Appendix C: Cost information

C1 Indicative costs (UK tunnels)

Table C1 summarises the key characteristics of several UK highway tunnels. The following tables provide indicative capital, maintenance, energy, staff and operational cost data relating to these tunnels.

Table C1 Details of tunnels

	Tunnel				
	A	*B*	*C*	*D*	*E*
Length (km)	1.1	0.65	0.95	0.4	0.4
No. of bores	2	1	1	1	2
No. of lanes/bore	2	2	2	3	2
Urban (U)/Rural (R)	R	R	R	U	R
Direction	2	1	1	Tidal flow	2

Table C2 Capital costs (1988 prices)

		Capital cost	
	No of units in tunnel	*Supply £k*	*Install £k*
Electrical supplies			620
HV Power supply cables	3 km	48	
LV Power supply cables	37 km	463	
Control and communication cables	27 km	120	
Tunnel panels			120
Distribution	24	157	
Emergency	18	121	
Ventilation	18	123	
Nitrogen foam system	2	7	
Smoke control	4	7	
Service building equipment	2		9
LV switchgear		142	
HV switchgear		155	
HV transformer		38	
Emergency generator/supplies			10
East & west emergency generators	2	75	
UPS, lights, computer	1	5	
Tunnel lighting *(incl. dimming units)*	3954	670	75
Tunnel ventilation *(Jet fans)*	72	197	27
Drainage and pumping *(including pumps, valves etc)*			6
Sumps	10	154	
Control panels	5	45	
Plant monitoring and environmental control system		444	39

Table C3 Annual energy cost (1998 prices)

	Cost		
Tunnel	*A (£k)*	*D (£k)*	*E (£k)*
Lighting	97	45	36
Ventilation	5	45	37
Pumping		45	8
Total	102	45	81

Table C4 Operating staff cost (1998 prices)

Tunnel	*D (£k)*	*E (£k)*
Staff	60	83

Table C5 Annual maintenance costs (1998 prices)

Tunnel	*A £k*	*B £k*	*C £k*	*D £k*	*E £k*
Electrical supplies					
Cabling (including power control & communications)	7	1.9	3.2		
Earthing	1	0.3	0.4		
Tunnel panels					
Distribution panels	6	1	2.4		
Emergency distribution panels	1.5	0.9	0.8		
Ventilation panels	2.4	0.36	1.2		
Nitrogen foam flooding system	2.7				
Tunnel smoke control panels	0.25	0.25	0.25		
Service building *(equipment)*					
M&E service buildings	6.5	3.5	6.1		
LV switch boards	2	1.3	2.8	1.6	
HV switch gear	7				
Emergency generator/supplies					
UPS system	5.4	5.7	8.5	21.1	
Emergency generators	0.7				
Battery tripping & closing units	0.8	0. 36	0.8		
Tunnel lighting *(incl. dimming units)*	56.5	10.5	16.3	17.6	
Tunnel ventilation *(Jet fans)*	59	19	45.5	11.8	
Fire safety engineering					
Fire extinguishers	0.6	0.2	0.6		
Tunnel fire fighting	3	0.6	0.8	16.5	
Drainage and pumping *(including pumps, valves etc.)*					
Sump pumping systems	17				
Sump control panels	1				
Gas detection equipment	18.5				
Communications					
Emergency telephone system[1]	11.4	9.2	13.7	27.8	
CCTV *(equipment)*	14.1	10.2	11.2	19.6	
Traffic control					
VMS system[1]	14.6	11.7	17.6	27.8	
Road marking				4.8	
Plant monitoring and control system *(environmental control system)*	40	50	18.4		
Other					
Global figure for maintenance					67.3
High level equipment[2]	23	6	5.4		
Instation equipment[1]	6.5	5.2	7.8		
Miscellaneous/other				4.8	42.1

[1] *See Table H1 and Table K1 for breakdown of equipment included.*

[2] *Maintenance and renewal of supports and roof bolts to lights, fans and other equipment.*

Table C6 Operating procedure costs (1988 prices)

Tunnel	*A*			*D*			*E*		
Procedure item	*Number of items per year*	*Cost per item £k*	*Cost per year £k*	*Number of items per year*	*Cost per item £k*	*Cost per year £k*	*Number of items per year*	*Cost per item £k*	*Cost per year £k*
Operational									
Daily inspection of tunnel				365	100	36.5			
Traffic management									
Planned lane closure	Indeterminate	0.5		100	80	8			77.0
Planned bore closure	32	2.1	68	5	300	1.5			
Maintenance procedures									
Carriageway cleaning	8	0.095	0.76						7.1
Gully empty[1]	8								
Wall washing	8	2.7	21	5	6.5	33			

[1] *Funded by others*

C.2 Indicative costs (international data)

The following tables collate cost data from a variety of overseas sources.

Based on information from a large number of tunnels in Norway, Sovik (1994) provided a means of calculating the life cycle costs of any tunnel from a classification scheme that includes safety class, above or below sea level, one or two way traffic, ventilation type, length, lining and paving. The data are summarised in Table C7.

Table C7 Annual operational cost data from Norway (Sovik, 1994)

	Maintenance £k/km/year	*Operation £k/km/year*	*Reinvestment (equipment) £k/km/year*	*Total annual cost £k/km/year*	*Number of tunnels*
Mean excluding 3 Oslo tunnels	12.9 (32.3%)	15.5 (35.4%)	14.2 (32.3%)	42.5	25
Mean of 3 Oslo tunnels	161.3 (23.2%)	132.4 (19.3%)	396.4 (57.5%)	690.2	3

[1] *Cost converted at 11.2 Kr=£1.*

[2] *Uncertain if data are expressed as cost per km of tube or cost per km of tunnel.*

[3] *Maintenance = cleaning, washing and other maintenance.*

[4] *Operation = power, telephone, lines and management cost.*

[5] *Reinvestment = capital cost of equipment per year/lifetime years (does not seem to be discounted).*

Table C8 Operational cost data from Chamoise tunnel (France)

Breakdown of 1996 annual cost £k/km/year/tube			
Fluid	*Washing*	*Equipment maintenance*	*Civil engineering maintenance*
21.6	7.7	12.4	0

[1] *Cost converted at 9.8 FFr = £1.*

[2] *Fluid = Power, water, oils, and telephones charges (PTT).*

[3] *Washing = Walls, pavement, signs, drains, luminaires, sumps, and safety gallery.*

[4] *Equipment maintenance = replacement and repair (new works such as improvement of equipment not included).*

[5] *Civil engineering maintenance = repairs (new works such as pavement restoration not included).*

Appendix D: Ventilation systems

D.1 Function and description of system

A tunnel ventilation system has two main functions. Firstly, to supply sufficient fresh air to all parts of the tunnel to reduce concentrations of exhaust pollutants to within acceptable limits. Secondly, in the event of a fire, to exhaust combustion products and control smoke movement. In Highways Agency tunnels the latter requirement generally determines the capacity of the ventilation plant. However environmental considerations, including avoiding health hazards to the neighbouring community from exhausted air in the vicinity of tunnel portals or ventilation stacks, are becoming an increasingly important aspect of tunnel ventilation design. A forthcoming TRL report will describe the purpose, operation and control of tunnel ventilation systems in more detail.

D.2 Description of maintenance procedures

Longitudinal ventilation

Jet fans are accessed for maintenance by rising access plant, during planned tunnel closures. A number of maintenance operatives, appropriate to the extent of the installation, maintain each ventilation fan in turn.

The typical maintenance procedures necessary for ventilation fans are broken down into 3 monthly, 12 monthly and 60 monthly activities. The maintenance specification involves: cleaning, checking mountings and terminals, run testing, blade clearance checking and adjustment, measurement and recording of run and starting current, vibration measurement, electrical continuity and insulation testing. After approximately 5 to 10 years the fan is removed to the factory for complete overhaul including stripping and repainting.

Transverse, semi-transverse and hybrid ventilation

Maintenance access to fan equipment in ventilation shafts will generally not require tunnel closures or special access equipment, since it is usual for motors and gearboxes to be mounted in a machine room outside the ventilation duct containing the fan. Duty and standby fans are normally provided so that a fan can be taken out of service without reducing the ventilation system capacity below acceptable levels.

The typical maintenance procedures necessary for shaft mounted fans are broken down into 3 monthly, 12 monthly and 60 monthly activities. The 3 monthly tasks involve cleaning, run testing and a visual inspection for any damage. Every 12 months, additional operations include checking bolts in mountings and impellers, terminal checking, blade clearance checking and adjustment, measurement and recording of run and starting current, vibration measurement, electrical continuity and insulation testing. After approximately 5 years the fan motor and gearbox are removed to the factory for complete overhaul including stripping and repainting. Manufacturers' recommendations for overhaul may be highly conservative and vary widely between 2 and 10 years. Because operating conditions differ considerably from one tunnel to another the optimum intervals between overhauls for a particular installation may best be established by trial and error.

Where dampers are installed it is normal to check operation and lubricate them every 6 months. Ventilation ducts, particularly extraction ducts, will require occasional inspection and cleaning.

Control equipment

The maintenance requirements for direct-on-line (DOL) and Star-delta starters are similar to those required for general electrical equipment, and are defined at similar intervals, see Section O.2.

D.3 Issues

General

The nature of ventilation equipment is such that individual fan performance does not normally deteriorate significantly between maintenance periods. If ventilation fans fail then they cease to function completely. Such failures are usually caused either by a fan motor failure or a fault in the fan control circuit. In exceptionally dirty environments it is possible for accumulation of airborne detritus on the fan blades to cause fan imbalance problems with the attendant risk to motorists caused by blade or detritus shedding.

Longitudinal ventilation

Problems associated with fan maintenance procedures tend to result from the layout of the ventilation installation. Inappropriate siting of ventilation fans during initial design (for example not leaving sufficient access space around the fan) tends to increase the maintenance costs as it takes more time to access terminal chambers, adjust blade clearances or remove and replace the jet fan. The procedures commonly require the use of large numbers of access plant. If any item of plant fails it can affect the scheduled completion of the works.

Prior to ventilation maintenance works, it is necessary to isolate banks of jet fans. Since most site plant is operated via diesel engines, ventilating the work place can become a problem.

Semi-transverse / hybrid ventilation

The basically symmetrical nature of most semi-transverse systems means that, in the absence of external influences on air movement (for example natural air flow through the tunnel or piston effect from traffic), there may be a null point close to the centre of the tunnel where it is difficult to induce movement. This is of particular importance when considering the configuration of fans for smoke extraction. The essential objective is to quickly achieve effective smoke control, particularly where a change of airflow is required between normal and fire modes of operation. In several tunnels, jet fans are installed solely for the purpose of smoke control.

In one tunnel reversibility of fans has been achieved by the use of variable pitch blades. If stopped in the 'supply' position, such fans may need to be run up to speed in the supply mode before the blades can be altered to 'extract'. This could compromise safety in some smoke extraction situations, as has been observed during ventilation tests. The variable pitch linkages can also be troublesome in use, principally impaired by airborne detritus, and require frequent checking and maintenance.

Controls

Starting of fans is normally controlled either by direct-on-line (DOL) starters or by Star-delta starters. DOL starters connect the fan motor directly to the electricity supply and for the first few seconds while the fan is running up to speed can draw a current of between six and seven times the normal running current. To reduce the impact on the supply it is usual to introduce a time delay function, typically 15 seconds, to limit the number of fans that can be switched on together.

Star-delta starters reduce the starting current by connecting the motor windings in star formation during the initial run-up period, then switching them into delta formation to enable maximum torque to be achieved. Typical starting currents with Star-delta starters are around three times the running current. Switching from star to delta operation is generally initiated by a time delay device, and because of the lower starting torque the time to run up to full speed is greater with this type of starter than with direct-on-line.

Of great significance is the comparatively long time it can take to start tunnel ventilation. A 15 second delay introduced into the starting sequence for tunnel ventilation fans means that for a tunnel with 36 ventilation fans switched individually it would take nine minutes to start all of the fans. Time for airflow to be established introduces another delay. If the management of an incident requires the ventilation fans to be reversed an additional delay is introduced as the ventilation control system is commonly designed to prevent the number of fan reversals per hour exceeding a specified value. There would then be a further delay (of 9 minutes) whilst the fans start in the reverse direction. Such accumulated time delays could be very significant when attempting to manage a tunnel fire. There should normally be an override control system to reduce the response time in emergency situations, although this procedure may increase the risk of damage to the electrical system.

Corrosion resistance of jet fans

The casings of jet fans for road tunnels in the UK are normally made of mild steel and painted. It is understood that stainless steel is specified in Austria. Although corrosion problems have been noted, particularly in silencers where moisture is retained against the casing within the acoustic padding, use of stainless steel is not considered to be economic because jet fans are in any case required to be removed for overhaul at intervals of 5 to 10 years. Use of plastic for structural components is not thought feasible because of the need to operate in specified fire temperature conditions.

Impellers are normally made from fire resistant GRP or aluminium alloy and are inherently resistant to corrosion.

Freewheeling

As described below, many UK road tunnels are effectively self-ventilating when traffic flows freely, requiring ventilation to operate only for brief peak periods. Traffic and wind induced air flows cause jet fans to turn and concern has been expressed that this contributes to unnecessary bearing wear. However some fan rotation is needed to ensure bearings do not seize, and speeds at freewheeling are not thought to contribute significantly to bearing wear.

D.4 Alternatives

Maintenance intervals

Consideration has been given to the alternative maintenance approaches of either conducting major overhauls on each of the fans or replacing them with new units. For the A55 tunnels by monitoring each of the fans and replacing with a spare when necessary on a worst first basis, it has been found cost effective to carry out a programme of rolling overhaul. The period to major overhaul can be extended by between 15% and 50% beyond that recommended by the manufacturer dependent upon the condition of the individual fan. Further details are given in Box 1.

The approach of rolling overhaul has logistical advantages. Firstly, replacement of a few fans (six on the A55 tunnels) can be conducted during normal maintenance closures, rather than during a long closure that would be required for replacement of all fans. Secondly, failures of fans are likely to be distributed over a period of years, rather than all occurring at exactly the same time.

Box 1 Comparison of alternative maintenance approaches

The manufacturer's recommendations are for complete overhaul after 5 years, which costs about £4700 per fan at current prices and involves the removal of each fan from the tunnel and a complete overhaul being conducted away from site. The overhauled fan is effectively as good as new. The cost of supply and installation of a new fan is estimated to be in excess of £6000, to which must be added the cost to remove and dispose of the old fan. Since the ventilation system can operate with some fans out of action (tunnel ventilation systems may provide acceptable levels of ventilation with 25% of fans out of commission), it is acceptable to allow for failure of some fans between maintenance closures and replace these during planned maintenance closures. For the A55 tunnels, six fans are held either as spares or undergoing overhaul and are available as replacements at the next planned closure.

The vibration levels and amount of corrosion are monitored during planned maintenance; the fans are graded by their condition; up to six of the worst fans are then scheduled for removal, overhaul and replacement during planned maintenance closures. At the A55 tunnels it has been found that the mean life before overhaul is required is between about 6 years and 6.5 years: some fans required overhaul after about 10 years, but some failed after 4.5 years.

Variable pitch reversible fans

By using reversible motors and bi-directional impellers the problems associated with the operation and maintenance of variable pitch fans can be avoided. However, published figures suggest that bi-directional impellers are around 25% less efficient and care should be taken that the ability to meet all relevant performance criteria is not compromised.

Maintenance of fewer, more powerful fans

There appears little alternative to the maintenance procedures adopted for the maintenance of jet fans. The work specification for a jet fan, and the amount of labour effort required to perform the maintenance, appears to be largely independent of the size of the ventilation fan. A maintenance crew could maintain a 22 kW fan in the same time as it takes to maintain a 12 kW fan.

The design of a road tunnel ventilation system is a compromise between many factors. These factors include number and diversity of location of the ventilation fans to reduce susceptibility to mass fan failure during a serious tunnel fire. Provided that a tunnel ventilation system satisfying such criteria could be designed to employ fewer, though more powerful jet fans a considerable maintenance saving could be made, with a corresponding reduction in whole life costs. The Medway and River Lee tunnels have employed this approach and use only 12 ventilation fans in each tunnel bore, although the driving force behind the Medway installation was reduction of construction costs

Acceptable levels of air quality

Energy and maintenance costs are directly linked to running hours, which in turn are determined by the set points for acceptable levels of pollution. At current levels of emissions, a small change in the set points can result in a significant change in running costs, and it is therefore important to make sure that trip levels are not set too low.

Acceptable concentrations of CO and NO_x should be correctly linked to exposure times. With free-flowing traffic, tunnel users will pass through the tunnel relatively quickly and their exposure time to pollution in the tunnel will be short. There may therefore be scope for automatic adjustment of set points linked to traffic flow, although because free-flowing traffic also generates a piston effect that assists tunnel ventilation, potential savings may not be as significant as first thought.

Tunnel ventilation systems are normally controlled by detectors which measure the concentration of carbon monoxide (CO) and obscuration in the road space. In most cases it is the CO level that initiates the ventilation. There appears to be no common standard for air quality in a tunnel and control systems may be set to switch on ventilation to its first level anywhere in the range between 35 and 65 ppm concentration of CO. At the time of compiling this report, the background level of CO outside a tunnel may be around 25 ppm in urban areas, rising to 50 ppm when traffic is heavy. The tunnel ventilation would therefore have to work hard to maintain an air quality close to these levels.

The current Health and Safety Executive (2000) recommendations for occupational exposure to CO are 200 ppm for 15 minutes and 30 ppm for 8 hours. It follows that, for maintenance personnel working in the tunnel for prolonged periods, a level of 30 ppm should not be exceeded.

Given that exposure to carbon monoxide has a cumulative effect, it would be wrong to permit concentrations in tunnels to approach the 200 ppm maximum. However, under normal operational conditions, users are unlikely to be in tunnel for more than a few minutes, even with the most congested traffic, and the use of an interim set point of, say, 100 ppm could be considered.

Calculations applying traffic flow data obtained for an actual urban tunnel to a typical twin bore 1.5 km tunnel show that with a set point for CO of 50 ppm, and emissions at 1990 levels, the annual energy consumption is about 1800 MWh, costing about £90,000. Raising the set point to 100 ppm would reduce this cost to about £11,000, that is reduction by a factor of 8.

However, it has been found that with the reductions in emissions over the past ten years, the majority of UK road tunnels have become effectively self ventilating when traffic flows freely, requiring ventilation to operate only for brief peak periods, for example when traffic is slow moving or stationary. The equivalent energy costs at predicted year 2000 emission levels are practically negligible. Since emissions are predicted to continue to improve for the foreseeable future, which will impact not only on air quality both inside and outside a tunnel, there is generally little to be gained financially by adjusting the set points for ventilation response to carbon monoxide or visibility, since this proposal has effectively been overtaken by improvements in vehicle emissions. However, the ruling criteria for ventilation in the relatively short tunnels currently owned by the Highways Agency should be reviewed periodically in the light of decreasing vehicle emissions, changes in traffic characteristics and increasingly stringent health and safety regulations. Although relatively little forced ventilation is required to maintain air quality at a safe level under normal operation, even with heavy traffic, it is important for drivers not only to be safe but to feel safe. There is scope for research into the necessity of ventilation for comfort, for instance to control odours from vehicle exhausts, as well as harmful gases and visibility, to maintain the confidence of tunnel users.

It should be remembered that there is unlikely to be scope for reduction of ventilation plant as a result of reduced emissions, since plant is almost always sized for the clearance of smoke under fire conditions. It is also necessary to have the capability to maintain a low concentration of CO, without assistance from the piston effect or external winds, to enable maintenance staff to work safely in the tunnel for prolonged periods.

Operator intervention

In many cases mechanical ventilation is only likely to be required during periods of traffic congestion. Interventions by the operator at such times might reduce vehicle emissions in the tunnel and consequently reduce the running time of ventilation and associated energy and maintenance costs. Such interventions include: ‘TURN ENGINE OFF’ signs and radio messages in stationary traffic, restricting entry to the tunnel such that vehicles do not queue in the tunnel, or closing a lane or bore. Most of these actions could be initiated automatically. However the latter options might increase congestion elsewhere on the local network and which might not be acceptable.

Natural ventilation

A number of shorter tunnels, around 400 metres in length, have been found to be effectively self ventilating during normal traffic conditions, principally due to the piston effect generated by vehicles passing through the tunnel. This suggests that forced ventilation may be unnecessary for such tunnels. However, in these cases careful consideration needs to be given to possible fire scenarios, particularly when loss of control of air movement could result in tunnel occupants being exposed to hazardous combustion products and smoke logging of the tunnel.

A detailed study, carried out on behalf of the Highways Agency, on the requirement for mechanical ventilation in shorter tunnels is nearing completion. The report will provide information on the maximum lengths of self-ventilating tunnels that may be considered under different conditions and discussion on ventilation control philosophies. It is essential that the local conditions are checked during design where mechanical ventilation is not contemplated.

Electronic starters

An alternative to the use of conventional direct-on-line starters and Star-delta starters is electronic variable speed control and / or soft starters (additional considerations in the use of soft starters can be found in Section F.5). Both types of device can be programmed to limit starting currents to a level that would avoid the need for time delay functions. Variable speed drives allow the motor speeds to be varied, thus permitting finer control of the response to air quality. Such a strategy would allow much faster response from the ventilation system. But it should be noted that variable speed fans are generally less efficient except at design speeds.

The potential of this use of soft starters or variable speed drives is to reduce the delays associated with fan starting, stopping and reversing during tunnel emergencies. Variable speed control of tunnel ventilation would also allow the ventilation rates to be quickly varied, in accordance with the requirements of the fire services, during a tunnel emergency. However, careful design is required to ensure that the higher frequency currents generated by these starters will not cause motor overheating or excessive harmonics in the supply and distribution network.

For a tunnel with a large number of jet fans, electronic soft starters can significantly reduce the time to bring the ventilation system up to full power. The additional cost for a tunnel such as Conwy, with a total of 72 fans, would be around £36,000 for a new installation. It would be difficult to install soft starters as a replacement for existing contactor starters without complete replacement of the motor control centres.

The advantages of soft starters reduce as the number of fans installed increases. However, it has been demonstrated elsewhere that there may be significant cost advantages in using fewer, more powerful fans, so this option should be considered first.

Designers of new tunnels should certainly consider the combination of fewer, more powerful fans together with electronic soft starters to minimise the total fan run-up time.

Predictive control

Experiments are being carried out in some countries, notably Japan and in Europe, to link ventilation controls to data on actual and expected traffic flows, to switch fans on before pollution reaches the upper limit of acceptability (and therefore to avoid overshooting the limit in practice). The overall benefits of this approach and the impacts on maintenance and energy costs are yet to be established, but first indications are that there is potential for savings.

Dust extraction

The removal of pollutants and particulates in the tunnel by means of filtration and electrostatic precipitation could be used to reduce the ventilation demand. Such systems are considered most appropriate to longer tunnels than are common in the UK. The capital costs in particular will be high due to the space required in the tunnel. As the production of pollutant gases falls due to tighter emissions legislation, the greatest benefits are likely to be realised in the reduction of particulates. Indeed, several systems for extracting particulates have been installed in tunnels in Japan, where there is a problem with particulate emissions from a large, ageing fleet of diesel lorries.

D.5 Value engineering review of alternatives

Fewer, more powerful fans

The cost of maintenance of jet fans is largely proportional to the number installed in a tunnel. The use of fewer, more powerful fans will therefore offer significant maintenance cost savings over the conventional approach of using numerous small fans distributed along the length of a tunnel.

For the purposes of this exercise, estimated costs for the Conwy Tunnel, which has 72 small fans, have been compared with Medway, which has 24 fans. Both fan installations have a certain amount of redundancy to cover the possibility of one bank of fans being disabled by a major fire.

The driving force behind the Medway installation was reduction in construction costs. By locating all fans in the cut-and-cover sections at either end of the tunnel it was possible to reduce the height of the central immersed tube sections.

In existing tunnels of rectangular cross-section it is likely that the internal height is determined by the original fans and that larger fans cannot usually be accommodated. This saving is therefore mainly relevant to new tunnels.

A value engineering review of installing fewer, more powerful fans is shown in Table D1. This shows a significant saving in whole life costs of over 42% (£559,000) for the case analysed.

Table D1 Value engineering review of jet fans

Fewer more powerful fans	*Design life: 20 years*		*Existing 72 small fans*		*Alternative 36 large fans*	
Function review						
Objective	*Importance rating*			*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.25			70		80
Sustainability	0.35			50		70
Health and safety	0.40			40		45
Total weighted score				51		63
Whole life cost						
	Interval (years)	*Present cost factor*[1]	*Estimated cost (£k)*	*Net present cost (£k)*	*Estimated cost (£k)*	*Net present cost (£k)*
Capital		1.0	432	432	288	288
Overhaul (5-yearly)	5	1.7	324	558	180	310
Maintenance (annual)	1	11.2	18	201	9	100
Maintenance (quarterly)	0.25	46.6	3	134	1.4	67
Total present cost				1325		766
Value ratio (Function/Cost)						
Value ratio (x10^{-6})				38.5		81.6
Normalised value ratio				1.00		2.12

[1] *Present cost factors are for a discount rate of 6.0%.*

[2] *For explanation of value engineering review see Section 3.3.*

The following factors may give rise to further cost savings if fewer, larger fans are used:

i Energy costs. Larger fans are more energy efficient than smaller ones, although this may be offset to some extent by a reduction in efficiency if the fans are located in niches in the tunnel roof. If the installation is properly designed, then the efficiency reduction due to recessing will be small (for example tilting the efflux 5° to 10° downwards, away from the ceiling improves the aerodynamic efficiency of the fan installation).

ii Construction costs. The height of rectangular section tunnels may be reduced if fans are kept out of the central section. For example, the immersed tube sections of Medway are about 300 mm lower than at Conwy. This reduces not only the amount of concrete used but also the depth of excavation to accommodate the tunnel.

iii Electrical system costs. A reduction in the number of fans simplifies wiring, switchgear and control gear with a corresponding reduction in costs.

These advantages must of course be weighed in the design process against possible operational disadvantages of using fewer more powerful fans. These might include the formation of regions of locally reversed flow (the Craya-Curtet effect) and changes in the aerodynamic efficiency.

Condition monitoring

Condition monitoring can take many forms, including measurement of vibration, running current, motor efficiency, temperature, etc. Of these, the most useful for tunnel fans is the measurement of vibration, and this forms the basis of the following considerations. This discussion is also applicable to drainage pumps (see Section F.6).

The electric motors in equipment such as jet fans and drainage pumps are difficult to access to check for bearing wear and any imbalance due to mechanical damage. Fans are mounted at high level above the carriageway and require tunnel closure and probably removal of sound attenuators to check for play in bearings. Imbalance is detected by measuring vibration and checking for excessive noise when running.

Measurement and analysis of vibration by means of sensors permanently attached to the fan and pump would permit any increase in wear leading to imbalance to be detected and continuously monitored, and the need for servicing to be predicted well in advance. Any sudden deterioration could be automatically indicated by alarms. This would not only do away with the need for manual bearing checks, but by providing continuous monitoring would provide much better evaluation of the plant condition than infrequent spot checks. The costs of the three monthly inspections might be saved by the use of condition monitoring. A value engineering review of this scenario for fans is illustrated in Table D2 and shows a clear benefit. However, since the three monthly inspections for fans and pumps include other tasks as well as checks for bearing wear and imbalance, introduction of condition monitoring will not obviate the whole need for access unless experience demonstrates that intervals for the associated visual inspections can also be extended.

In practice tunnel ventilation and pumping installations are designed to meet their design performance with a certain level of failures, and so the consequences of some failures in service may be acceptable. However, in safety critical systems (for example where failure of a fixing or fan impeller could result in debris falling onto the road) thorough risk assessment will be required to support a proposed reduction in the inspection regime.

It is therefore concluded that condition monitoring is desirable for its ability to detect plant deterioration and predict failure more reliably than the checks currently used. However, it might not reduce the need for inspection and maintenance to a level that would justify the cost of installation of the necessary sensors and supporting equipment. There will probably always remain some need to carry out periodic checks for mechanical damage and security of fixings.

Table D2 Value engineering review of condition monitoring of fans

Condition monitoring of fans			*Existing*		*Alternative*	
	Design life: 20 years		*No condition monitoring 72 fans*		*Condition monitoring 72 fans*	
Function review						
Objective	*Importance rating*			*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.25			50		75
Sustainability	0.35			50		75
Health and safety	0.40			50		60
Total weighted score				50		69
Whole life cost						
	Interval (years)	*Present cost factor*[1]	*Estimated cost (£k)*	*Net present cost (£k)*	*Estimated cost (£k)*	*Net present cost (£k)*
Capital		1.00			126	126
Maintenance (quarterly)	0.25	46.6	2.9	134		
Total present cost				134		126
Value ratio (Function/Cost)						
Value ratio (x10^{-6})				373		548
Normalised value ratio				1.00		1.47

[1] *Present cost factors are for a discount rate of 6.0%.*

[2] *For explanation of value engineering review see Section 3.3.*

Appendix E: Lighting systems

E.1 Function and description of system

The function of tunnel lighting is to maintain a base level of lighting within a tunnel, and enhanced lighting in the tunnel entrance and exit zones, such that design traffic speeds can be safely maintained. Current standards for lighting of highway tunnels are defined by BS 5489: Part 7: 1992.

Tunnel entrance lighting is divided into a number of zones, each lit to a progressively lower level to provide a stepped reduction in luminance between the relatively bright exterior conditions and the tunnel interior zone. As the daylight outside increases or decreases, groups of luminaires are switched on or off in stages so as to ensure that the minimum lighting requirements are always achieved. Typically each stage of lighting would double the level of light produced by the previous stage. This relatively coarse method of control means that a small increase in external daylight can result in a 100% increase in the entrance zone light levels and energy consumption. The tunnel lighting level almost always exceeds the true requirements, and the entrance zones are therefore normally over-lit.

Tunnel lighting systems usually comprise a combination of fluorescent (MCF) luminaires and either high pressure sodium (SON) or low pressure sodium (SOX) luminaires, specifically designed to withstand the tunnel environment. Improvements in the efficiency and colour rendering of SON lamps, together with their smaller size, means that they are now preferred to the older SOX lamps. The reasons for the mixture of lighting types are two-fold:

i In the tunnel interior, where the light levels are relatively low, MCF linear fluorescent tubes provide a more uniform appearance free from apparent flicker at normal traffic speeds. SON and SOX lamps are more powerful and are more suitable for use in the entrance and exit zones where increased light levels are needed for the transition between external and internal conditions.

ii Traditional SON and SOX luminaire designs have not been capable of instantaneously re-striking (re-lighting) following a power failure. This limitation is inconsistent with continuous safe tunnel operation. To provide a base level of lighting during the re-strike period, MCF luminaires are normally used for the lowest level of lighting throughout the entrance and exit zones, with SON and SOX used for higher levels only.

Uninterruptible power supply (UPS) systems are sometimes used to maintain supplies to sodium lamps on battery power for a limited period of time to avoid loss of operation during interruptions to the mains supply.

Tunnel lighting control is achieved either by switching lamps on or off, or by dimming. The latter approach is only used at present for control of MCF lamps to differentiate between base level day time lighting and night time lighting, and has the advantage that all fluorescent tubes will share the same burning hours. The alternative is to switch off typically 50% of the fluorescent lamps at night. SON and SOX luminaires in entrance and exit zones are switched on and off in stages to give varying levels of luminance.

Tunnel lighting stages are switched by contactors, usually in the main lighting control panel, and are supported by a variety of ancillary equipment, such as miniature circuit breakers (MCBs).

Tunnel lighting is most effective when installed at high level within the tunnel. In some tunnels the lighting is installed along the tunnel haunches, whilst in others it is suspended directly above the centre of the carriageway. Since safety procedures would in many cases prohibit high level working whilst the tunnel is open to traffic, it follows that in order to perform lighting system maintenance bores must normally first be closed to traffic.

E.2 Description of maintenance procedures

The routine maintenance requirement for the luminaires normally has three main components: cleaning, re-lamping and repairs. In maintenance terms there are two principal designs of luminaire commonly in use in road tunnels. Some have removable end caps that provide access to the luminaire terminations, gear tray and lamps (end access). Others provide access to the luminaire internal equipment by a hinged glass front cover (front access). End access luminaires are typically arranged on brackets that allow each luminaire to be lowered by approximately 200 mm for maintenance purposes. The cleaning specification involves cleaning the outer surfaces of the luminaire and the glass front; thus for cleaning it is not necessary for each luminaire to be lowered. In addition to maximising the light transmission through the luminaire glass, cleaning also serves to remove deposits of road traffic film and unburned hydrocarbon deposits from the general body of the luminaires, hence minimising the risk of fire and corrosion. For re-lamping, each end access luminaire must be lowered and the end caps removed to gain access to the luminaire internals.

The maintenance requirement for tunnel lighting control equipment comprises routine electrical distribution system activities relevant to the particular type of switchgear installed. Typical procedures at 3 monthly, 6 monthly and 12 monthly intervals are described in Section M.2. The maintenance requirements for dimming systems depend upon the specific type of dimming control equipment provided. Some dimming equipment requires extensive periodic calibration works (as defined within the manufacturer’s instructions) to ensure that it continues to operate correctly. Other dimming systems require no calibration work at all.

E.3 Maintenance costs

Table E1 gives representative costs for operations at various maintenance intervals. These include the provision of plant, supervision, and site operatives but exclude any hardware or tunnel closure and site management costs. The plant hire element of these maintenance costs is approximately £1.00 to £1.50 per luminaire; thus the labour element is the major cost. Table E2 gives representative lamp costs.

Table E1 Typical lighting maintenance costs (1998 prices)

Maintenance period	*Maintenance cost per luminaire (£)*
12 months	8.5
24 months	9.5
60 months	11.0

Table E2 Typical lamp costs (1998 prices)

Type of lamp	*Lamp purchase cost (£)*
MCF Tube	1.66
100W SON	6.50
150W SON	6.50
250W SON	7.00
400W SON	8.00

E.4 Issues

High-level access plant is required to gain access to the lighting installation for maintenance. Such plant is expensive to purchase (typically of the order of £30,000 per unit); it is common to hire such plant for the duration of the maintenance works. The serviceability of such 'on hire' plant can be variable. It is expedient to ensure that any such plant is inspected prior to arrival at site and that the use of the plant is only sanctioned when a copy of the inspection certificate is lodged with the tunnel management. The failure of an item of access plant can contaminate the carriageway (with hydraulic or diesel oil) and prevent the works programme from being completed.

A bulk lamp change may require the use of many such access lifts depending upon the length of the tunnel and the extent of the lighting installation. Extensive operations of this type can cause traffic congestion within the tunnel, and lead to unacceptable levels of vehicle exhaust pollution caused by the plant. Any other works requiring coincidental tunnel access must be managed so as to prevent access contentions.

Tunnel lighting systems are designed with a specified 'maintenance factor' typically of 85%, that is it is permissible for the lighting levels within the tunnel to decrease to 85% of the initial value whilst normal traffic speeds are maintained with safety. Such a strategy means that a tunnel is over illuminated by approximately 17.5% with new lamps and clean luminaires. Savings could be made if the excessive illumination could be safely reduced.

Factors which detrimentally affect the lighting levels include lamp ageing, dirt on the luminaires and dirt on the tunnel walls (which decreases the reflected light values) and ageing of tunnel wall finishes. Thus the cleaning of the tunnel walls is closely linked to the maintenance strategy for the luminaires.

Prior to re-lamping, it is necessary to isolate sections of luminaires. This can have a detrimental effect on the ability to perform other works at adjacent sites.

Lighting maintenance procedures are very labour intensive. Lighting system and/or luminaire design expedients to reduce the amount of labour required would significantly reduce the maintenance costs.

Entry to the front access type is generally much easier than in the end access type resulting in a faster (and cheaper) maintenance cycle. Problems have been reported where end access luminaires are spaced too closely in the longitudinal direction. Front access luminaires are generally to be preferred.

A common design of luminaire is supported by inverted stainless steel bolts, the heads of which locate in 'T' slots formed in the extruded aluminium body. These slots are highly susceptible to the accumulation of extraneous matter, including exhaust pollution particulates. This detritus combines with moisture, salt from de-icing operations and the residue of detergents used for tunnel cleaning to form a corrosive cocktail that attacks the luminaire supports. Corrosion and failure of the aluminium extrusion has been observed at these points, thought to be due to galvanic corrosion between the dissimilar metals, exacerbated by high stress at the point of contact, and the residues described above. The extent of this problem appears to vary from one tunnel to another, and may depend on the particular grades of aluminium alloy and stainless steel used, as well as on the severity of the environment. The majority of those luminaires affected will require removal and repairs before the end of their designed operational life. A cost-effective repair involves removal of the luminaire, cleaning, stripping down and painting. A plate is then used to spread the load over a greater area of the extrusion slot and to make the aluminium/stainless steel interface less critical. Non-metallic washers and/or grease may also be used to separate dissimilar metals and reduce contact with corrosive deposits. This repair costs around £55 (at 1999 prices), comparing favourably with a cost of around £400 for a replacement luminaire and bolts of the correct grade of stainless steel. Such measures may yield significant whole life cost savings.

Measurements of tunnel luminance in two tunnels have shown lighting levels achieved are in accordance with design standards. However an instance was observed of the *switch off* for lighting stages being delayed longer than necessary. Clearly, optimising the switching levels and time delays in design and during maintenance would result in energy savings. Also, in view of the potential energy savings it is recommended that calibration of photometers and lighting control equipment be considered a key part of the maintenance regime.

E.5 Alternatives

BS 5489, counterbeam lighting and daylight screens

The lighting levels required in BS5489: Part 7: 1992, counterbeam lighting and daylight screens, have all been reviewed with the following conclusions (Bird, 1999).

Concern expressed about lighting levels may have its origin in the staged nature of lighting control, wherein lighting levels are often substantially higher than necessary. Dimmed control of lighting would smooth such steps.

The conditions where savings may be made by adjusting lighting to traffic speed are limited. It is not recommended that speed limits be imposed to allow of economy of lighting.

With regard to entrance lighting, current methods of determining levels are presently under review by the International Commission on Illumination (CIE). It is recommended that the method in draft CEN (1996) be used to determine threshold lighting. This is broadly equivalent to the method of BS5489: Part 7: 1992, but uses a greater number of subdivisions which would result in economy. Additionally increasing visibility by including visual aids would allow a lower class of lighting to be used or, where conditions warrant it, higher lighting levels would be justified on technical grounds. Consideration should be given to reduction of lighting in the second half of the threshold zone in accordance with the recommendations of the draft European standard (CEN, 1996). On climbing approaches to tunnels consideration should be given to a reduction of stopping sight distance (SSD).

Satisfactory experience in the Netherlands and elsewhere has provided a strong case for considering the use of counterbeam lighting. Such systems generally require less lamp flux to provide a luminance equivalent to that from symmetrical lighting installations (van Bommel and de Boer, 1980). However, it is not possible to discount possible objections to counterbeam lighting under UK conditions. These might only be resolved by a trial installation at a new or refurbished tunnel, with provision to revert to conventional lighting should these prove unsatisfactory.

Advice in BS 5489: Part 7: 1992 is confirmed by experience in the Netherlands that, although the use of daylight screens should not be completely discounted, it is unlikely that a good economic case could be made for them based on current electricity costs. They are also known to be prone to certain problems associated with snow and ice. However the longer term environmental benefits of reduced energy consumption should be taken into account.

Research is currently underway at the Transport Research Laboratory into the development and use of simulator technology to provide a means of investigation of factors associated with illumination on driver performance. This technology may be appropriate to the future design of tunnel lighting systems.

Reduction of access zone luminance

BS5489: Part 7: 1992 (Section 17.6) suggests measures for reducing the luminance of surfaces visible in the access zone. These include: dark facades and carriageway outside the tunnel, tree planting and reducing the effect of low level sun and the amount of visible sky. Vejlby Thomsen and Gudum (1995) make other suggestions that increase visibility including: straight approach to tunnel, light coloured carriageway inside the tunnel, retro-reflective road markings and a large tunnel entrance to maximise daylight penetration.

Lamp changing policy

There are two main policies for dealing with lamp replacement (Zuman, 1997):

i burn lamps to destruction and replace as required;

ii planned cyclic replacement or bulk changing at predetermined burning hours.

For the base level lighting, with current tube technology, the first policy is not considered feasible in a tunnel, because the relationship between the annual running time and expected life of the lamp means that frequent failures would be expected. In order to maintain the required level of lighting, frequent random replacements would be required. This would in turn require frequent tunnel closures, with consequent cost and disruption to traffic.

Trials carried out on the A55 tunnels in North Wales demonstrated that for acceptable levels of lighting, optimum performance could be obtained if the cleaning frequency of the luminaires is set at 12 months and the lamp replacement set at 24 months. These figures were found by leaving short sections of lighting unchanged. Accumulations of dirt on the luminaires were assessed and the effect of extending the operating life of the lamps was tested. It is normally possible to predict incipient failure because the lights would dim rather than fail. It was found that by specifying ‘tri-phosphor’ tubes these maintenance frequencies were achievable. This represented a halving of the manufacturer’s recommended frequencies. In the case of the higher intensity entrance zone luminaires, because they typically run for only 1000 hr/year, it was found cost effective to maintain higher lighting stages on a breakdown-repair basis, when the relatively few failures are replaced during planned maintenance closures. The same was found to be true for other lighting components such as gear trays and connectors. Luminaires that fail between scheduled lighting maintenance activities are repaired on an as-required basis. For tunnels where contractors perform the lighting maintenance, any such additional repairs must be specified as the duty of the main mechanical and electrical contractor.

The maintenance procedure for any tunnel lighting system should be optimised around the particular system, employing the general principles outlined above.

Luminaire supports

The design of luminaire support used in many tunnels acts as a trap for foreign matter and can become a significant corrosion point. Greater attention should be paid during luminaire design to ease of cleaning, the elimination of points of high stress and corrosion traps, and the use of more corrosion resistant materials. The glass face of luminaires could be treated with an anti-stick coating to prevent traffic film from adhering to the glass face and reducing light transmission.

Alternative light sources

A number of advances have been made in lighting technology in recent years, and systems using induction and sulphur lamps, light emitting diode (LED) technology and new dimming techniques for discharge lamps are becoming available. All are at relatively early stages of development and are therefore expensive and unproven.

Induction lamps have a service life of up to 60,000 hours. This compares very favourably with the 17,500 hours being achieved from existing electronically controlled tri-phosphor MCF types, or the 25,000 to

30,000 hours from SON-T types. Light output is comparable to MCF fluorescent tubes, but they are not dimmable and, being compact sources, may not be suitable for interior zone lighting because of flicker effects.

Sulphur lamps are very intense light sources, currently up to 1.4 kW, being developed in the United States. They may be used in conjunction with light tubes, typically up to 20 metres long per lamp, or 40 metres with a lamp at each end. The lamps use a magnetron to irradiate sulphur with microwaves in an argon filled bulb. Dimming is possible down to 20%. Life expectancy of the lamp itself is predicted to be between 10 and 20 years, but the weak link at present is the magnetron, with a life of about 3 years. A motor to rotate the lamp and forced ventilation for cooling are also required, which add to the energy consumption. These lamps are already being trialled in some Italian road tunnels. The attraction of these devices is that light sources only need to be installed at approximately 40 metre intervals, with a potentially great reduction in labour costs for maintenance.

Significant international research effort is being dedicated to the development of high intensity, white, light-emitting diodes (LEDs). Current lighting industry research programmes are aiming to develop white LEDs as a replacement for compact fluorescent, halogen, incandescent and automotive light sources (Electrical Review, 2 February 1999). The global LED market is currently worth around £1.1B and is growing at 15-20% per year. It can be expected that within a few years the use of LEDs as a source of tunnel lighting will become a realistic proposition. LEDs have a life expectancy of 100,000 hours, or around 12 years. With such technology it may be feasible to install a luminaire that requires no internal maintenance.

The potential for the majority of the alternatives outlined above is largely indeterminate at the current stage of development.

Dimming of entrance zone lighting

It is not possible to switch lighting stages on and off rapidly because this would reduce lamp and control gear life and lamps take some 10 minutes to warm up. Problems of short starter life have been reported at the Southwick Hill tunnel, thought to be due to the short switching delay of about 10 minutes. The use of dimmable luminaires coupled to a suitable control system would enable the entrance zone lighting to be altered rapidly to follow more closely the changes in external daylight and avoid excessive energy consumption. Also it would allow lighting level to be altered rapidly in response to actual speeds in the tunnel, for example to reduce levels when low speeds occur during traffic congestion, and rapidly increase levels when speeds increase. It also introduces the possibility of compensation for reduced luminance arising from lamp age and accumulated dirt if light levels inside the tunnel are monitored, and standardising on one size of lamp for a range of design outputs.

Another recent development is the availability of dimmable discharge lamp control gear This allows SON lamps of up to 1000W to be dimmed to 30% of their rated output. This equipment has not yet been used in a tunnel environment, so life expectancy is unknown. The dimmable ballasts could be installed up to 80m from the luminaires with up to 20 units grouped in one sealed enclosure, which would simplify maintenance. With this system luminaires could be smaller and lighter since they would no longer contain a ballast, although a starting amplifier unit is required at the luminaire. Lamp life is also expected to be doubled by using dimmable ballasts.

It will be appreciated that the lighting and the lighting control system are indivisible for the purpose of performing value engineering audits on alternatives. The inclusion of dimming equipment for the SON luminaires would mean that the switchgear to switch between lighting levels would not be needed. The lighting control system design then changes so as to provide a variable output control signal to the dimmable control gear. It is therefore unlikely to be practical to retrofit dimmable control gear to existing tunnel lighting installations, since it represents a significant change to tunnel infrastructure and operations. Such a system should only be considered for new tunnel installations and for the major refurbishment of existing tunnels.

E.6 Value engineering review of alternatives

Use of dimmers for threshold lighting

Very detailed information on traffic speeds is available from the variable speed limit section in the south west sector of the M25. It was hoped to combine this with actual lighting data from one of the M25 tunnels, albeit from a different sector, to make a preliminary evaluation of potential cost savings. Unfortunately due to a change in tunnel operating system it was not possible to obtain this, therefore lighting data was obtained from the Conwy tunnel and was combined with M25 traffic speed data. However this still enables conclusions to be drawn in principle and provides an illustration of the process.

Using this base data four notional lighting scenarios were considered as follows:

i Undimmed. This represents the actual lighting executed during the day with the current arrangement, controlled in stages according to exterior light level. The switching levels and delays are arranged to avoid excessive switching on and off in response to rapid changes of exterior light level, for example during cloudy spells. In this arrangement and for the purpose of this cost comparison a total annual energy cost at the Conwy tunnel is estimated at about £83,000.

ii Optimised. Examination of the actual lighting level suggested that at this tunnel the switching levels and delays may be optimised to reduce the period for which stages remain lit when no longer required. If delays were reduced to 10 minutes the annual energy cost would be about £73,000, representing a saving of 12% of the current estimated costs. However this probably represents an extreme optimisation and might result in reduced lamp and control gear life. In practice optimisation might result in rather lower savings, but the savings can be made with little cost by reviewing the settings at each tunnel.

iii Dimmed. This illustrates lighting power consumption that would occur if dimmers were introduced that enabled lighting level to closely follow that demanded by exterior light level. Savings occur by smoothing the steps and avoiding stages remaining lit when no longer required due to the switching levels and delays. The annual energy cost with this arrangement would be about £62,000, representing a further saving of 13%.

iv Dimmed lighting with speed control. Speed sensors could also be used to control dimmers that also reduce lighting levels when speeds are low in all lanes. Use of this arrangement at the Conwy tunnel, combined with the traffic speed pattern of the M25, would result in an annual energy cost of about £57,000, representing a further saving of 6% from the previous arrangement. However it is thought that the M25 traffic conditions are unique, with high design speed normally requiring high levels of entrance zone lighting and consistently lengthy periods of reduced speed during the morning and evening peaks. This may not be reproduced generally across the network. Also, careful consideration should be given to safety of the system such that at no time are lower lighting levels introduced than required by the speeds: for example consideration should be given to situations of congestion clearing rapidly and traffic speeds increasing.

A typical evaluation over one day is illustrated in Figure E1. Similar evaluations were made on three other days and for both carriageways, and lighting energy costs for these are shown in Table E3 and illustrated in Figure E2. A value engineering review of dimming options is presented in Table E4, which shows marginal savings in whole life cost, but enhanced value from dimmed lighting systems. However it should be noted that the costs of dimming equipment used are a relatively large part of the total cost. This is because this equipment is relatively new and only presently available from one UK source. It is therefore possible that this element of the costs will reduce significantly in the future.

Dimming to compensate for ageing of lamps and changes in wall reflectance

A value engineering review of the use of dimming of base lighting to compensate for lamp ageing and changes in wall reflectance is shown in Table E5. This review assumes that bulk re-lamping will take place every 1½ years. The review is based on the cost of lighting the Medway tunnel, using the loading averaged over 24 hours, scaled up to a 1km length of tunnel.

Lumen output of fluorescent lamps falls steeply from 100% to 90% over the first 1500 hours of use. Between 1500 hours and 10,000 hours lumens fall more gently to 80%. Assuming the required light output corresponds to the above 80% value, dimming may be implemented as follows:

i First 1500 hours: undimmed average light output is 95%. Output dimmed to 84% to give 95% x 84% = 80%. Circuit power corresponding to 84% dimming is about 91% of full load power.

ii Next 8500 hours: undimmed average light output is 85%. Output dimmed to 94% to give 85% x 94% = 80%. Circuit power corresponding to 94% dimming is about 98% of full load power.

iii Remaining 3140 hours to make up 1.5 years: no change.

A feedback control system will be required for each lighting section to measure the actual level of lighting in the tunnel and adjust the dimming accordingly. Note that this would also automatically compensate for any reduction in lighting due to dirt on luminaires and walls.

If dimming equipment were already installed for reducing light levels from daytime to night-time stages, the addition of a photocell and control interface would not be a major task. Retrofitting would cost about £1000 per 50 metre section, that is about £40,000 for the whole 1 km tunnel.

The value engineering exercise shows that the introduction of dimming to compensate for lumen depreciation in lamps in the interior zone is not economic as a retrofit option, even where time–based dimming equipment is already in use. It could be considered as a useful feature for new installations where the additional capital cost over a time-based dimming system would be marginal. However, even in this case the energy savings would be small in comparison to the total energy costs. Similar conclusions are likely in the case of entrance zone lighting, but the relationship between power consumption and light output is not presently known in sufficient detail to make meaningful calculations of cost.

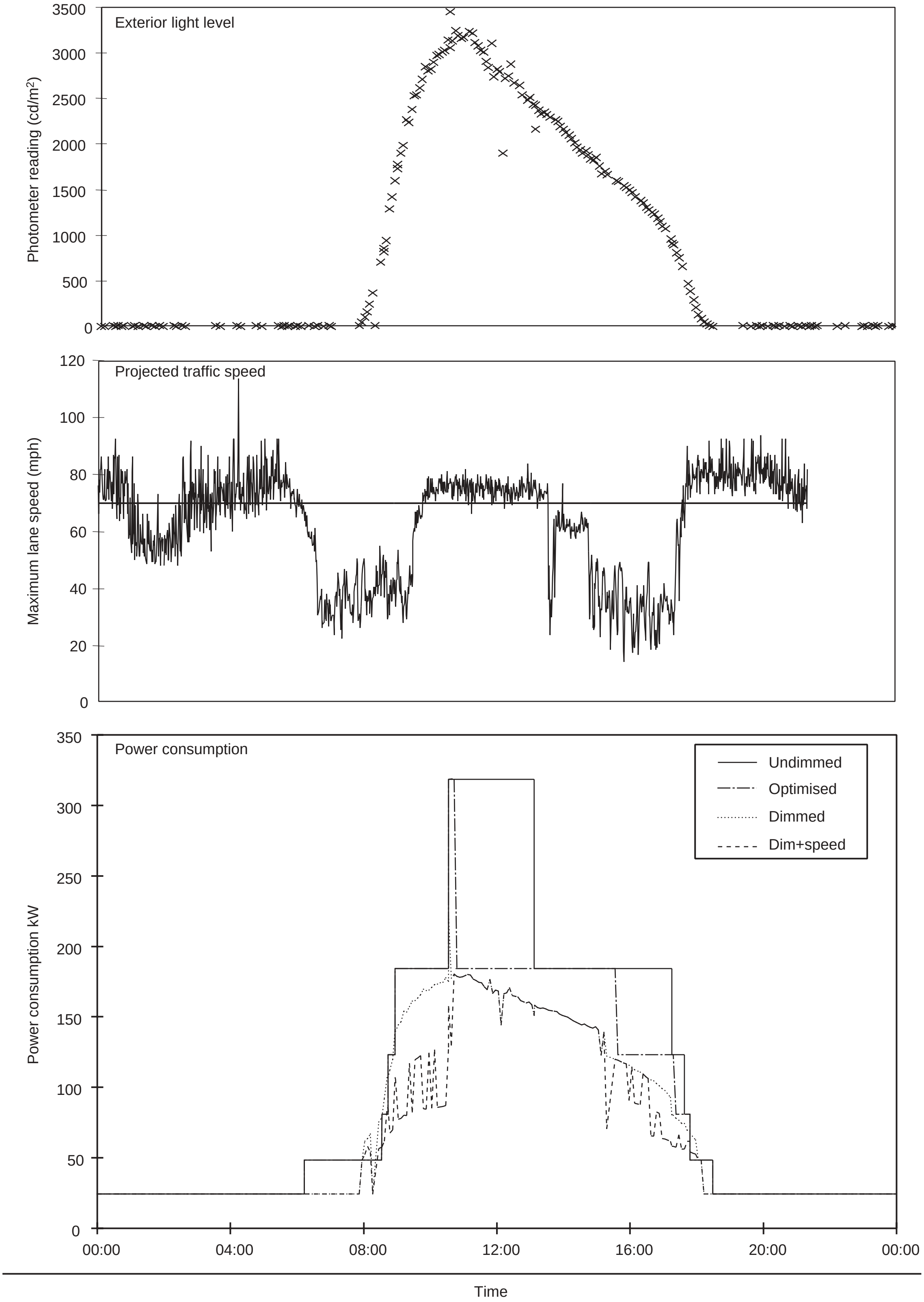

Figure E1 Typical daytime light levels, traffic speed and power consumption (based on M25 data for October 21, 1997)

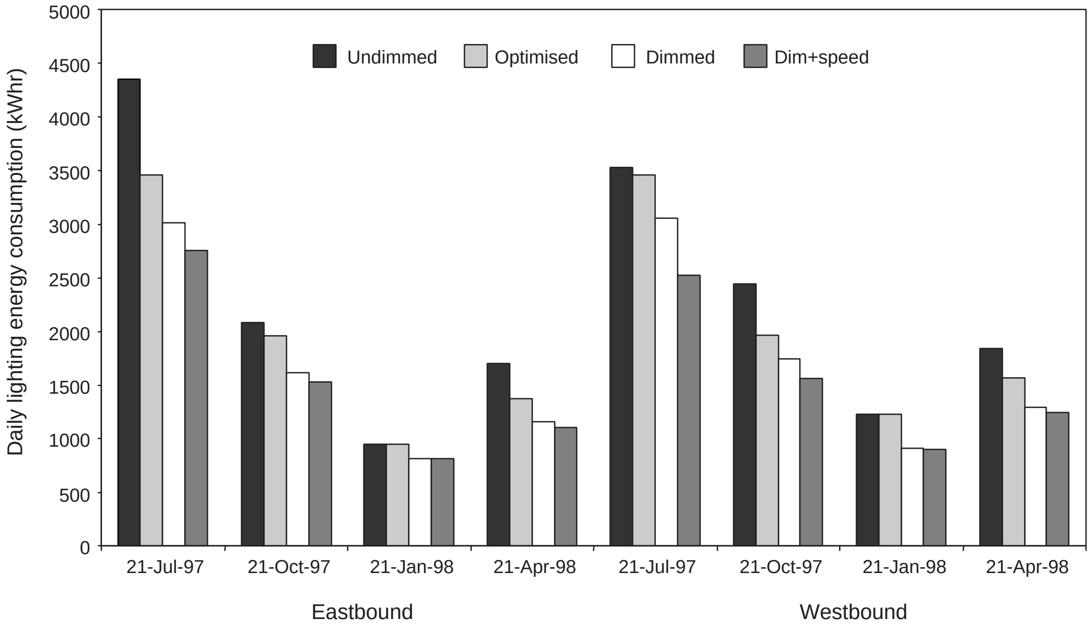

Figure E2 Daily lighting energy consumption

Table E3 Power consumption, costs and savings

		Daily power consumption (kWh)			
		Undimmed	*Optimised*	*Dimmed*	*Dimmed with speed control*
Eastbound					
	21-Jul-97	4350	3458	3013	2758
	21-Oct-97	2082	1957	1614	1525
	21-Jan-98	949	949	821	813
	21-Apr-98	1703	1370	1158	1109
Westbound					
	21-Jul-97	3531	3461	3051	2522
	21-Oct-97	2447	1966	1744	1564
	21-Jan-98	1233	1233	908	902
	21-Apr-98	1841	1568	1293	1251
	Average daily energy/bore (kWh)	2267	1995	1700	1555
	Annual energy cost @5p per unit (£)	£82,743	£72,829	£62,065	£56,774
	Saving on previous option (£)		£9,914	£10,763	£5,291
	Saving on previous option as % of undimmed		12%	13%	6%

Table E4 Value engineering review of entrance lighting

Dimming of entrance lighting	*Function: light tunnel* *Design life: 20 years*		*Existing* *Undimmed*		*Alternative* *Dimmed entrance lighting*		*Alternative* *Dimmed entrance lighting, also traffic speed sensitive*	
Function review								
Objective	*Importance rating*			*Rating (1 to 100)*		*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.25			60		55		50
Sustainability	0.35			50		75		80
Health and safety	0.40			45		45		45
Total weighted score				50.5		58		58.5
Whole life cost								
	Details	*Present cost factor*[1]	*Estimated cost (£k)*	*Net present cost*	*Estimated cost (£k)*	*Net present cost*	*Estimated cost (£k)*	*Net present cost*
Capital	Lighting	1	745	745	745	745	745	745
	Dimmers and control	1			220	220	220	220
	Speed related controls	1					40	40
Maintenance	Annual	11.2	57	638	45	504	50	560
Energy	Annual	11.2	82	918	62	694	56	627
Total present cost				2301		2163		2192
Value ratio (Function/Cost)								
Value ratio ($x10^{-6}$)				21.9		26.8		26.6
Normalised value ratio				1.000		1.22		1.21

[1] *Present cost factors are for a discount rate of 6.0%.*

[2] *For explanation of value engineering review see Section 3.3.*

Table E5 Value engineering review of interior zone dimming to compensate for lamp ageing and wall reflectance

Dimming to compensate for lamp ageing and wall reflectance			*Existing*		*Alternative*	
	Design life: 20 years		*No dimming*		*Dimming*	
Function review						
Objective	*Importance rating*			*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.25			50		50
Sustainability	0.35			50		55
Health and safety	0.40			50		50
Total weighted score				50		52
Whole life cost						
	Interval (years)	*Present cost factor*[1]	*Estimated cost (£k)*	*Net present cost (£k)*	*Estimated cost (£k)*	*Net present cost (£k)*
Capital		1.0			40	40
Energy cost first 1500 hours (16% dimmed)	1.5	7.2	9	65	8	59
Energy cost next 8500 hours (6% dimmed)	1.5	7.2	51	369	50	360
Energy cost remaining 3140 hours (undimmed)	1.5	7.2	19	136	19	136
Total present cost				571		596
Value ratio (Function/Cost)						
Value ratio ($x10^{-6}$)				87.5		86.9
Normalised value ratio				1.00		1.00

[1] *Present cost factors are for a discount rate of 6.0%.*

[2] *For explanation of value engineering review see Section 3.3.*

Appendix F: Pumped drainage systems

F.1 Function and description of system

Most road tunnels incorporate a drainage system to provide containment for extraneous water flows into, and spillage within, a tunnel (and associated carriageway) and to provide a means of removing them from the tunnel. A pumping system is usually only provided if the tunnel construction does not facilitate gravity drainage.

A typical tunnel drainage system comprises a number of sumps. Where the approach roads run downhill into the tunnel portals it is usual to provide sumps located at the portals to intercept surface water that would otherwise enter the tunnel. Further sumps may be located beneath the carriageway at any low points within the tunnel.

Within each sump there are a number of pumps. These are usually specified to be flameproof and submersible. They are normally controlled via level monitoring equipment designed to start a pump when the level in the sump exceeds a specified limit and to stop it when the level has fallen to a (lower) specified limit. If the level continues to rise with one pump operating, further pumps will be switched in until the maximum pumping capacity is reached. A variety of different types of level monitoring equipment is available, including float switches, capacitance probes, ultrasonic and radio frequency probes.

The sump and pumping system should be designed to cope with specific maximum inflow conditions. Typically for a portal sump this should correspond to a 1 in 100 year storm. Because storm water will normally be intercepted before it enters the tunnel, any sumps within the tunnel should be sized to different criteria. The maximum inflow is commonly taken to be the flow of water from two fire hydrants operating simultaneously.

Pump duty cycling is usually achieved by an electro-mechanical relay, and is a means by which the run times for a number of pumps, situated within the same sump, can be equalised. It is usually interposed within the local pump control systems. Following the completion of a pumping cycle, the pump duties rotate so that the next pump in turn is the first to operate the next time there is a pump demand.

In addition to normal water flows, the design of the pumping system is also required to facilitate the safe handling of an accidental spillage on to the carriageway. It is not uncommon for petrol or diesel fuel to be spilt on to the carriageway during a road traffic accident. Tunnel sumps are usually equipped with gas detectors, to detect spillage of petrol and an inert gas foam blanketing system that discharges into the sump automatically should flammable gas concentrations exceed a safe level. This is discussed further in Sections G.1 and L.1. Environmental legislation forbids the discharge of noxious substances into the environment. Any such spillage into a sump must be contained and dealt with in the appropriate manner. With current technology this requirement can only be sensibly achieved by the use of remote monitoring using instrumentation and closed circuit television to enable an accurate assessment of any incidents to be made without delay.

F.2 Description of maintenance procedures

The maintenance requirements for pumps are typically defined at 3 monthly, 12 monthly and 5 yearly intervals. For each of the periodic pump maintenance activities it is necessary to gain access to the pumps. Since the sumps are confined spaces an access procedure, which complies with the Confined Spaces Regulations 1997, is necessary. In addition to pump maintenance, maintenance of other sump equipment such as pipework and valves is scheduled for the same time, thus reducing mobilisation overheads.

The 3 monthly maintenance activity typically comprises a visual inspection of the pumps, conducted with the pump in its operating location. The 12 monthly maintenance activity entails removing the pumps from the sump and conducting a limited internal inspection of each pump. The 5 yearly maintenance activity entails replacing each duty pump in turn with a spare and sending the duty pump to a certified workshop for a complete overhaul.

All of the above maintenance tasks should be capable of being carried out during routine single bore closures. However, where a sump receives inflow from both bores, there is a very remote possibility that a spillage in the open bore may present a hazard to staff carrying out maintenance in the other bore, and appropriate procedures must be instituted to manage this risk.

The maintenance requirements for direct-on-line (DOL) and Star-delta starters are similar to those required for general electrical equipment, and are defined at similar intervals, see Section O.2.

The maintenance of pump duty cycling systems, sump level control equipment and sump level monitoring equipment is usually conducted as a part of pump control panel maintenance, for reasons of efficient maintenance scheduling. Typical procedures at 3 monthly and 12 monthly intervals are described in Section O.2.

F.3 Costs

Table F1 gives representative costs for operations at various maintenance intervals for a typical sump containing three pumps.

Table F1 Typical sump maintenance costs (1998 prices)

Maintenance period	*Maintenance cost per sump (£)*
3 months	55
12 months	1030
5 years	6560

F.4 Issues

The personnel required to perform routine 3 monthly activities do not need to be specialists in the maintenance of flameproof equipment. Thus, a general mechanical and electrical contractor can train his own staff to perform these tasks correctly. Such a strategy reduces maintenance costs as the mobilisation costs for specialised pump maintenance contractors is usually much higher than for general mechanical and electrical contractors.

Most pump control systems comprise standard electrical control components that have been developed over many years. In particular, the use of electro-mechanical relays for pump duty cycling must now be considered to be old technology. Many motor starters combine additional safety features within them, for example built in overload protection and automatic no-volt protection. Features such as these can be expected to be developed further and greater use should be made of integrated electronic protection, to replace electro-mechanical devices.

Tunnel sumps are often of irregular shape; thus the most useful measure of level within such sumps may be the percentage of the sump volume that is filled. It is thus important that sump level monitoring systems are specified to be capable of volumetric calibration. Such systems can then be accurately calibrated to provide sensible measurements to the tunnel operator and to provide a pump level control function.

F.5 Alternatives

Dual mid-tunnel sumps

For sub-aqueous immersed tube twin bore tunnels, such as the Conwy, Medway and Lee tunnels, it is usual to construct mid tunnel sumps as chambers common to both tunnel bores. This is normally achieved by interconnecting sump chambers beneath the carriageways in each bore by a number of pipes. It is understood that this strategy is adopted in order to obtain the desired minimum sump volume in a cost-effective manner. As a consequence, if a spillage does occur it will have an immediate effect on both tunnel bores and can necessitate the immediate closure of both tunnel bores which can result in significant traffic disruption. A further consequence of this design is the possibility of ‘pressure piling’, if a sudden build-up of flammable gas is ignited before an effective foam blanket can be established. Pressure piling occurs when an explosion in one chamber causes a shock wave to pressurise the gas in a second chamber prior to explosion in the second chamber. The consequence of pressure piling is that the severity of the explosion which occurs in the second chamber is greatly increased.

Separate sump chambers for each tunnel bore would eliminate any risk of pressure piling and would facilitate the operation of one bore in contraflow whilst a spillage in the other bore was attended to.

Dual outflow pipes from mid-tunnel sump

It is common to design tunnel sumps with only one outflow pipe. With this arrangement any significant problem with the outflow pipe will have an immediate effect on the safe operation of the tunnel and could result in tunnel flooding with attendant major disruption to traffic. The provision of dual outflow pipes from the mid-tunnel sump would reduce the risk of delays to traffic, and allow remedial works to be scheduled on a planned basis.

Dry well

Alternatives to established tunnel pumping systems usually comprise variations on the engineering implementation of the scheme. It is possible to adopt a separate pump and motor (dry well) arrangement such that the motor is not submersed. This arrangement usually results in a larger civil engineering component to the scheme and therefore greater capital cost, however, maintenance may be easier and safer with a resulting benefit in whole life terms.

Use of soft starters for pumps

Tunnel pumps are usually started and stopped via direct-on-line (DOL) starting (for smaller pumps), or via Star-delta starters (SDS) for larger pumps. Typical control systems are designed to start and stop the pumps automatically in accordance with the level in the sump. Although pump sizes will have been optimised to minimise the number of stops and starts, certain inflow conditions may require the pumps to be started and stopped many times per day. The impulse load that occurs when starting electrical machines causes significantly more wear within the machine than occurs during steady state running. The use of ‘soft starters’ to gradually accelerate such machines has been found to significantly reduce starting transients and associated wear. By limiting starting currents, economies in the size of the associated power supply cabling may also be possible. But the maintenance requirements associated with the use of variable speed controllers and soft starters are greater than for existing DOL or SDS designs.

Use of condition monitoring for pumps and pump motors

Pump motors are usually squirrel cage induction machines. The condition of these types of motors can be assessed by a variety of established condition monitoring techniques, such as line current spectral analysis, without the need to remove the pump from the sump. Generally, a maintenance strategy based on the condition of the pump/motor assembly, rather than on manufacturers’ recommended intervals, can be developed through the application of condition monitoring.

Many tunnel pumping systems are based on the provision of three pumps within a sump. This level of provision allows for one pump to be out of commission whilst maintaining two pumps available for use. It may be that the same level of system reliability that is achieved by using 3 pumps could be achieved by the use of proactive maintenance systems, including condition monitoring to support two pumps. However, in the case of sumps located within the tunnel it may not be considered appropriate to act immediately on the information provided by condition monitoring which might require an unscheduled tunnel closure to effect repairs. In this scenario reliance must be placed on only one pump until the next scheduled access, which might not be acceptable.

Use of electronic duty cycling controls

A small programmable electronic device, such as a small programmable logic controller (PLC), could provide the pump duty cycling function. The adoption of such devices would increase the reliability of the duty cycling system and reduce the maintenance costs. However, overall savings would be small, because of the relatively low capital and maintenance costs involved.

F.6 Value engineering review of alternatives

Condition monitoring

The general discussion and conclusions relating to condition monitoring of jet fans is also applicable to pump motors, see Section D.5. However in the case of pumps there are potentially greater savings in maintenance because they are located in potentially hazardous confined spaces, and need to be removed and partially dismantled for any mechanical checks to be made. Pumps have the additional drawback that it is normally not recommended to allow them to run dry, and therefore checks with the motors running would have to be made in situ in the sump.

Table F2 shows a value engineering review of condition monitoring for pump motors. It compares three options: three pumps per sump with three monthly inspections, three pumps per sump with condition monitoring and two pumps per sump with condition monitoring. Costs of three monthly inspections of pumps are about 30% more than for fans, but the task includes a greater number of items not associated with the motors themselves, such as the functional checking of level detectors and controls. When these are taken into account, the costs of checking fans and pumps in isolation are likely to be comparable. The costs of installing a condition monitoring system for pumps is also likely to be comparable to that for fans.

The review shows a small benefit from the use of condition monitoring on a three pump system. It also demonstrates that much larger benefits could be gained from a two pump system with condition monitoring (assuming that the operational risks associated with such an arrangement were acceptable).

Table F2 Value engineering review of condition monitoring for pumps

Condition monitoring of pumps			*Existing*		*Alternative (1)*		*Alternative (2)*	
	Design life: 20 years		*No condition monitoring*		*Condition monitoring*		*Condition monitoring*	
			9 pumps		*6 pumps*		*9 pumps*	
Function review								
Objective	*Importance rating*			*Rating (1 to 100)*		*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.25			50		65		75
Sustainability	0.35			50		65		60
Health and safety	0.40			40		50		55
Total weighted score				46		59		62
Whole life cost								
	Interval (years)	*Present cost factor*	*Estimated cost (£k)*	*Net present cost (£k)*	*Estimated cost (£k)*	*Net present cost (£k)*	*Estimated cost (£k)*	*Net present cost (£k)*
Capital cost of monitoring		1.00			11	11	16	16
Additional pumps		1.00	18	18			18	18
Maintenance (quarterly)	0.25	46.59	0.36	17				
Total present cost				35		11		34
Value ratio (Function/Cost)								
Value ratio (x10^{-6})				1320		5620		1830
Normalised value ratio				1.00		4.25		1.38

[1] *Present cost factors are for a discount rate of 6.0%.*

[2] *For explanation of value engineering review see Section 3.3.*

Appendix G: Fire protection systems

G.1 Function and description of system

Fire extinguishers

The function of tunnel fire extinguishers is to provide the vehicle driver with a means of fighting a small vehicle fire. Tunnel fire extinguishers are usually provided within the chambers of tunnel emergency panels. They would contain either a dry powder extinguishant, suitable for fires involving carbonaceous solids, flammable liquids and flammable gases (classes A, B and C), or aqueous film forming foam (AFFF), suitable for carbonaceous solids and flammable liquids (classes A and B) only.

Fixed fire fighting equipment

Fixed tunnel fire fighting equipment is intended for use by the fire services, or suitably trained fire fighting teams, in the event of a tunnel fire. It usually comprises reel-mounted hoses permanently plumbed to the fire hydrant water main. If a fire occurs within the tunnel the fire-fighting team do not have to deploy and connect their own hoses, thus minimising site mobilisation time prior to attacking the fire.

Fire hydrant water main

The function of the fire hydrant water main is to provide a source of water for fire fighting within the tunnel and tunnel approaches. The fire hydrant water main usually comprises a 200mm cast iron water pipe, charged to a pressure of at least 4 bar. The fire main may also comprise part of the local potable water distribution main.

Nitrogen foam flooding system

The function of a nitrogen foam flooding system is to exclude air from the liquid surface to prevent the risk of an explosion in a sump. It is normally triggered by gas detectors (Refer to Section L.1) to operate before the lower explosion limit (LEL) is reached, or by heat detectors.

The system usually comprises a number of nitrogen gas bottles, a foam generating set, a control system and a number of foam-generator nozzles. The foam-generator nozzles are installed within the sump to discharge nitrogen foam on to the liquid surface within the sump. They are connected to the foam-generating set by pipework. When the control system receives a discharge signal from the gas detection system (or its own heat detection system) it causes the nitrogen to be discharged into the foam-generator set and foam generation to start. The sump pumps and ventilation system are then automatically disabled. The system continues to discharge until all the nitrogen bottles have emptied. The system generates a foam blanket that lies across the top of the sump, preventing an explosive environment from occurring. The system is designed such that the nitrogen bottles continue to discharge for 10 to 15 minutes following completion of the foam blanket. This ensures that the environment within the sump is made fully inert.

The foam blanket will eventually break down, typically after an hour, depending on the other substances present. Inflow of water can accelerate this process. Facilities are normally provided for the fire brigade to inject additional foam into the sump to maintain the foam blanket.

Automatic gas discharge fire extinguisher

Rooms within the tunnel service buildings containing safety related equipment are normally equipped with automatic gas discharge fire extinguisher systems, to limit the effects of any fire that may occur. These rooms are typically the high voltage and low voltage electrical switchrooms, battery room and computer/communications equipment room.

The oldest systems may still be designed to use Halon gas, now prohibited from new installations. More recent installations may use carbon dioxide (CO_2). The most recent are likely to use synthetic gases based on a nitrogen/argon mixture which has the advantage of being breathable in limited quantities.

G.2 Description of maintenance procedures

The maintenance intervals for both fixed and portable fire extinguishers are given in BS5306. The maintenance procedures for fixed tunnel fire fighting equipment depend upon the exact equipment concerned. The majority of the maintenance comprises functional checks to ensure the system works, that hoses are intact and free from damage, that nozzles are present and that reels and valves work correctly. Reel mounted hose pipes should be thoroughly flushed out. Such checks would usually be performed at 3 monthly intervals. There may be a requirement to periodically replace hoses with new ones.

The maintenance of the fire hydrant water main should include checks on the hydrants and on the isolator valves. These typically include at 3 month intervals test of valve operations and checks for leakage with and without blanking caps in position. At 5 yearly intervals overhaul of valves will be in accordance with manufacturer’s instructions.

The maintenance of the nitrogen foam flooding system should typically includes 3 monthly checks that: all panels are clear of alarms, all bottles are in place, secure and at the correct pressure, and all connectors and earthings are free of signs of corrosion, damage or overheating. A test firing of the system should be carried out with a purging of foam in accordance with the manufacturer’s instructions at intervals of 12 months.

G.3 Issues

Fire extinguishers

The discharge of a dry powder fire extinguisher within a tunnel causes a cloud of particles of such density that visibility within the tunnel can be totally obscured. The inappropriate discharge of such extinguishers can cause a severe hazard to traffic. Hazards to traffic can also arise from the inappropriate use of fixed fire fighting equipment.

Fire hydrant water main

If a fire hydrant water main also serves as a part of the local potable water supply, the tunnel operator must have procedures to ensure adequate fire fighting capability in the event of a supply failure or reduction in pressure. In particular, mutually agreed procedures with the water supply company must be established such that the tunnel operator receives advanced notification prior to any maintenance activities that may compromise the supply.

Nitrogen foam flooding system

Nitrogen foam generator sets usually rely upon bottles of nitrogen sited adjacent to the generator set. The nitrogen bottles are usually very heavy and difficult to install. Great care must be taken to ensure that the interconnecting pipework is secure and does not leak. Special working procedures during the maintenance of such systems includes the wearing of eye protection. The nitrogen bottles are charged to a pressure of 175 bar. The consequences of a traffic accident resulting in severe damage to the nitrogen bottle enclosure and displacement of the bottles are extremely serious. The injuries and damage resulting from such an accident could be substantially greater than those normally expected in a traffic accident.

The maintenance works associated with the nitrogen foam system include an annual test discharge. Care must be taken to ensure that no one is within the sump when this test is conducted. Following completion of this test the sump should be completely ventilated and oxygen tests conducted to ensure a breathable atmosphere prior to any one being permitted to enter the sump.

Fire service personnel will be able to respond more effectively to an incident in a particular tunnel if they are thoroughly conversant with the exact equipment in use. Suitable opportunities should be provided, during planned maintenance tunnel closures, to enable them to make periodic familiarisation visits.

Tunnel sumps are provided with an additional foam inlet for use by the fire services. The type of foam used within the foam-generating set must be compatible with that used by the local fire service. Certain foams are incompatible and contact between these different types of foam results in early degradation of the foam.

If there are constant water flows into the tunnel (perhaps caused by a breach in the waterproofing around the tunnel) the tunnel sump will require frequent pumping out. The resulting high flow rates into the sump serve to reduce the effective life of a foam blanket, as the rising level within the sump will quickly cause the foam blanket to be breached. The tunnel operator must have procedures in place to manage this eventuality.

G.4 Alternatives

Fire extinguishers

There appears little alternative to the use of fire extinguishers within tunnels. It may be more appropriate to use an AFFF extinguisher rather than dry powder to avoid the dangers posed by inappropriate use. Gas discharge extinguishers containing carbon dioxide or FM200 could also be used, but because of the pressure of the discharge and very low temperature of the nozzle they can be hazardous to the user if used inexpertly.

Fixed fire fighting equipment

The value of providing of fixed fire-fighting equipment (e.g. hose reels) is related to the methods of working of the local fire service. The current alternative to its provision is the use of the fire services own equipment.

Nitrogen foam flooding system

The nitrogen bottles used within nitrogen foam flooding systems could be sited at a location not susceptible to vehicular impact damage, for example in a service bore if provided. However the pipework and associated engineering would be more complex and might increase the whole life system costs.

Sprinkler type systems

Following the recent serious fires in the Mont Blanc and Tauern tunnels, there has been widespread discussion of the potential of sprinkler type systems to quickly control a tunnel fire before it spreads, and to cool air sufficiently for people to escape. Such systems have generally not been recommended because of concerns that:

- they may destroy stratification of smoke overlying clear air;
- a fuel or oil fire may be exacerbated;
- most fires occur within a vehicle and so the seat of the fire cannot be directly targeted by sprinklers;
- chemicals may be present that react adversely with water;
- stream may scald people at some distance from the fire;
- discharge over moving traffic may introduce additional hazards.

Some of these problems may be addressed by water mist or foam systems but further work is being undertaken to review systems for rapid detection and suppression of fires.

Appendix H: Communications: telephone systems

H.1 Function and description of system

The provision of telephone systems varies from one tunnel to another, and historically has been determined largely by the requirements of the tunnel operator and the local police and fire authorities.

Up to three separate systems may be provided, fulfilling the following functions:

i An emergency telephone system (ETS), to enable the public to summon assistance in the event of an incident.

ii A smoke control telephone system, to enable the fire brigade to communicate between one end of the tunnel and the other.

iii An internal telephone system, for use by maintenance staff.

Increased use by maintenance personnel and emergency services of hand-held and vehicle mounted radios or mobile telephones has rendered the latter two systems largely obsolete, provided that suitable radio relay facilities are available to maintain radio communications within the tunnel.

The ETS provides reliable communications between specific locations within the tunnel (such as emergency panels and smoke control panels) and a remote location. The latter may be either the tunnel control room (for manned tunnels) or the local police control centre. The ETS comprises a number of telephone instruments installed within accessible and clearly marked cubicles, frequently within the tunnel emergency/distribution panels. Each of the telephone sets is connected to an outstation concentrator unit and thence via a trunk line to the instation and answering panel at the control centre. Emergency telephones are provided with a flashing light above the cubicle to give visual notification of an incoming call. This is necessary because a ringing tone would not be audible above the relatively high ambient noise level in the tunnel caused by traffic motion and tunnel plant.

H.2 Description of maintenance procedures

Ideally testing all aspects of operation of the emergency telephones should be carried out at intervals of 1 week, and of other telephones at intervals of 3 months. However because of access limitations testing is frequently limited to planned tunnel closures. The telephone should be cleaned and inspected for defects and correct number labelling at the same time as testing. At intervals of 1 year any battery supplies to telephones should be tested, and at intervals of 2 years the batteries should be replaced.

H.3 Maintenance costs

Table H1 presents maintenance cost data for the emergency telephone systems in three of the tunnels that are listed in Table C1.

Table H1 Maintenance costs (1998 prices) for emergency telephone system

Tunnel		*A*	*B*	*C*
Breakdown of equipment served				
Emergency telephones	No	35		35
Breakdown of maintenance cost				
Emergency telephone system	£k	11.375	9.16	13.65

H.4 Issues

Emergency telephones by definition are used under exceptional circumstances. However they need to be 100% operational when required. The only way to ensure with total certainty that an emergency telephone is functioning is to live test it frequently, but very regular tests may be impractical and costly. However, the successful testing of any telephone that is connected to the same outstation unit as the tunnel telephones will give the tunnel operator confidence that the outstation unit is functioning correctly, although the speech paths to and from individual tunnel telephones have not been tested.

Commonly, the complete emergency telephone system will be a bespoke set of equipment produced by a low volume manufacturer. Over the expected life of the system, expertise and support for such systems can be expected to diminish, as technology changes, and the tunnel operator may experience problems with maintenance support. The level of service that such a system can provide will quite quickly appear to be antiquated, as improvements in technology become common place.

Smoke control and internal telephones are largely redundant because of alternative means of communication.

H.5 Alternatives

Alternatives to existing ETSs involve changes to the detailed engineering of the installation. The incorporation of remote test facilities on the tunnel phones to provide the ability to feed test tones along the speech path from instation to outstation to tunnel phone and back again would greatly increase the tunnel operators confidence that the system is working correctly. If the off-hook switch was replaced by encapsulated reed switches, and the off-hook facility was achieved by incorporating a magnet into the phone handset there would be great confidence that the system would correctly function when so required. Such test facilities would provide far greater confidence that the ETS was working correctly and reduce the number of special tunnel accesses required to investigate alleged ETS failures, with an attendant reduction in traffic delays.

Where possible the ETS should consist of standard products from a recognised volume manufacturer of telecommunications equipment. This would tend to greatly reduce the capital and maintenance cost of ETSs. Consideration should be given to using a modern feature-rich private automatic branch exchange (PABX) that would provide most of the basic functions of the ETS and provide additional facilities such as built in call logging etc. Additional test features could be added to this basic system to provide a cost-effective ETS.

Appendix I: Communications – radio relay systems

I.1 Function and description of system

Tunnel structures tend to block radio communication between the tunnel interior and the outside world. Communication is typically lost about 50 metres in from either portal. Radio relay systems provide continuity of radio coverage for hand-held and vehicle mounted radios for the whole length of the tunnel.

A radio relay system is designed to handle specific radio channels and typically serves, as a minimum, radio channels used by the police, fire and ambulance services, when responding to incidents. Each organisation may use a number of fixed radio frequencies, or channels, within the tunnel. This requirement may be satisfied by the provision of separate transmitters and receivers for each channel or a more complex base station arrangement capable of intelligent channel selection.

Some tunnels also provide a relay service for the tunnel operator/maintainer, commercial or BBC radio channels and mobile telephone service providers.

A typical tunnel radio relay system comprises a leaky feeder antenna through each bore of the tunnel, linked to a number of transceivers in a tunnel service building. A leaky feeder antenna is a specially constructed coaxial cable installed along the length of the tunnel that acts as a wide band distributed antenna system, allowing radio frequency (RF) signals to leak in or out of the cable along its length. An alternative to the leaky feeder is a series of discrete antennae along the length of the tunnel. If the tunnel portals are located in cuttings, it may also be necessary to provide ‘Yagi’ antennae outside the portals to give sufficient radio frequency coverage on the approach ramps. In order to reduce the number of leaky feeders or other antennae it is normal to combine the output of the transmitter and the input to the receiver onto a single cable. A pre-requisite for this is a split frequency channel arrangement. A diplexer must be added between the coaxial feeder cable and the transmitter and receiver to block high power transmissions that would otherwise damage the receiver circuitry. The radio communication equipment that will actually be operated within the tunnel will typically be medium power (approximately 25 Watt ERP) vehicle radios and lower power (2 Watt to 5 Watt ERP) hand held radios.

For optimum signal quality the transceivers are normally linked to the appropriate users’ remote base stations by land lines, so that the tunnel system behaves as an additional transmitter/receiver on the local area wide communications network. In cases where a land line connection to the tunnel service building is not feasible, an external antenna may be located in the vicinity of the tunnel to receive transmissions ‘off-air’ and rebroadcast them inside the tunnel. However, this method rarely gives satisfactory performance because of the problem of feedback between external and internal antennae.

The transmitter and receiver that comprise a single channel operate on different radio frequencies (the reverse of the frequencies that the mobile radio uses) so that the system can operate in ‘full duplex’ or ‘talk through’ mode, where the transmitter and receiver operate simultaneously. This provides point to point communications between two users within the tunnel by re-broadcasting the received signal.

I.2 Description of maintenance procedures

Radio relay systems are designed to operate at remote unmanned locations and maintenance requirements are therefore minimal. The equipment is often designed such that cabinet ventilation fans are not required. In order to ensure that the systems are functional and available for use, a weekly on-air test of all channels for acceptable speech quality is recommended. On an annual basis it is necessary to check the acceptability of system frequency accuracy, transmitted power levels, receiver sensitivity and selectivity, and transmitter output and audio levels to and from the control centre.

I.3 Issues

It is important that the radio relay systems are specified so as not to cause interference to or be susceptible to interference from other items of tunnel equipment. The same arguments apply to other items of tunnel equipment in that they should not produce unacceptable levels of radio frequency interference that may compromise the operation of the radio relay systems.

The equipment cost to provide radio coverage in the tunnel can be high. Users could share common equipment, rather than providing a number of standalone systems, although the risk of common mode failure increases.

The testing of every channel can be a logistical problem. For example, the police may be unable to carry out frequent on-air radio checks but may also be unwilling to allow the tunnel operator access to a police mobile transceiver in order to undertake the checks on their behalf.

There is no alternative to regular maintenance checks of radio equipment. The Radio Communications Agency is the authority responsible for management of the radio spectrum. They would take action against an organisation that was causing radio interference due to lack of maintenance of their radio equipment. By initially purchasing equipment of a proven quality and stability from a reputable source, the maintenance can be kept to a minimum.

In order to have confidence that the systems are 100% available for use a set of equipment that self-tests and provides permanent test tones down all audio paths should be specified.

During a tunnel incident the noise levels from ventilation fans, fire engine water pumps, vehicles etc is so high that audibility of the radio relay transmissions can be a problem. Such problems may be overcome by building headphones and microphones into the protective helmets worn by members of the emergency services.

I.4 Alternatives

The alternatives to current radio relay system designs are expected to result from technology advances in the field of digital electronics.

The inclusion of a text transmission system as a part of the radio relay system would assist in the transfer of information during a tunnel incident in conditions of high background noise.

Appendix J: Communications – CCTV systems

J.1 Function and description of system

The function of the closed circuit television (CCTV) systems is to provide video coverage of the inside of a tunnel and the tunnel portal and maintenance crossover areas for traffic monitoring, assessment of incidents and general observation of the structure.

A tunnel CCTV system is a bespoke configuration of proprietary components, designed to satisfy the requirements for a particular site. The CCTV cameras are installed inside weatherproof housings, and may be equipped with pan, tilt and zoom (PTZ) facilities. Inside the tunnel, cameras are mounted clear of the traffic space on brackets attached directly or indirectly to the lining. Outside the tunnel cameras are usually mounted on top of a high rigidity mast. Some such masts are equipped with camera raising and lowering equipment, to facilitate maintenance access to the camera assembly. Other lighter duty lattice structured camera poles are designed with a hinged section to allow maintenance access to the camera assembly.

The video output from the camera can be transmitted to the control centre by various means, and via a number of intermediate transmission stations. For some installations the transmission media may be fibre optic cabling. These transmission systems may either be single channel (only transmitting the output from one camera) or multi-channel (typically transmitting the output from 12 or 24 cameras). For other installations, it may be appropriate to wire directly from the camera, using high quality co-axial cable to the control centre or to an intermediate site.

It is also possible to transmit colour CCTV pictures over a twisted pair of audio cable, by using proprietary launch amplifiers and receivers. It is common to have to ‘correct’ the video signal after it has been transmitted over such media owing to the differential frequency spectrum loss from the video signal.

For some applications it may be appropriate to digitise and compress the video signal and transmit it over a digital transmission network to the control centre. Again, some loss of picture quality may be expected due to the limited bandwidth of available equipment.

When the video signals arrive at the control centre they are commonly fed into a video matrix, which allows any of the input signals from the cameras to be switched to a defined monitor. There is a control system associated with the video matrix that facilitates the selection of each of the camera inputs, and may include features such as automatic sequencing of pictures and display of a selected scene on receipt of an alarm signal (for example from opening of an emergency door). The control system also interfaces with each of the CCTV cameras, via the transmission system, such that signals can be sent to the camera to control pan, tilt and zoom and camera wash/wipe facilities.

J.2 Description of maintenance procedures

The detailed maintenance procedures depend on the particular type of cameras in use. Servicing, cleaning and testing of a typical modern charge coupled device (CCD) type camera system will be carried out at intervals of 6 months and may involve removal of the camera to the workshop.

J.3 Maintenance costs

Data from three tunnels (A, B and C, listed in Table C1), which each had either five or six cameras per bore, showed that the mean cost of annual maintenance per CCTV camera was approximately £1100 at 1998 prices.

J.4 Issues

Older CCTV installations may use tube based cameras, which suffer from relatively poor image quality and low light performance. Camera technology has advanced rapidly over the past few years, particularly with the introduction of charge coupled devices (CCDs) for reception of images. Low light performance has vastly improved and the cost differential between colour and monochrome systems has reduced to the extent that monochrome is now rarely specified. The additional visual information available from colour cameras is most useful for tunnel safety monitoring and enables better identification of vehicles.

It is important to ensure that tunnel cameras are supplied with electricity from the UPS supply to ensure continuity of safety surveillance during mains-power supply failures.

The pan and tilt heads are generally sealed long life items that only require external cleaning. The exception to this is when additional components are fitted inside the pan and tilt heads. Such components may include orientation feed back systems, sometimes based on potentiometers, that provide signals which define the 3 dimensional orientation of the pan and tilt head platform, and hence the camera. If such facilities are provided it is necessary to remove the pan and tilt head to inspect these components.

The majority of CCTV camera transmission systems are based on analogue transmission technology. In order to multiplex camera signals on to a single fibre the multiplexer must operate at up to 500MHz for a 12 camera installation and up to 1GHz for a 24 camera installation. Analogue transmission technology of this type is susceptible to distortion from a number of different sources. If the video signal level in a channel within the system exceeds specification, intermodulation distortion can occur as the harmonic component of the signal starts to interfere with signals in higher channels.

Access to the bottles containing fluid for wash/wipe facilities is normally very difficult, and in practice the effectiveness of the wash function is not always very good.

Location of cameras at high level in tunnels is necessary to give a good view under normal traffic conditions. However, being close to the ceiling they will quickly become obscured by smoke in the event of a fire and should not therefore be relied upon for use under fire conditions.

J.5 Alternatives

The cost of CCD based cameras has fallen considerably owing to mass production. It may now be possible to increase the number of cameras within a tunnel and omit the requirement for pan and tilt heads. This would result in cost savings for the pan and tilt heads and for the associated camera control boards and control transmission systems. Such a system would require cameras to be mounted to view traffic in both directions to facilitate monitoring under contraflow conditions. However there is significant benefit to the safe operation of a road tunnel by having PTZ facilities available on a tunnel camera which enable the operator to focus on incidents within the tunnel. A mixture of cameras with PTZ facilities and fixed cameras would probably cost a similar amount to an existing installation and would provide a more resilient overall CCTV infrastructure. Pan and tilt heads are reliable established technology. Alternatives would be in the detailed engineering (use of different materials etc) rather than in the concept.

The output from CCD cameras is a standard 1 Volt peak to peak video signal. CCD cameras are inherently digital devices. It is possible for the output to be a standard digital video signal (for example MPEG II) and for the subsequent transmission also to be digital. This would eliminate the traditional analogue transmission problems (such as inter-modulation distortion, phasing etc). The reduction in system component count would result in a higher reliability, lower cost system with consistent picture definition. Furthermore a change to digital camera outputs and a digital transmission system would enable video pictures to be transmitted to any location served by a high-speed digital communications system. Limited quality pictures can be transmitted via a telephone line. Such a facility would enable remote viewing of camera images by a specialised emergency service (such as the National Chemical Emergency Centre, or Bomb Disposal) in the event of a serious tunnel incident requiring specialised emergency resources.

Automatic incident detection

The advent of powerful, cheap computing and image processing software has made possible the concept of drawing operator’s attention to tunnel incidents automatically. Such a system could for example use CCTV cameras to detect stationery traffic and either alert an operator or automatically turn traffic signals to red. However the benefits and reliability of such a system is not proven in comparison to a system using detector loops on the road surface.

Appendix K: Traffic control – tunnel VMS systems

K.1 Function and description of system

The function of a tunnel variable message sign (VMS) system is to provide a means of indicating to motorists that a tunnel lane is closed, that a tunnel is closed completely, that a tunnel is in contraflow or any combination of the above.

Variable message signs associated with tunnels are generally of two types: matrix or rotating prism. Matrix signs are used as lane control signs at tunnel portals and in the tunnel interior to indicate lane availability or closure by means of a matrix of coloured points of light forming green arrows or red crosses. Older types use an array of coloured lamps to give the required indications. More recent designs are based on fibre optic technology to reduce the number of light sources required. Rotating prism signs are used to display more complex messages relating to tunnel closures and diversions and because of their larger size are rarely used within tunnels but are post or gantry mounted on the tunnel approaches. Small rotating prism signs are, however, sometimes used within tunnels to indicate speed restrictions, where these are variable.

A typical VMS system will include internally illuminated tunnel signs, internally illuminated post mounted and gantry signs, and a number of different types of rotating prism signs. Each of these different signs has a different maintenance requirement.

Tunnel VMS systems vary significantly within their detailed designs. They generally comprise a number of sub-elements, combined together to form a bespoke configuration for the particular tunnel complex. The roadside and/or gantry mounted signs are manufactured by proprietary variable message sign manufacturers, and are controlled via a local control box. The local control box also contains additional facilities such that the sign can be controlled from a remote location via a local electronic controller / sign driver. At the remote location, additional equipment is provided to facilitate the remote control. It is common for the signing control system to be a based on industrial microprocessor technology, configured and programmed in accordance with system requirements.

K.2 Description of maintenance procedures

Owing to the wide variety of different designs it is inappropriate to consider the maintenance requirements for the control system in detail. The variable message signs are the system elements that require the most maintenance.

Typical maintenance requirements for internally illuminated gantry and post mounted signs are a weekly inspection of operation and for defects. An internal inspection is normally carried out at intervals of three months. Typically at intervals of six months bulbs should be replaced and at intervals of one year mechanical and electrical equipment is serviced.

K.3 Maintenance costs

Table K1 presents maintenance cost data for the emergency telephone systems in three of the tunnels that are listed in Table C1.

Table K1 Maintenance costs (1998 prices) for VMS system and instation equipment

Tunnel		*A*	*B*	*C*
Breakdown of equipment served				
Tunnel signs	No	40	14	24
Gantry signs	No	28	4	19
Prism signs	No		23	33
Breakdown of maintenance cost				
VMS system	£k	14.625	11.7	17.55
In-station equipment	£k	6.5	5.2	7.8

K.4 Issues

It is the experience of a number of tunnel operators that VMS for tunnel closure or lane closures are not regarded by the public as mandatory, and that nothing less than a physical barrier will guarantee that no vehicles will attempt to disobey them. There is therefore an element of doubt about the effectiveness of these signs for controlling traffic and to protect operatives or emergency services personnel attending an incident who may be in the tunnel prior to the laying of cones.

The control system for VMS is safety related and requires type approval. The consequences of a malfunction of the control system may be that contrary signing is presented to motorists, which could result in an accident. Any modifications, additions and software updates to the control system may invalidate this approval and must be thoroughly tested off-line prior to installation in the tunnel VMS system. Following installation a re-validation test must be conducted to ensure that the VMS system is operating as intended.

Experience with some VMS systems has highlighted a number of functional limitations that may lead to operational difficulties and need to be eliminated in design. These include the following:

i If the control system fails during implementation of a lane or tunnel closure plan the variable message signs may not maintain their current aspects. The control system should be designed to fail to a safe state and to facilitate recovery from this situation in a structured manner without completely stopping traffic whilst the signing systems are reset.

ii When signing is set for maintenance operations, for example contraflow, the implementation of an emergency signing plan may override advance signing in such a way that it creates a danger for approaching motorists.

iii Where control is distributed, failure of one part of the VMS system may lead to a loss of co-ordination of signing between one part of the system and another.

iv If the VMS system is designed to ‘count down’, as one would expect with a typical motorway control system, there may be an unacceptable delay in implementing lane restrictions in response to an incident.

Bulbs for internally illuminated tunnel signs can be designed to operate at a number of different voltages, usually either 24V (70W H3 tungsten halogen lamps) or 10V (50W dichromatic lamps). H3 lamps are much less expensive than dichromatic lamps, however the heat generated by H3 lamps has been found to degrade the fibre bundles in many tunnel signs, resulting in a much reduced operational sign life. The cost associated with reduction in sign life is much greater than the additional cost of dichromatic lamps, therefore the use of dichromatic lamps results in lower whole life cost.

The complex mechanisms associated with rotating prism type signs result in a much higher maintenance requirement than for internally illuminated signs. However prism type signs currently have the advantage that they do not require a power supply to maintain an aspect. Advances in light emitting diode (LED) technology are starting to erode this advantage (see below).

K.5 Alternatives

The work associated with modifications to a tunnel control system can be extensive, requiring offline testing and post installation validation testing. The VMS control system could be constructed around a set of safety validated software tools such that new signs and signing plans could be introduced into the control system by a pre-validated method. The software tools could recognise a database of different sign types and have all the relevant characteristics of the signs available. The whole life cost for such a system might be much lower than for existing designs and would form the basis of a generic design that could be used in any tunnel. It could be a free issue item to a contractor for a new tunnel. The only bespoke aspect of the system would be the local configuration. It would facilitate the rapid implementation of system modifications and updates. It would greatly reduce signing system change costs and lead times and help the tunnel operator to provide a better service.

The use of generic electronics components for a tunnel signing control system would decrease the amount of bespoke design in the hardware aspects of a tunnel VMS control system resulting in a reduction in whole life costs. This might be achieved through the application of components used in equipment for the second generation National Motorway Communications System (NMCS2, TA 72: DMRB 9.4.1). Spares for a signing system based on generic components would be far easier to manage and would be common between a number of different tunnels. Spares holdings, and associated costs would reduce accordingly.

Internally illuminated signs for tunnels can now be constructed using high intensity LEDs rather than fibre optic bundles with tungsten or halogen bulbs as the light source. The life expectancy for such LEDs is in excess of 100,000 hours, and the power requirements are much lower (typically 50% of that for the most efficient conventional sign design), resulting in a considerable reduction in whole life cost. The resulting signs can be lighter, require smaller supporting structures, be much more reliable and require less maintenance. The replacement of prism type electro-mechanical signs with enhanced message signs, based on high intensity LED technology is therefore now a practical alternative. Such signs can be used to provide useful information to motorists, rather than giving instructions that motorists often ignore. The use of such signs has the potential to reduce the maintenance required by complex electro-mechanical signs, and to provide an enhanced level of service to the motorist, thereby reducing traffic delays.

Electro-mechanical signs do have the advantage that they do not require a power supply to display a new aspect once they have rotated to display it. However, the low power requirements of LED sources implies that a reasonable back up power supply could be provided for an LED sign from a battery source.

K.6 Value engineering review of alternatives

LED technology

For a tunnel bore with 20 variable message signs LED technology would imply a reduction in electricity usage equivalent to approximately £1,250 per annum (2000 prices), that is £62.50 each per sign per annum. In addition there would be no requirement to change bulbs twice per year at a materials cost of £20 per annum, and so the maintenance cost would reduce significantly, perhaps yielding a further saving of £20 to £30 per sign per annum. Total cost savings per annum for such signs, from these sources, would be expected to be £100 to £110 per sign per annum. The capital cost for LED signs is currently around the same as that for conventional signs and is expected to fall further. The life expectancy of the LED signs is expected to exceed conventional signs by 20% to 30%. Thus the cost of ownership over a 10 year period would be expected to be 50% to 60% of that for a conventional sign.

Appendix L: Tunnel ECS and plant monitoring systems

L.1 Function and description of system

General

The function of the environmental control system (ECS) is to provide a means by which signals to control the tunnel lighting and ventilation systems can be generated. The ECS may also provide a means of communicating the status of these systems and measurements of gas levels, pollution levels and luminance levels to a remote location. It is also usual for the ECS to handle alarms, status information and remote control signals for other tunnel plant, particularly electrical switchgear and emergency and fire protection systems.

Because of the variety of designs of ECS they are discussed in generic terms in this appendix. The potential application of micro electronics to the control of equipment in highway tunnels was discussed in a TRL report by Bennett *et al.* (1984).

ECS processing elements

ECSs are based on computer technology. Technical advances in the use of computer systems for plant control and the availability of standardised graphical software have provided the potential for cost-effective innovative design solutions. The design of tunnel ECSs has evolved with technology over the past 10 to 15 years. Older, computer based ECSs were designed around dual redundant central computers that contained all the control logic to operate the tunnel systems. This control logic was implemented as computer 'tasks' or 'processes'. Newer designs use a central computer linked to programmable logic controllers (PLC's, commonly referred to as outstations) at strategic locations corresponding to the principal concentrations of plant. All control and other information is passed along a common data transmission network. The PLCs are programmed to receive information about ambient lighting conditions and air quality from local sensors and to output the appropriate control commands to the lighting and ventilation plant. They also gather plant status information from the associated plant and relay it to the central computer. PLCs often utilise 'ladder logic' to build the control functions. This system enables control sequences to be broken down into discrete steps for simplicity of programming and troubleshooting. The central computer receives manual control signals, for plant override or updating of control parameters, and relays them to the appropriate outstations. An operator's position is normally provided with a graphical user interface for user-friendly display of plant status and control options. SCADA (Supervisory Control And Data Acquisition) software is usually employed to manage data communications between the central computer and the outstations.

The majority of existing ECSs are a bespoke configuration of industrial computers and/or PLCs, operating proprietary-based software packages that have been configured for use at the site. Such combinations allow the exact control requirements, for any particular tunnel, to be achieved cost-effectively.

Field instrumentation

Field instrumentation is used to provide measurements of environmental variables to the ECS. This type of instrumentation usually comprises carbon monoxide (CO) sensors, visibility (obscuration) sensors, anemometers for ventilation control and photometers for lighting control. CO and visibility sensors function by measuring the absorption of a specific wavelength of infrared light either by CO or by particulates in the air. These absorption measurements are then used to compute the concentrations of the respective pollutants. If CO levels exceed a predefined limit, or if tunnel visibility falls below a predetermined level, the relevant outstations will cause the ventilation system to start and run until acceptable levels are attained. Photometers employ light sensitive electronic elements to measure ambient light levels (luminance) around the tunnel portals. The outstations responsible for lighting control receive the signals from the photometers and use them to control tunnel entrance and exit zone lighting levels. Tunnel interior zone lighting may also be controlled by a time clock function to switch between day and night time levels of illumination.

Gas detection systems (see also Section G.1)

It is usual for tunnel sumps and similar confined spaces to be equipped with oxygen sensors and flammable gas sensors, to detect potentially hazardous atmospheres within the sumps. The range of different types of gas that may be monitored is quite variable; in the majority of installations the gas sensors are of the electro-chemical cell type. If such a system detects flammable gas then it is usual for an alert to be given at 20% of the lower explosive limit (LEL) for that gas. At 30% LEL the operation of sump pumps would be inhibited and automatic fire protection systems initiated.

Hydrocarbon sensors will normally be calibrated on hexane which gives a calibration equivalent to petrol vapours. If there is a danger of accumulations of methane (for example in cable draw pits), gas sensors calibrated to measure methane may be installed. In some locations there is a danger that hydrogen sulphide may be produced by the action of acidic waters on sulphur bearing rocks. In such locations one may find hydrogen sulphide gas sensors.

Oxygen depletion monitors are used to detect the presence of gases which may not be hydrocarbon based but which will nevertheless reduce the 'breathability' of the air because of displaced oxygen.

It should be noted that such gas detector systems are not sensitive to diesel spillage (owing to the low volatility of diesel fuel), and therefore such systems cannot be relied upon to provide complete coverage.

L.2 Description of maintenance procedures

The majority of equipment is computer based. The maintenance routines that apply are unique to the particular type of system installed. Typically every three months computer cooling fans and air filters should be cleaned, computer and PLC connections should be checked, back up copies of software should be taken and the following should be tested:

i All aspects of computer system operation and response.

ii Capacity and fragmentation of computer hard discs.

iii Local PLC memory battery.

At intervals of 12 months voltage and earthing of PLCs should be tested.

The maintenance requirements for both CO & visibility sensors are peculiar to each individual manufacturer. Typical sensors would be cleaned, serviced and calibrated at 3 monthly intervals

The maintenance requirements for gas detection systems are similarly peculiar to the exact type of system. Typical systems would require cleaning, checking connections, calibration and testing of operation at 3 monthly intervals. At intervals of 12 months the gas sensor is normally replaced.

L.3 Issues

General

In many road tunnel installations the provision of emergency controls, such as ventilation control from smoke control panels, is achieved via the central computer which, in turn, activates inputs to an outstation in the ventilation control panel. This then causes the ventilation to start in the normal way. During a tunnel fire there is a high probability that control cables and equipment will suffer fire damage. Such damage may prevent the ventilation system from functioning. To design emergency controls to be activated via the central computer serves to introduce a possible failure mode into the emergency controls, which are safety critical systems. Safety critical control systems based on computer technology require high reliability, multiply redundant design criteria that far exceed the design specifications for typical road tunnel ECSs.

It is important to consider carefully what is required of the various parts of the system, in the event of failure of a piece of equipment. For instance, if there is a loss of communication between the central computer and outstations, it may be better for the outstations to continue to control lighting and ventilation in accordance with the latest instructions received from the in station, rather than to revert to a default level.

ECS processing elements

Computer hardware, such as that used to implement ECSs, has advanced significantly over the past 15 years, in terms of speed, reliability and physical size. Computer equipment is now accepted to have a relatively short operating life. Supporting older computer technology can be more expensive than replacing it with a modern system.

Many tunnel systems, in addition to the ECS, use computer equipment. It appears appropriate to implement all such systems around a common computer operating system, such that the operator can achieve economies of scale when supporting system software. The common factor is the software, and software configuration. The type of software chosen should therefore be such that it can be supported for several upgrades of operating hardware, without significant changes. This would avoid the substantial off-line validation testing which is required prior to upgrading hardware or software, because many emergency functions are implemented via the ECS.

Sensors

Tunnel instrumentation is the key to safe and economic operation of tunnel plant. If a particular sensor or type of sensor requires frequent maintenance and is prone to failure, the maintenance costs become excessive. Rugged CO sensors have been used in harsh industrial environments for many years, as for example flue gas analysers in coal fired power stations. It has been found that these types of CO sensors are built to a much higher standard than other available sensors, require much less maintenance and are considerably more reliable. A similar finding has been made for visibility sensors. A rugged variant of this type of sensor has been used on airfields for measuring ambient air opacity for many years and has been found to be very reliable with low maintenance requirements.

Year 2000 problems

In the past it was realised that in many cases it was cheaper to adapt low cost 286 or 386 computer chips for specific applications rather than to develop purpose-made devices. This meant that calendar functions were available where they were not necessarily needed. Such chips were frequently built into systems such as motor control devices, fire alarms and telephone switchboards. However, date-related problems can only occur if the calendar is actually used. In general, therefore, only devices that actively use date-related functions are at risk. For these devices the change from 31/12/99 to 01/01/00 is not the only date on which problems could occur. Many older process control devices are programmed to recognise dates up to 9/9/99, after which their date awareness will cease. There have been estimated to be six such dates upon which various types of system could malfunction. Non-compliant devices were still being sold as recently as 1998, so age cannot be taken as an indicator of compliance. Also it cannot be assumed that dates will have been set correctly in all date aware systems.

It seems to be generally accepted that there are many devices, or combinations of devices, for which the possibility of malfunction cannot be adequately predicted. However, adoption of a ‘wait and see’ policy risks placing great pressure on resources for remedial works on non-essential systems.

L.4 Alternatives

System design

Traditional ECS designs have featured duplicate central computer systems, operating in a ‘hot standby’ mode, so that if the ‘duty’ processor should fail the ‘standby’ unit could immediately take over. The reliability of modern computers is such that a parallel device is not justified. It is also sometimes the case that equipment provided to link and co-ordinate the two processors can in itself be an additional cause of system failure. It is now accepted that ECS design should be as simple as possible to minimise the equipment count. Reliable system designs, based on high bandwidth ring communication PLC systems, offer levels of performance and resilience that could only historically be achieved with hardwired controls.

One would expect a modern ECS system to comprise a central PC as the graphical user interface, with a RAID drive (that is an array of hard disks configured so that if one disk fails, the others can re-constitute any data held on the failed disk). All system configuration changes, such as changes to operating parameters, would be implemented from this point. This central computer would communicate with the outstations connected via a ring data communications network. The software would be such that switching any number of outstations out of circuit would have no effect on the response speed for the remainder of the system. The preferred means of communication with outstations would be via dedicated fibre optic cables to eliminate the possibility of electromagnetic interference from other tunnel equipment.

Control logic

Modern control software, based on neural network or fuzzy logic technology, offers the potential to provide control systems that continuously and automatically adapt to changes in the operating environment. Such systems are potentially capable of matching tunnel lighting and ventilation demands to the requirements of a large number of variables including tunnel traffic speed and density, rate of rise of pollution levels, absolute pollution levels and predicted traffic flows. Such software should be capable of avoiding situations where a small change in the external circumstances results in an unnecessarily disproportionate response by the tunnel plant. It should aim to reproduce more closely the human reasoning process which takes a global view of many factors and makes a judgement on the most reasonable response. The ability to optimise environmental control in such a manner holds the potential for significant energy savings.

A difficulty associated with the use of this type of advanced automated control system is being able to understand what the controller is doing (and why) for any given set of system inputs. Tunnel ECSs, based on neural processing / fuzzy logic technology would have to include a user friendly interface that allows the tunnel operator to determine the controller’s response, and logical ‘reasoning’ to any set of inputs.

Tunnel traffic controller

Recent tunnels may be provided with a tunnel traffic controller (TTC) to handle and interpret traffic flow data from inductive loops in the carriageway and to control matrix and variable message signs associated with the tunnel. The TTC is equipped to interrogate the ECS to obtain data on plant status relevant to its traffic control function. There may be advantages in arranging for information to flow from the TTC in the reverse direction so that, for instance, the ventilation control algorithms could take advantage of traffic flow data. The ability to receive traffic flow data from the TTC would permit closer and more predictive control of the ventilation system, by anticipating changes in levels of pollutants before critical levels are reached. While it is doubtful that this will bring significant energy savings, there may be advantages in reducing the occasions when fans are run at full capacity. Reverse data flow would also open up the possibility for emergency control of certain items of plant, such as lighting and ventilation, from the traffic control centre.

The possibility exists of combining the functions of the TTC and the ECS in-station in a single computer which would allow significant simplifications to be made to software and hardware. This has successfully been done in the Medway tunnel. However, unless a standard design for both software and hardware can be established there could be problems relating to type approval of the equipment for use in its traffic control function. Also the ability to tailor ECS software to the specific needs of individual tunnels might be lost.

Linking ECS to CCTV

In recent systems it is common practice to link the ECS to the CCTV controller, so that certain defined events, for example opening of an emergency door, will cause the scene of the event to be displayed on a CCTV monitor screen, possibly with an accompanying alert signal. A link to the TTC could extend this facility to automatically display the front of a queue of stationary traffic, for instance, to speed identification of any incidents requiring the operator’s attention.

Sensors

System instrumentation remains the key component in the safe and cost effective operation of tunnel ECSs. It is envisaged that alternatives to existing CO & visibility sensor designs would include much longer measurement paths such that the measurement is a more representative sample of the tunnel air quality and not just a localised effect. This would allow the ECS to determine more accurately the appropriate levels of ventilation.

Advances in gas sensing technology (such as the ‘electronic nose’) hold the potential of detecting a much wider range of chemicals facilitating the remote identification of chemical spillage within the tunnel confines. Such information, during the early phases of a tunnel incident, offers the potential for the early application of a safe and effective incident management plan.

Monitoring records and reports

In order to perform its control function for tunnel lighting, ventilation and power distribution systems, the ECS has access to information on environmental conditions within the tunnel such as switching of plant and running times. It would also be relatively easy to monitor energy consumption at strategic points on the power distribution network. Software is available to automatically compile periodic reports on system performance and energy consumption, and to predict future energy consumption and costs. Such information could be of great value for budgeting purposes. A further possibility is to analyse actual data to predict the effect of changing performance criteria, for instance air quality set points, to permit optimisation of the system performance and avoid unnecessary use. Such reports could be requested and received at any remote location via a modem or similar link.

The production of such reports on systems performance has the potential to reduce running costs if it can be demonstrated that equipment set points can be adjusted to reduce ventilation fan running times. However, this has not been proved and the primary motivation for this facility is as a useful management tool for prediction of running costs and maintenance needs. This information could easily be made accessible not only to the maintaining agent but also directly to the overseeing organisation.

Appendix M: Electrical systems – HV distribution and protection

M.1 Function and description of system

The function of the high voltage (HV) distribution and protection systems is to provide a controlled source of high voltage electrical energy to the main tunnel power transformers. A regional electricity company (REC) usually provides the electrical supplies for the operation of a tunnel and associated ancillary services. These electrical supplies provide the permanent power source to the service plant with locally generated temporary power supplies usually available for emergency supply in the event of a mains power failure. The permanent supplies normally comprise one or two fully rated high voltage (11kV) feeders, derived from the REC distribution network. Where two feeders are provided, if one supply fails the tunnel can normally be supplied with power via the other. Thus the alternative supplies need to be independent of each other at as high a level as possible in the distribution network in order to minimise the chances of a single fault disabling both supplies simultaneously.

The primary electrical distribution to road tunnels may be arranged in a number of different ways depending upon the local HV distribution network operated by the particular REC. A common method of distribution is one in which both independent HV supplies, from the REC, are terminated within a HV switchroom at one end of the tunnel. Interconnecting cables are then installed to provide HV supplies to another HV switchroom at the other end of the tunnel. Another common method of distribution is that one independent HV supply is terminated directly at each end of the tunnel in HV switchrooms. A single interconnecting cable, through the tunnel, then provides for resilience of supply.

High voltage circuit breakers are usually provided with power solenoid operating mechanisms. The DC closing and tripping supply to each switchboard is provided from dedicated tripping and closing battery units located within the respective HV switchrooms. Mechanical interlocks formed through ‘Castell’ type key mechanisms are usually provided within each circuit breaker section to impose a fixed sequence of switchgear operation. This prevents the incorrect operation of circuit breaking units and isolators, thus preventing danger to personnel.

Bus zone relays are employed to monitor the busbars within the HV switchboard and protect against internal faults. The relays are able to detect areas of the board in which a fault has occurred and switch out the relevant faulty section, allowing the healthy part of the board to remain energised.

M.2 Description of maintenance procedures

The typical 3 monthly maintenance activities should incorporate visual inspections for signs of overheating and checks to ensure that relays, meters and indicators are operational. Owing to the comparative infrequency of operation of tunnel HV switchgear it may be appropriate to include the trial operation of the switchgear to ensure the switchgear does not become sluggish in operation.

At intervals of 12 months maintenance activities should include removal of each circuit breaker on a one by one basis so as not to compromise the reliability of supply to the tunnel. Each circuit breaker should be serviced according to the manufacturer’s instructions with particular emphasis being placed on the lubrication of selector switch blades and vacuum roller contacts, friction pins, bearings and pivot. Vacuum bottle wear clearances should be checked and bottles outside limits should be replaced. All mechanical interlocking facilities should be checked for operation and overall condition. Voltage transformer (VT) chambers should be visually checked and all terminations and connections to each circuit breaker should be thoroughly examined. The protection systems associated with each circuit breaker should be tested annually using secondary current injection testing techniques.

M.3 Issues

Where it is necessary to distribute HV electricity within a network not under the control of the REC, onerous requirements are placed upon the system designer to ensure that the operation of protection systems is properly graded and that HV faults within the tunnel HV distribution network do not trip the REC supply switchgear. In order to ensure correct grading it is necessary to comprehensively protect the tunnel HV network with protection relays. The additional complexity introduced into the HV network design results in a much higher capital cost for a HV switchboard than would be the case for a typical REC switchboard. The additional protective equipment provision both complicates, and adds cost to, the maintenance cycle.

In order to manage an HV network it is necessary to have procedures in place for the correct operation of the switchgear and distribution system. If these requirements are fulfilled using internal staff, it is essential that a formal HV Authorised Person training procedure is instigated and maintained.

Section M.1 referred to two common methods of providing HV supplies to a tunnel and in particular the provision of two ‘independent’ supplies. The specification of independent supplies is intended to ensure that common mode failure points are eliminated. It must be remembered that although the 11kV feeders may be independent, the upstream sources from which the 11kV is derived (usually 33kV) may not be. It is also possible that, at some time in the future, the REC may reconfigure its 11kV network distribution arrangements resulting in the 11kV supplies being derived from a common source. Such changes result in a corresponding decrease in the resilience of tunnel supplies.

HV distribution supplies to tunnels have been found to be more ‘operationally’ fault tolerant if an open point in the HV supply ring exists at one of the tunnel service building HV distribution points. Faults on either of the supplies to the tunnel, or the associated distribution network, cannot then result in total supply failures to the tunnel. It is operationally more acceptable to have some supplies available rather than to have none.

The cost of electricity comprises a fixed and a variable element. The fixed element comprises charges for annual declared supply capacity; annual maximum demand, annual reactive demand and other fixed cost elements. The variable element comprises charges for the amount of electrical energy used, the cost of which varies according to the time of day, week and year (assuming a seasonal time of day (STOD) tariff which is normally the most appropriate). The cost of electrical energy can be much lower if provided at 11kV, owing to pool purchasing arrangements. In addition, the fixed costs are reduced if electricity is supplied from an HV substation, rather than from the HV network. The fixed cost per kVA of declared supply capacity (DCS) is much lower (for 1997/8 typical costs were £12.48 per kVA at network compared with £8.40 per kVA at substation). A typical 1 km twin bore tunnel could have a DCS of 1500kVA, thus saving approximately £6,000 per year in DCS costs. Further, adopting to take an 11kV supply at a substation also reduces fixed Annual Maximum Demand Charges (by approximately 10%) and results in reductions in the distribution elements of the unit charges and the reactive demand charges.

The power demand of a typical tunnel fluctuates widely according to the time of day and operational circumstances. There is a nearly constant base load consisting of base level lighting and control and communications equipment. There is then the boost lighting which increases according to the level of external daylight, and ventilation which generally increases at peak periods when emissions are at their highest. Drainage pumping plant will operate occasionally depending mainly on weather conditions. Finally, emergency conditions, for example a major fire, may require lighting, ventilation and drainage to be running close to their maximum levels simultaneously. The result is that incoming supplies have to be rated to serve the maximum foreseeable load, which in most UK tunnels will be the emergency condition and which will only rarely, if ever, be required, while the actual consumption for much of the time will be considerably less. The fixed element of energy costs is therefore related to a supply capacity that is not needed for most of the time.

Although there have been significant improvements in the reliability of power transmission equipment in recent years, some operators report an increase in the occurrence of outages due to unplanned network switching operations, some of which may take several hours to resolve. The frequency of supply failures varies widely from one tunnel to another and from year to year. Supplies in city centres appear to be the most reliable, while those in rural or semi-rural areas are most prone to interruption. It must therefore be assumed that complete loss of mains power, sometimes for several hours, will almost certainly happen from time to time and that suitable standby systems must be provided if a tunnel is to remain open under these circumstances.

M.4 Alternatives

If generators are to be provided, it may be worth considering using them not only to cover for mains failure conditions but also to work in parallel with the mains supply to supply the emergency peak load over and above the normal day to day power requirements. A further step would be to use local generation for peak lopping, to supply peak period demand and only to take the base level of energy from the REC. This would then allow charges related to mains supply capacity to be reduced to a minimum.

While the savings on electricity charges are attractive, there will be significant increased costs, associated with the generation plant, which should be considered as follows:

i Increased running hours will increase maintenance and fuel supply and storage requirements.

ii If the incoming mains supply is reduced to a level where it cannot support the whole of the tunnel plant then some duplicate generation equipment will be needed for redundancy.

iii Synchronising switchgear and controls will be complex and expensive.

iv Typical standby generators may not be intended for frequent or prolonged use.

v The space requirements for additional plant and equipment may preclude upgrading of existing tunnel generation for peak lopping.

vi It is unlikely that running generators continuously and exporting surplus power to the grid will be cost-effective on the scale considered here.

It is becoming more and more unacceptable to close tunnels as a result of electricity supply failures. Ventilation supplies to tunnels should be assured such that normal operation can continue without interruption under mains failure conditions. It is recommended that increased availability of electrical supply to road tunnels be adopted as a major design criterion. It is fully expected that the importance of this aspect of tunnel management will increase as the road network is subjected to the increasing pressure of traffic growth.

Emergency supplies have traditionally been provided by diesel generators; specified to supply a certain ‘critical’ base load. Ventilation systems have not traditionally been supported by such supplies, on the basis that most tunnels are to some extent self-ventilating under normal operational conditions and therefore an acceptable environment can be maintained for a limited period, although emergency cover for smoke clearance will be lost. Ideally, the tunnel should close if ventilation supplies are lost for a significant period. However, in practice the difficulty of enforcing a tunnel closure means that most operators would be reluctant to do this unless it is absolutely necessary. As traffic densities continue to increase, and techniques of road network management are employed to make best use of the road network, the pressure not to resort to emergency closures of road tunnels will continue to increase.

For a single tunnel operation, the resources required to manage and operate even a small HV distribution network are quite considerable. It is possible to design the distribution system such that the HV distribution becomes a part of the REC responsibilities and allocate tunnel staff resources to other duties.

Where it is decided that a HV network is required, consideration should be given to the provision of self-powered protective devices and self-charging circuit breakers to eliminate the need for tripping and closing supplies.

It may also be found that the relative simplicity of design of SF_6 (sulphur hexafluoride insulated) switchgear may make it cost-attractive as an alternative to the use of vacuum switchgear.

M.5 Value engineering review of alternatives

Replacing dual supplies with a single supply

A value engineering review comparing a conventional supply comprising dual HV supplies with a single HV supply is shown in Table M1. As the overall reliability of even two HV supplies cannot be guaranteed, a single standby generator is included. For the single HV supply two standby generators operate in parallel which should give overall reliability as good as, if not better than, the other arrangement. Both arrangements require uninterruptible power supply equipment. The single HV supply shows considerable saving in whole life cost and better value. The main saving is in REC standing and availability charges for the reduced supply.

Use of standby generator for peak lopping

A value engineering review of using existing generators for peak lopping is shown in Table M2. This compares the above scenario where two generators are provided in parallel with a single HV supply with a DCS of about 1500kVA, with an alternative using similar equipment to reduce the peak demand on the incoming supply to 400kVA.

The estimated load profile for a typical day shows three peaks in demand. Two correspond to traffic peak periods, when ventilation may be expected to be used in response to congested traffic. The third is around midday when lighting is at its peak. Outside these periods the load is unlikely to exceed 400 kVA.

One 500 kVA standby generator equipped for parallel operation with the mains and arranged to operate when load demand exceeds 400 kVA will be sufficient to support peak loads under all normal operating conditions, and will enable power drawn from the mains to be limited to 400 kVA. Should the mains fail, the second 500 kVA standby generator will bring the total available power to 1000 kVA, sufficient for an adequate response to all emergency situations. In this instance the top two stages of boost lighting would be inhibited to reduce the emergency load to within the capabilities of the generators.

The costs given previously already include for synchronising switchgear. The extra costs for load shedding of lighting is negligible. If one generator runs for about 5 hours per day, the fuel consumed will average about 550 litres per day or 200,000 litres per year. It should be noted that, because running a generator at part load is inefficient, the generator would be run at full load and the surplus power used to provide part of the base load. At 12p/litre the cost of fuel will be about £24,000 p.a. (approximately 6p/unit) of which an estimated 50% would be replacing base load.

The corresponding saving on electricity purchased will be a reduction of the availability charge on a single supply by (1500 – 400) x £1.6 = £1,760 per month or £21,000 per year. The increase in costs per unit of electricity consumed is complex to calculate and depends very much on the load profile of the tunnel, the tariff applied and the prevailing cost of diesel fuel. However, an initial estimate indicates a possible rise of about 2% on a daily bill of about £300, which equates to £6/day or £2,000 per year.

The significant whole life cost saving shown in Table M2 is represented by the difference between the present cost of the availability charge saved and the extra fuel consumed supplying demand above the 400kVA threshold. Overall the review indicates a slight value benefit in the use of existing generators in this configuration for peak lopping.

Table M1 Value engineering review of HV supplies

HV power supply strategy	*Design life: 40 years*		*Existing* *Two HV supplies*		*Alternative* *One HV supply*	
Function review *Objective*	*Importance rating*			*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.25			99		95
Environmental Impact	0.35			50		55
Health and safety	0.40			80		70
Total weighted score				74.25		71
Whole life cost	*Details*	*Present cost factor*[1]	*Estimated costs (£k)*	*Net present cost*	*Estimated costs (£k)*	*Net present cost*
Capital	Cables	1	100	100	50	50
	Transformer & switchgear	1	100	100	50	50
	Standby generator	1	100	100	200	200
Maintenance – cables	Inspect 3 monthly	61.43	1	61	0.7	43
	Test annually	14.95	2.4	36	2	30
	Test 6 yearly	2.1	4.5	10	2.5	5
REC charges	Monthly standing charge	185	6.6	1221	3.3	611
Maintenance – generators	Annual	14.95	2	30	4	60
Total present cost				1658		1049
Value ratio (Function/Cost)						
Value ratio (x10^{-6})				44.8		67.9
Normalised value ratio				1.00		1.52

[1] Present cost factors are for a discount rate of 6.0%.

[2] For explanation of value engineering review see Section 3.3.

Table M2 Value engineering review of using existing generators for peak lopping

Use existing generators for peak lopping	*Design life: 20 years*		*Existing* *Two generators - no lopping*		*Alternative* *Peak lopping*	
Function review *Objective*	*Importance rating*			*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.25			50		50
Sustainability	0.35			50		40
Health and safety	0.40			50		45
Total weighted score				50		45
Whole life cost	*Interval (years)*	*Present cost factor*[1]	*Estimated cost (£k)*	*Net present cost (£k)*	*Estimated cost (£k)*	*Net present cost (£k)*
Capital						
Availability charge	1	11.16	21	234	2	22
Fuel cost (to cover peaks)	0.083	141.07	9.5	1339	9.8	1386
Total present cost				1573		1408
Value ratio (Function/Cost)						
Value ratio (x10^{-6})				31.8		31.6
Normalised value ratio				1.00		1.00

[1] Present cost factors are for a discount rate of 6.0%.

[2] For explanation of value engineering review see Section 3.3.

Appendix N: Electrical systems: transformers

N.1 Function and description of system

The function of transformers is to transform electrical energy from high voltage to a voltage suitable for the operation of tunnel electrical equipment (typically 415V, 3 phase, 4 wire systems).

A typical tunnel transformer would be rated at 1000 kVA, 11kV / 415V. The specification of transformers in sizes and types corresponding to those normally used by RECs in their distribution networks can considerably improve the time to obtain spares or replacements, should the need arise, since suppliers frequently keep one or two units in stock for such eventualities. However, it will be appreciated that the detailed specification for transformers is determined by whole tunnel electrical system and significant variations about the above rating will be found in practice. It is usual to provide ONAN (Oil Natural Air Natural cooled) transformers with oil level indication, silica gel breather, filling and drain points and winding temperature alarm units. Off load tap changing facilities typically allow an open circuit voltage selection within the range 404V to 445V.

N.2 Description of maintenance procedures

The 3 monthly maintenance should include visual inspections of the correct oil level, condition of breather silica gel cartridges (for discoloration) and confirmation of normal operating temperatures.

The 12 monthly maintenance should include checking of transformer cable terminations. An oil sample analysis should be carried out to ascertain oil condition and provide historic data such that the degradation rates of the transformer oil and transformer insulation may be monitored.

N.3 Issues

Transformers are generally very reliable, with lives in excess of 30 years and very high operational efficiencies. The majority of failures in older transformers occur as a result of time dependent thermal ageing, leading to a degradation of the paper insulation. Transformer oil can easily be replaced or recycled. Degradation of winding insulation requires the removal of the transformer for refurbishment.

Measurements of oil-gas (chromatography), moisture levels, acidity levels, dielectric properties and high pressure liquid chromatography (HPLC) have been shown to correlate with the remaining life of transformer insulation. It has also been shown that the detection of furfuraldehyde, a derivative of paper, using HPLC is one of the best indicators of degradation of paper insulation in HV transformers. Use of these methods can provide the information, which enables planned maintenance to be scheduled on a predictive basis.

N.4 Alternatives

For new installations it may be cost effective to specify air-cooled low loss transformers, which are cheaper to maintain and have even higher operational efficiencies than the more traditional oil-cooled designs.

Appendix O: Electrical systems – LV distribution and protection

O.1 Function and description of system

The function of low voltage (LV) electrical distribution and protection systems is to provide a controlled source of LV electrical energy for sub distribution to the tunnel and to associated ancillary services.

The outputs from the main tunnel power transformers are supplied to one or more LV switchboards. The LV switchboards provide the sub distribution for the tunnel and ancillary services. The LV switchboards usually incorporate circuit breakers, to control the supply of electrical energy to the LV switch board bus, and banks of other switching devices (such as switchfuses, fused switches and contactors). Many such switchboards contain the facility to switch emergency generator supplies on to the LV bus automatically should the main supplies fail.

The switchgear associated with a LV switchboard has a specifically designed arrangement of protective equipment, selected to provide security of supply and automatic safety tripping should a fault occur. Over-current, under-voltage and earth fault relays provide protection for the mains transformers and LV switchboards. In the event of an impulse surge (such as a lightning strike), or a prolonged fault, the relay will trip the appropriate circuit breakers to isolate the relevant busbars.

Where supplies are provided to the tunnel systems at HV, additional control circuitry and protective devices are placed between the HV and LV switchboards such that the HV switchboard, transformers, and LV switchboard operate as a combined system. This ensures that the distribution system is able to switch out faulty sections of the network with the minimum possible disruption to tunnel service supplies. The system as a whole is designed to supply the installed loads under all reasonably foreseeable ‘single fault’ failure conditions.

Where two independent incoming supplies are provided, it is preferable to bring each supply by its own transformer to a separate busbar on the main LV switchboard. This then makes it possible to switch tunnel equipment from one incoming supply to the other within the low voltage system without involving the specially trained ‘Authorised Persons’ who would be needed to operate HV switchgear.

O.2 Description of maintenance procedures

The 3 monthly maintenance should include ‘good housekeeping’ tasks such as cleaning the switchgear, replacing any faulty indicator lamps and identifying any signs of obvious equipment malfunctioning. The correct rating and installation of protective devices should also be checked at this interval.

The 6 monthly routines should include ensuring that all switchboard cable connections are tight and that all internal components are free from obvious signs of damage.

The 12 monthly maintenance should include inspection of the condition of relay and contactor switching contacts; any contacts showing excessive burning should be replaced. Main switchboard circuit breakers should be withdrawn from service (one at a time) and serviced in accordance with the manufacturer’s instructions. The switching contacts of air circuit breakers (ACB’s) should be checked for any pitting or other surface damage and metal vapour deposits should be cleaned from the arc chutes. All mechanical linkages, friction pins, bearings and rollers should be lubricated and the correct operation of solenoid or stored energy operating mechanisms tested. The 12 monthly maintenance will require access to the busbar chambers of the switchboard to ensure that the bus is in good condition and that all connections are tight. These works necessitate the complete isolation of parts of the switchboard. The protection systems associated with each breaker should be tested annually using secondary current injection testing techniques.

Testing of the correct operation of the mains failure switching modes of the LV switchboard should also be conducted at 12 monthly intervals. These works are conducted as a part of the final tests to prove that all HV and LV works have been completed and that the emergency switching modes of the electrical distribution system function correctly.

O.3 Issues

It has been found that the majority of electrical faults are caused by loose connections. It is generally accepted that electrical connections should be checked for tightness as a routine maintenance item. Care needs to be taken to ensure that the connectors are not over tightened. Over tightening can lead to broken wires within the connector and the creation of intermittent faults that are very difficult to identify.

O.4 Alternatives

Alternatives to LV distribution and protection will comprise changes to the detail of the engineering.

The indicator lamp units, used to indicate the status of the LV switchboards and the associated protective devices, are traditionally based on filament bulbs which have an operating life of approximately 2,000 hours; or about 3 months of continual operation. It is now possible to replace such units with high intensity light emitting diodes (LEDs) with a typical operating life of 80,000 hours, thus reducing the maintenance replacement requirements to about twice during the operating life of the switchgear. Solid state instruments with LED or liquid crystal displays also offer greater reliability than moving coil instruments.

Appendix P: Electrical systems: battery tripping and closing units

P.1 Function and description of system

The function of a battery tripping and closing unit is to ensure that a supply is available to operate protective and control devices within the switchboards. The batteries ensure that the protective devices will continue to operate for a limited number of operations if all mains supplies fail.

Battery tripping and closing units consist of a number of batteries and a battery charging system. The control and protective devices within both HV and LV switchboards are designed to operate from a direct current (DC) supply. It is essential that the battery tripping and closing units operate correctly, as loss of supply from these units will render the protective devices within the main switchboards inoperative.

P.2 Description of maintenance procedures

The 3 monthly maintenance should include visual inspections of components, terminations, and battery stack electrolyte levels and general condition. Battery stacks should be discharged at 3 monthly intervals and the correct functioning of low voltage alarms should be recorded.

The 6 monthly maintenance should include the measurement and recording of individual cell voltages.

The 12 monthly maintenance should include ensuring that the float and boost charge levels are set in accordance with the manufacturer’s instructions. The settings of all the units’ alarms and trip levels should also be calibrated and recorded.

P.3 Issues

It is possible to design an electrical distribution system that does not require tripping and closing units to power the system protective devices. Such a design has the advantage that system protection is distributed amongst the circuit breakers and results in the elimination of the tripping and closing units as a common mode failure point for the protection system.

P.4 Alternatives

The requirement for these units could be eliminated completely provided that the main switchgear was specified accordingly.

For installations where batteries are deemed to be necessary, the technology now exists for automatic monitoring of battery condition and prediction of life expectancy. While it may not be economic to install such a system purely for a tripping and closing battery, it may be feasible to include monitoring of these batteries via an extra channel on a monitoring system provided for other battery arrays, for instance serving uninterruptible power supply (UPS) sets.

Appendix Q: Electrical systems – earthing

Q.1 Function and description of system

The function of the earthing system is to provide a low resistance path to earth so as to safely discharge leakage currents.

The main earthing arrangements for a tunnel may take many differing forms, however, they frequently comprise a number of conductive copper mats, buried in the ground adjacent to a tunnel service building. Earth cables, which connect the extraneous metal parts of electrical equipment and lightning protection systems, are connected to the earth mats. More recently constructed tunnels may use reinforcing steel in buried concrete structures as part of the earthing system.

Q.2 Description of maintenance procedures

The 3 monthly maintenance should include visual examinations of all accessible cables, joints and bonds for signs of damage or corrosion. This includes lightning protection tapes and down conductors.

The 5 yearly maintenance should include the testing of the earth mats and main earth cabling systems to ensure that low resistance paths to earth are within design specification limits.

Q.3 Issues

When periodically testing main earth mats or earth pits it is necessary to disconnect the main earth connections to it. This can leave the distribution system without a safe earthing system. Earthing installations should be designed to be split such that a part of the earthing system can be left in operation whilst the other half is tested.

Q.4 Alternatives

Alternatives to earthing will comprise changes to the detail of the engineering possibly including the use of electrically conducting polymers in the place of copper, to eliminate the risk of corrosion of the earth mats.

Appendix R: Electrical systems: tunnel control panels

R.1 Function and description of system

The function of tunnel panels is to house equipment that provides local electrical sub-distribution, local control for tunnel services and emergency service equipment.

There is a considerable variation in the design of tunnel panels. Typically they house distribution and control equipment for tunnel electrical distribution, emergency distribution, emergency equipment, smoke control, sump control, lighting control, and ventilation control. They may also contain CCTV and ancillary supplies as well as fire extinguishers, emergency telephones and fire hydrants. The value engineering issues around the contents of such panels have been addressed elsewhere within this report. This appendix addresses the panels themselves, and typical maintenance operations that would be carried out on electrical distribution and control equipment in the panels.

Tunnel panels are usually constructed from 6mm thick, 316-grade stainless steel, with door seals to provide an IP65 level of environmental protection, although older panels may be of mild steel, zinc sprayed and painted. They feature a number of separate chambers to house supply points or equipment specific to the tunnel (for example CCTV supplies, incident detection equipment, lighting distribution fuses / MCBs, fire hydrants, emergency telephones and fire extinguishers). Access to all sub-distribution chambers is via tamperproof locks with special keys to prevent unauthorised access.

R.2 Description of maintenance procedures

Stainless steel panels, in road tunnels, are susceptible to surface corrosion. The maintenance normally required for such panels is external cleaning and internal vacuum cleaning. Routine checks should be carried out to ensure that earth connections to panel doors are tight and that door furniture (such as door closers, hinges, and locks) works correctly and is not corroding. The integrity of door seals should also be checked. Leaking door seals will allow tunnel-washing water to penetrate the seals and damage sub-distribution, control or emergency equipment.

The protective coatings applied to mild steel panels are easily penetrated by stone chippings and other debris thrown up from the road surface, and rusting will quickly set in at the point of damage. Protective coatings are frequently thinner on the corners and edges of panels and these points are more vulnerable to breakdown of the protection. These panels require frequent attention to repair damage to the paint finish to prevent incipient rust from spreading.

R.3 Issues

It is usual for electrical distribution and control panels, serving tunnel lighting, ventilation fans, drainage pumping plant, communications and CCTV equipment, to be located in the side walls of the traffic bores of a tunnel. In older tunnels access for maintenance was frequently gained, while the tunnel was carrying live traffic, via raised walkways on one or both sides of the carriageway. Increases in traffic density and a growing awareness of the health hazards associated with exhaust emissions mean that the time spent by personnel on such walkways is now kept to an absolute minimum. In addition, recent tunnel designs have done away with raised walkways to provide space for a stopped vehicle to be parked at least partially off the carriageway to minimise the obstruction and hazard to other traffic. Where this is the case, no access at all is permitted while the tunnel is open to traffic because of the risk of an operative being struck by a vehicle.

While emergency panels need to be in the road bores so as to be accessible to tunnel users, many other panels do not necessarily need to be located there. It is now normal practice to locate lighting and ventilation control panels in the main low voltage switchrooms, where they are accessible at all times for testing and inspection. However, this results in an increase in the number of cables running from the switchroom to the plant located in the tunnel.

Tunnel panels often exhibit a higher rate of surface corrosion than an equivalent panel, housed outside a tunnel. This is because a tunnel environment has a higher degree of air borne contaminants than is found outside a tunnel, and there is no rain to wash such contaminants from the panel. Tunnel panels are almost exclusively specially built for a particular tunnel application. They are correspondingly expensive, and have a long lead-time if a replacement panel is required.

Most modern road tunnels have such panels situated at road level, adjacent to the carriageway. An incident within a tunnel that results in extensive damage to such panels may result in the loss of extensive services within the tunnel. Such service loss can be sufficiently serious to prohibit the safe operation of the tunnel.

Washing water penetration has been reported in the panels at the recently opened Fore Street tunnel, despite specification of stainless steel panels to IP65. At Holmesdale tunnel a similar problem was reported with mild steel panel doors which were thought to have become misshapen after a second coat of paint. Polythene sheets have been suspended inside the panel to protect equipment.

R.4 Alternatives

Panel materials

The cost of manufacturing special tunnel panels from 316-grade stainless steel, to IP65 standard of environmental protection is very high. Cost savings could accrue if an alternative approach was adopted based on proprietary panels. The outer casing of a tunnel control panel should be designed to be sufficiently robust that the impact of a vehicle would not compromise the services provided from the panel. This could imply a very large protective structure, or the re-siting of the panel to a position where it is less likely to suffer damage, such as within a service bore adjacent to the main bores. Such a bore would normally be combined with an escape bore. Panels housed in such a bore would not require the same degree of mechanical or environmental protection as panels mounted within a tunnel bore.

Service bores

Bored tunnels with a circular cross-section will normally have an invert below the road deck which is used both as an air supply duct for ventilation and a route for electric cables and pipework for drainage and fire protection systems. A typical two-lane tunnel would have sufficient headroom within the invert to accommodate electrical distribution and control panels. However, they would need to be located close to the centre line, where the headroom is greatest, and the consequent additional resistance to air flow may be unacceptable. The safety of staff working in the invert, where emergency ventilation could lead to high air velocities, would also need to be carefully reviewed.

Although tunnel inverts are frequently damp due to seepage of water through joints in the tunnel lining, and potentially highly corrosive to steelwork, the environment would still be preferable to the traffic bore. If such a tunnel can successfully be longitudinally ventilated, avoiding the need to use the invert as a ventilation duct, then the location of electrical panels in the invert could be a practical proposition.

Cut-and-cover and immersed tube tunnels are normally of rectangular cross-section with dimensions as small as possible to minimise excavation and construction costs. In older tunnels cabling and pipework would run in the hollow interior of raised walkways; in later tunnels with no raised walkways they would be run in cast-in ducts beneath the verges and carriageway. As constructed, these tunnels rarely have anywhere to locate electrical panels except in the side walls of the road bores, although some tunnels in the Netherlands incorporate ducts for transverse ventilation and cabling.

Concerns about safe means of escape from tunnels under waterways, where egress can only be made at either end, have led to the introduction of separate escape passages between the two road bores in a number of tunnels overseas. Typical of these are the River Lee Tunnel in Ireland, the Noord Tunnel in the Netherlands and the Øresund Tunnel in Denmark. Since an escape passage only needs to be about half the height of the road bore, the remaining space is available for services and is ideal for electrical switchgear and control gear.

In the above instances the provision of a dedicated service bore is unlikely to be justified on economic grounds alone. However, if there is a requirement for an escape passage or ventilation ducts to be incorporated into the structure then the opportunity could be taken to include a service bore.

Internal panels

An alternative to the existing tunnel panel design is the use of additional internal panels, housed inside the main tunnel panels, to provide the required levels of environmental protection. The outer panel would then become a mechanical protection device for the inner panel, and provide additional protection against washing water ingress. Since the role of the outer panel casing would be changed to mechanical and primary environmental protection, construction material specifications could be amended accordingly and repair or replacement costs would be reduced. However, the additional depth required to accommodate two stages of protection could be a disadvantage where space is at a premium.

R.5 Value engineering review of the use of a service bore

A value engineering review of the use of a service bore to house panels and services for a rectangular cross-section tunnel is given in Table R1. The costs of adding a service bore are nearly all additional, offset to some extent by reductions in operating costs, tunnel closure costs (including traffic diversions) and reduced down time in the event of a fault. These are very difficult to quantify and will vary widely between one tunnel and another. The following discussion gives an approximate idea of the additional costs involved.

Distribution and control panels

In a typical twin bore tunnel, 1 km long, there may be 20 electrical distribution panels and one mid-point pump control panel. Moving these to a central service bore would enable enclosures of lighter construction and lower IP rating to be used instead of stainless steel, saving about £1,000 per panel or £21,000 in total.

Ventilation and lighting control panels

Relocating these panels from the LV switchroom (where they are assumed to be integral with the LV switchboards) to the service bore (where they will be distributed according to the major groupings of equipment) is likely to result in very little cost difference. It is assumed that the cost of the increased number of panels will be almost exactly offset by the generally lighter standard of construction for smaller units.

Cabling

Cabling systems vary widely according to the type of tunnel and the design of the various electrical systems. However, if it is assumed that there are the equivalent of 30 cables running the whole length of the tunnel, at an average installed cost of £10/metre, and that by locating panels into a service bore these can be replaced with 20 larger cables at an average of £12/metre, then the saving will be £60,000.

Lighting and ventilation to the service bore

It is estimated that the costs of lighting and ventilation to the service bore itself will be about £40,000 for each system.

Maintenance costs

The inspection and maintenance costs for a typical tunnel distribution panel are estimated to be about £2,000 per year. For a whole tunnel this would be about £40,000. Relocation of these panels to a service bore would permit access during normal working hours without tunnel closures, and this could reduce costs by 50% to £20,000 per year.

Conclusions

The net present cost of constructing and equipping a separate service bore will be around £3.6 million for a 1 km tunnel, while the potential savings arising from improved access to equipment are only about £220,000 over 20 years. It is clearly not economically justifiable to provide this facility in isolation. Construction costs have therefore been eliminated from Table R1.

However, if suitable space exists as a consequence of the need to provide an escape passage, or the availability of an obstructible invert, then there may be benefits in using this space for the location of electrical panels. However, such measures cannot be evaluated by simple consideration of whole life costs. The true benefits are more difficult to quantify, taking the form of improved access to investigate and respond to system faults, and for replacement or refurbishment of panels or components, which in turn would reduce the down time of equipment. Whether or not this is significant depends on the circumstances of the individual tunnel under consideration.

Table R1 Value engineering review of locating panels and services in a service bore

Location of panels and services in existing service bore			*Existing*		*Alternative*	
	Design life: 20 years		*Extra costs if no service bore*		*Panels in service bore*	
Function review						
Objective	*Importance rating*			*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.25			50		75
Sustainability	0.35			50		50
Health and safety	0.40			40		70
Total weighted score				46		64
Whole life cost						
	Interval (years)	*Present cost factor*[1]	*Estimated cost (£k)*	*Net present cost (£k)*	*Estimated cost (£k)*	*Net present cost (£k)*
Capital (panels)		1.00	21	21		
Capital (cabling)		1.00	60	60		
Capital (lighting and ventilation)		1.00			80	80
Maintenance	1	11.16	20	223		
Total present cost				304		80
Value ratio (Function/Cost)						
Value ratio ($x10^{-6}$)				151		803
Normalised value ratio				1.00		5.31

[1] *Present cost factors are for a discount rate of 6.0%.*

[2] *For explanation of value engineering review see Section 3.3.*

Appendix S: Electrical systems – emergency supplies

S.1 Function and description of system

Uninterruptible power supplies (UPS)

The function of UPS is to maintain supply without a break in the event of interruptions to the mains electricity supply. In addition, UPS also serve to provide a transient free, stable supply for sensitive electronic equipment.

UPS battery installations vary widely from one tunnel to another; the oldest tunnels may have very little UPS cover, while more recently constructed tunnels may have systems providing in excess of 100 kVA standby UPS power.

Static UPS systems usually comprise a set of batteries, an inverter and a battery charger. The inverter normally draws power from the mains supply and feeds it to the connected load. In the event of any interruption to the mains supply, power is drawn from the battery and converted to alternating current to feed the load for as long as the break lasts, or until the battery voltage drops to its lowest permissible level. The size of the battery stack is therefore proportional to the length of time (autonomy) for which the UPS is required to operate. The longer the operating time, the larger the battery stacks.

Rotary UPS perform a similar function, but employ a continuously driven motor/alternator combination to power the load. If the mains fail, the motor is driven by the battery. As static UPS technology has improved over recent years, this form of UPS has become less popular, mainly because of its high initial cost and need for mechanical, as well as electrical, maintenance.

Two types of battery are commonly used; vented nickel-cadmium (Ni-Cad) or valve regulated lead acid (VRLA). The latter are commonly misleadingly referred to as ‘sealed’ or ‘maintenance free’, neither of which are accurate descriptions. Stacks of single cells or monoblocs (up to 4 cells in a single unit) may be used. Vented nickel-cadmium or lead acid batteries can emit hydrogen and for safety reasons must be housed in a separate room, well ventilated and designated a Zone 2 hazardous area. Although it is not strictly necessary to segregate ‘sealed’ valve regulated lead acid batteries from other electrical equipment, they, too, can emit hydrogen if overcharged and so require good ventilation. Also, for temperature control reasons, it is desirable to locate them away from heat generating equipment.

Standby generators

The function of standby generators is to provide a power supply, to defined tunnel services, in the event of mains power failure.

Standby generators usually comprise a diesel driven alternator complete with bulk fuel storage, fuel management and the control gear necessary to switch the output of the generator onto the tunnel electrical distribution system. The generator will start automatically and be switched to serve essential electrical loads if the incoming mains supply fails. It will normally continue to run after mains power is restored, relying on manual intervention to switch the essential loads back on to the mains supply when it is deemed safe to do so. A resistive or resistive and inductive load bank is sometimes provided to enable the generator to be tested on load without the need to connect it to operational equipment.

S.2 Description of maintenance procedures

Uninterruptible power supplies (UPS)

Typical maintenance requirements for UPS systems include cleaning and inspection at intervals of 3 months. Servicing is not normally required. Typically operation should be tested at intervals of 3 months, and a battery discharge test carried out at intervals of 6 months. The latter test involves applying the fully rated load to the battery and measuring the voltage over a set period of time. This determines the performance of the battery stack as a whole, but does nothing to detect irregularities in individual cells. Cells or monoblocs can be discharge tested individually, but with 1000 or more cells in a tunnel installation this is a very lengthy process. Discharge testing alone is unsatisfactory as a means of estimating battery condition. Some failure modes of cells, for instance overcharging and drying out, can lead to a short term increase in performance before rapid failure, and the act of discharge testing can actually precipitate subsequent failure. Failure of a discharge test may result from a very small number of deteriorating or defective cells, the remainder being healthy. However, it is common for a complete battery stack, typically costing £8,000 or more, to be replaced if the discharge test yields unacceptable results, when, in fact, maybe only two or three cells or monoblocs actually need replacement. The cost of replacing a single monobloc would be around £200 (1998 prices).

Standby generators

Typically every 3 months servicing of the standby generator should include checking of levels, belts, starter batteries, leaks and lubrication where necessary. Typically a test run should be carried out at intervals of 3 months. This should include the following checks; test run for one hour using load bank at 100% load, noting the oil pressure and temperature, engine speed, exhaust temperature, load bank settings, water temperature, turbo air pressure, alternator battery charge current and alternator output (volts, amps, kVA, frequency, power factor), battery charger current and voltage prior to starting. Operation of control panels, associated lamps and alarms should also be tested. It should be noted that certain generators may need to be run more frequently than every three months to maintain adequate lubrication. At intervals of 1 year servicing typically includes a full lubrication and adjustment service. During servicing, checks for any excessive vibration, leaks, alarm operations, lights, vents, building and door damage should be carried out. Repairs to the building housing the generator should be made as necessary.

S.3 Issues

The battery stacks associated with UPS installations are very expensive to purchase and to maintain. A significant part of the cost of maintaining a UPS is in maintaining the battery stack, and the total number of cells needs to be kept to a minimum. For the majority of UPS designs, the battery stack is not required until a mains failure occurs, and continuous charging is not conducive to an extended battery stack life because batteries generally provide the best performance when they are cyclically charged and discharged.

The life and performance of valve regulated lead-acid batteries is very sensitive to temperature. Optimum performance is at around 20ºC to 25ºC. Typically battery life is reduced by 20% for every 5ºC by which the ambient temperature exceeds 25ºC. Control of the ambient temperature should be considered if the battery room regularly exceeds this value.

Nickel-cadmium batteries are less affected by ambient temperature and potentially have a longer service life. However, they require more maintenance than valve-regulated lead-acid types and may soon be prohibited for environmental reasons.

Some tunnels do not have standby generation available. The electrical distribution system for such tunnels often include UPS with large battery stacks that can provide 2 hours support for around 8 to 10% of the base load lighting. Battery stacks suitable for this type of application will typically comprise 186 cells, costing £100 to £200 each (1998 prices).

Issues relating to standby generation are addressed in Appendix M**.**

S.4 Alternatives

Battery monitoring

Battery condition monitoring can take several forms, and may involve measuring voltage, impedance or resistance and temperature. The most basic form measures voltage alone. Cells or monoblocs may be monitored individually, or, more commonly, in groups of, say, 16 cells or 4 monoblocs. Monitoring connections are made to either end of each group of cells and the voltage measured periodically. Results may be easily recorded and analysed, using a dedicated low specification PC (or the PC already provided for plant monitoring and control, if the operating system is compatible). Any groups where the voltage deviates significantly from the average for the installation are identified. These groups would contain possibly defective cells and can easily be located for inspection. Trends may also be analysed over a period of time to view the effects of ageing of the installation and predict the optimum point for replacement of the complete battery stack. The need for discharge testing may be reduced to once every 12 months through monitoring with failed cells easily located, making possible a policy of replacement only of failed cells or groups instead of premature replacement of healthy units.

Standby generator as an alternative to batteries

As an approximate rule of thumb, if standby power is required for more than about 15 minutes it would be more cost-effective to provide a small diesel generator rather than additional batteries, with a UPS/battery provided to support the load while the generator is starting. Such a set could be based on a variety of proprietary prime movers, including LPG powered units, capable of room sealed low level flue installation.

Future developments of fuel cells

Automotive traction research has resulted in the development of small, compact fuel cells. Such fuel cells are currently under trial for both automotive and domestic electrical applications, and, with a suitable inverter, are expected to provide a potential alternative to a generator/ battery/UPS combination.

Hybrid generator/UPS

Another approach would be to use a hybrid standby generator/rotary UPS combination. In these devices a diesel engine is linked to a rotary UPS via a flywheel, which is normally driven by the mains supply. If the mains fails, the flywheel supplies sufficient energy to start the diesel engine and to power the connected loads until the diesel takes over. In theory this system should need no batteries at all, relying instead on the kinetic energy stored in a flywheel. This approach does, however, have an obvious limitation if the diesel fails to start and it is important to allow for possible generator failure.

S.5 Value engineering review of alternatives

Battery condition monitoring

A value engineering review of battery condition monitoring for UPS batteries is shown in Table S1. The size, type and performance of battery stacks vary widely from one tunnel to another according to the designer's preference and the conditions of use. For the purposes of this assessment a hypothetical installation of six UPS sets is assumed, each with sufficient battery capacity to supply 40kVA for 1 hour. The corresponding six battery stacks would each consist of 64 x 6 volt monoblocs, which would be monitored in groups of 4.

The time spent on discharge testing would be halved with battery monitoring, saving about £300 per year on labour costs. Smaller savings on visual inspections would be more or less offset by the time spent on gathering and analysing performance data. The major savings would be in the avoidance of premature replacement of healthy cells. The life of VRLA batteries in UPS applications should be around 10 years. However, current practice leads to replacement of batteries on average about every 5 years.

Replacement of six stacks of batteries as described above costs about £50,000 (at 1998 prices). This means that current replacement costs for a tunnel average about £10,000 per year. If battery monitoring equipment is used to identify defective monoblocs and, say, 10% of the 6 x 64 monoblocs (= 38 units) require replacement before bulk replacement is indicated, say after 8 years, costs over 8 years will be £50,000 + (38 x £200) = £57,600, or £7,200 per year. To this should be added the capital cost of the battery monitoring equipment (£18,000), less the savings in labour for discharge testing (£300/year)

The financial benefits of installing battery condition monitoring in this analysis are shown to be significant, although there may be a considerable variation between one installation and another. There is also the additional benefit of greater information about the health of the battery installation, which will assist in planning maintenance and in preventing unexpected failure. This further tips the balance in favour of considering this provision for new and refurbished systems. Since UPS systems are primarily used to power safety related systems, anything that will improve the reliability of these systems will, in turn, enhance the safety of the tunnel. It is understood that some UPS manufacturers are considering the integration of battery monitoring into UPS equipment. This analysis suggests that this will bring cost benefits for new installations.

Table S1 Value engineering review of battery condition monitoring

Battery condition monitoring			*Existing*		*Alternative*	
	Design life: 20 years		*Replacement every 5 years*		*Condition monitoring*	
Function review						
Objective	*Importance rating*			*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.25			50		55
Sustainability	0.35			40		75
Health and safety	0.40			50		70
Total weighted score				47		68
Whole life cost						
	Interval (years)	*Present cost factor*[1]	*Estimated cost (£k)*	*Net present cost (£k)*	*Estimated cost (£k)*	*Net present cost (£k)*
Capital		1.00	50	50	68	68
Replacement cells	5	1.72	50	86		
Replacement cells	8	1.02			58	59
Extra testing if no monitoring	0.5	22.97	0.15	3.4		
Total present cost				140		127
Value ratio (Function/Cost)						
Value ratio (x10^{-6})				333		536
Normalised value ratio				1.00		1.61

[1] Present cost factors are for a discount rate of 6.0%.

[2] For explanation of value engineering review see Section 3.3.

Appendix T: Cabling and mechanical and electrical support systems

T.1 Function and description of system

Tunnel electrical systems use a large variety of different cables. Cables range from single core unarmoured cables, through single and multi-pair communications cables and wire armoured power cables to HV cables. To reduce the risk of toxic fume production in the event of a tunnel fire, all of these cables should be sheathed in low smoke, zero halogen (LS0H) material.

Tunnel cable handling systems comprise cast-in or buried ducts, conduits, trunking and cable tray or ladder. Individual cables may be cleated directly to the structure. Metallic components of support systems are almost always manufactured from either hot-dipped galvanised mild steel or from stainless steel. Stainless steel is currently more commonly specified. The layout of each system is bespoke, assembled from standard sets of parts.

Mechanical supporting systems vary in accordance with the exact requirements of each individual tunnel. Such systems are used to support equipment such as tunnel luminaires and tunnel ventilation fans and are commonly manufactured from either galvanised mild steel or stainless steel.

In the context of this appendix the term ‘mechanical and electrical support systems’ is taken to cover all supporting systems for mechanical and electrical services, for example cables, pipework and equipment.

T.2 Description of maintenance procedures

Cables and support systems are not normally cleaned, unless this is incidental to cleaning of the equipment served or is necessary to facilitate inspection. Tunnel cables and mechanical and electrical support systems are commonly inspected at intervals of 3 months and extensively tested every 5 years.

The 3 monthly interval inspection and maintenance normally includes a visual inspection of accessible cables and metalwork for signs of damage, defects, loose fixings or corrosion. Remedial action is taken as necessary. In addition, at 5 yearly intervals all power cables should be tested for continuity, insulation resistance between cores and earth and for circuit earth fault loop impedance. Communications cables are similarly maintained except that there is no requirement to perform an earth loop impedance test. There is, however, an additional requirement to retest the frequency response of audio communications cables to revalidate the audio channels. All screws and bolts securing support systems and equipment to the tunnel soffit are normally torque tested.

Costs for these works are a function of the extent of the cabling, cable handling and mechanical supporting systems in use at the tunnel. Particularly significant costs are the costs of re-testing all cables at 5 yearly intervals and torque testing screws and fastenings.

T.3 Issues

There is little alternative to the use of extensive cabling and mechanical and electrical support systems within road tunnels.

Tunnel ducting systems can be very wet. The insulation of cables insulated with cross-linked polyethylene (XLPE) compounds can break down if it comes into sustained contact with water, and only cables designed for prolonged immersion in water should be used.

Although the chemical resistance of cable sheathing materials is generally very good, long term exposure to certain substances, such as oils and tar, can cause local softening and destruction of the sheath. This has been known to result from seepage of such substances from surrounding contaminated ground.

The mechanical and electrical supporting systems used in tunnels are highly susceptible to corrosion. This can also lead to failure from secondary causes such as cracking or metal fatigue. Corrosion problems may be due to one or more of the following factors:

i Installation in a continually wet environment (for example cable pits, drainage sumps).

ii Electrolytic corrosion due to contact between dissimilar metals, differential stresses or stray electrical currents.

iii Chemical attack from tunnel cleaning detergents, particles from vehicle exhaust smoke or impurities in groundwater seeping in from the surrounding soil.

iv Condensation in untrafficked zones, for example shafts or galleries.

See also Section E.4 for the effects of corrosion on supports for tunnel luminaires.

T.4 Alternatives

There is a significant opportunity to use fibre optic cables in the place of copper cables for tunnel data and communications systems. The use of fibre optic cables would improve the reliability of data and communications transmission systems by reducing the probability of field wiring failures and eliminating susceptibility to induced electromagnetic interference. Such a system would have to include a fibre optic interface which would normally be based around an LED. Such interfaces are a further potential failure point, although the reliability of these systems is very high (the mean time before failure for an LED is approximately 100,000 hours). If implemented as a part of the environmental control system (ECS), a twin path ECS ring communications system would further increase system reliability.

Some mechanical and electrical support systems could be fabricated from an appropriate grade of fire retardant industrial plastics. The use of industrial plastics, such as glass-reinforced polyester, for cable tray and ladder and certain mechanical supporting systems would eliminate the risk of corrosion and the need for earthing of such systems (and the associated periodic maintenance). It would also be expected to be faster to install, with lower whole life costs. However, systems manufactured from such materials are generally less rigid than the equivalent metallic components, resulting in a need for closer spacing of supports. The different coefficient of expansion may also need to be taken into account.

An opportunity exists to replace existing galvanised supporting components for lighting systems with stainless steel. This would be expected to improve the whole life cost of the system.

T.5 Value engineering review of alternatives

A value engineering review comparing the use of stainless steel with hot dipped galvanised protection of components for lighting supports is shown in Table T1. This assumes that in the corrosive tunnel environment galvanised components would require replacement at intervals of 15 years on average and replacement cost is that same as initial installation. The calculation also neglects the remnant value of components which will not be life-expired at the end of the design life (if required this factor could be added into the calculation if required). It also assumes that the stainless steel does not corrode. Taking account of potential traffic delay costs during the replacement of galvanised components, the use of stainless steel components shows a slight advantage in value ratio, although the whole life cost is greater. Further benefits are the increased confidence in the security of components and reduced occupational health and safety hazards by avoiding the further construction activity of replacing components.

Table T1 Value engineering review of corrosion protection of lighting supports

Lighting and cable support			*Existing*		*Alternative*	
	Design life: 20 years		*Hot dipped galvanised support*		*Stainless steel support*	
Function review						
Objective	*Importance weighting*			*Rating (1 to 100)*		*Rating (1 to 100)*
Availability	0.30			60		90
Sustainability	0.35			50		75
Health and safety	0.40			50		75
Total weighted score				56		83
Whole life cost						
	Interval (years)	*Present cost factor*[1]	*Estimated cost (£k)*	*Net present cost (£k)*	*Estimated cost (£k)*	*Net present cost (£k)*
Capital (supply supports)		1.00	55	55	165	165
Capital (install supports)		1.00	50	50	50	50
Inspection	1	11.16	2	22	2	22
Maintenance	1	11.16	5	56	2	22
Replacement (supply)	15	0.18	55	10		
Replacement (install)	15	0.18	50	9		
Traffic delay cost (tunnel closure)	15	0.18	68	12		
Total present worth costs				214		260
Value ratio (Function/Cost)						
Value ratio (x10^{-6})				261		319
Normalised value ratio				1.00		1.24

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[1] Present cost factors are for a discount rate of 6.0%.

[2] For explanation of value engineering review see Section 3.3.

[3] Traffic delay cost for replacement of supports: 20 night closures @£570 per hour (night time closure) based on lane rental costs for a dual 2 lane trunk road and 40,000 ADT

Appendix U: Tunnel service buildings

U.1 Function and description

Many items of electrical and mechanical equipment associated with road tunnels are bulky and require additional space for access and maintenance. It is normally uneconomic to provide suitable space within the main tunnel structure, and therefore separate structures, known generically as service buildings, are provided locally to the tunnel. For tunnels with semi-transverse or hybrid ventilation, service buildings may be combined with the ventilation buildings housing the main ventilation plant and, possibly, access via stairs to and from the tunnel. There may be one or more such buildings, located above or below ground, over the tunnel or adjacent to it, and containing some or all of the following equipment.

Incoming electricity supply high voltage switchgear and transformers

Because high voltage switchgear must only be operated by an appropriately qualified ‘Approved Person’, it is normal for high voltage equipment to be located in a dedicated, locked room.

Main low voltage switchboards and control panels for lighting and ventilation systems

These are usually located together in the main low voltage switchroom.

Standby generators and fuel tanks

Diesel generators can be a source of significant noise and vibration, and therefore need to be located away from any areas where this might be a problem. Underground locations are undesirable because of the need to duct high volumes of cooling air to the engine and to discharge the exhaust.

UPS sets and batteries

Batteries, even so-called ‘sealed’ types, require reliable ventilation to prevent the build-up of explosive vapours. Wet-type cells should be installed in a separate room, which must be designated as a Zone 2 hazardous area. Temperature control is needed to maximise battery life.

Equipment cubicles for computer, communications and CCTV equipment

To avoid problems arising from electromagnetic interference, this equipment should be kept away from electrical power systems.

Local control facilities

As a minimum requirement, there should be a local control position capable of monitoring and operating plant during maintenance activities. Appropriate CCTV, traffic control and communications facilities will also be provided, according to the needs of the site. Such a facility may also be used as a backup to a remote operator’s terminal in the event of communications systems failure, or as an incident control room for use by the emergency services.

To provide for the needs of the above systems, service buildings will normally incorporate the following features:

i normal, emergency and standby lighting;

ii power supplies for maintenance and test equipment;

iii air conditioning to maintain the temperature of batteries and electronic equipment within the limits required for correct operation;

iv fixed fire extinguishing systems for rooms with a significant fire risk or containing essential equipment (typically electrical rooms, electronic equipment rooms and generator rooms);

v raised ‘computer’ floors for electronic equipment rooms and main LV switchrooms, for ease of access to the large amount of cabling;

vi intruder and fire alarm systems;

vii basic mess and washroom facilities for maintenance staff;

viii vehicular access and car parking for maintenance vehicles;

ix pedestrian access to the tunnel;

x a workshop and storage facilities for spares and traffic signs are less commonly provided, but nevertheless valuable.

U.2 Description of maintenance procedures

Maintenance of the tunnel equipment located in the service buildings is covered in the relevant Sections elsewhere in this report. The building services systems in general require little maintenance, and in many respects can be maintained as and when failures occur. Annual inspections should be undertaken and any necessary touching up of paintwork and maintenance of the roof should be carried out at this time. Cleaning of the gutters and weeding should also be carried out at intervals typically of 1 year. Routine functional and safety checks should be carried out at least once a year on all electrical equipment (to satisfy the Electricity at Work Regulations), air conditioning (to ensure performance is within acceptable limits) and emergency lighting and security systems (to verify correct operation).

U.3 Issues

The preferred location for a service building is over, or immediately adjacent to, one portal of a tunnel, where ease of access for vehicles and pedestrians to the tunnel can be combined with a minimum route length for electrical cables. The greater the distance from the service building to the tunnel, the greater will be the size of cables required to overcome voltage drops. Location of a service building at ground level minimises construction costs and maximises access for maintenance and plant replacements.

Transformers, standby generators and fuel tanks are best located outside the service building, where ventilation requirements and fire risks can more easily be resolved.

In many cases the location and form of service buildings is heavily influenced by the land available and planning constraints, and are often fixed in the early stages of consideration of a project before design commences. This can lead to operational disadvantages, for instance the need to drive a considerable distance or to implement special traffic management measures to get from the service building to one or both tunnel bores.

Location of large plant items below ground level can considerably complicate access for replacement, and the land take for a service building below ground will generally be greater than the equivalent above ground structure. Natural ventilation will also be less freely available.

In a number of tunnels, a dedicated control room is provided with separate control terminals for a tunnel operator and a maintenance engineer to work side by side. In almost all cases this is unnecessary duplication of equipment, and provision of a separate room for the equipment is not justified.

In many cases tunnel service buildings are the signing-in point for tunnel maintenance staff. It is therefore useful if space is provided for this and furnished with a desk and chairs. This space should be directly accessible from outside without the need to pass through rooms containing equipment.

U.4 Alternatives

The location and appearance of a service building is more often than not dictated by external requirements. However, the established custom of locating service buildings close to portals is not necessarily the most efficient approach as far as electrical systems are concerned. For existing tunnels there will be little that can be done to improve upon fixed locations of equipment and cable routes. However, for a new tunnel, a simple cost-benefit analysis should be carried out, before the sites of the service buildings are finalised, to determine the optimum compromise between cable route lengths and ease of access between the service building and the tunnel.

In general, the maximum practical ‘reach’ of low voltage services into a tunnel from a service building is about 500 metres. This means that a 1 km tunnel could be served either by two service buildings, one at each end, or by a single, central building. The latter approach is not always feasible, for instance in river crossings, but, where it is, considerable cost savings may be possible by reducing the total structural and equipment costs. However, such savings must be set against loss of operational convenience arising from less convenient road access to the tunnel.

An approach commonly used on the Continent, but less in the UK, is to integrate the service buildings into the portal or ventilation structures, with access via service roads from either side of the main through route. This has the advantages of minimising structural costs and cable route lengths, while providing good access to either tunnel bore. It may also provide a useful diversion route for vehicles that may be trapped on an approach road by an unexpected tunnel closure. Aesthetically, the result may be to increase the visual bulk of the portals, requiring careful architectural detailing for an acceptable appearance. This may mean that such an approach is favoured by those who are less reticent about the appearance of their tunnels.

When renewal of control equipment is undertaken, careful consideration should be given to the operator interfaces actually required. In most cases a single terminal to combine engineering and operational requirements will suffice.

Abstract

Achieving value for money in operation and maintenance of equipment in tunnels is increasingly important and areas are sought where economies can be made without compromising safety or increasing congestion. To address this need a value engineering review has been undertaken of highway tunnel equipment.

The review was based on the procedures in the Highways Agency Value for Money Manual, and comprised a value management and value engineering workshop and subsequent detailed reviews. The operators of ten sets of tunnels were consulted together with various suppliers. Additionally general experience reported at meetings of the Highways Agency Tunnel Operators' Forum and the UK Tunnel Operators' Forum was incorporated.

The principles of value engineering are summarised and a specific methodology is proposed for dealing with tunnel equipment. It was found that it was unrealistic to define unique optimum solutions for all tunnel equipment because of the many site specific factors associated with highway tunnels. However, it was possible to identify the areas in which changes were likely to have the most significant impact on value.

For each of the main systems the function, typical maintenance, common problems and possible alternatives associated with the equipment, are discussed in the report. Where adequate information is available options have been costed and a number of detailed value engineering reviews are presented showing the implications of particular alternatives. Over 60 specific areas of possible improvement have been identified and are listed in the report.

Related publications

TRL448	*Value management for tunnel procedures* by S Bird, J E Potter, D M Hillier and K H Bowers. 2001 (price £35, code H)
CR252	*Study of the costs of cut-and-cover tunnel construction* by A R Umney and D Miller. 1991 (price £20, code D)
CR63	*A study of the operating costs of road tunnels in the United Kingdom* by A M Rossell and B R Pursall. 1988 (price £20, code C)
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