Sustainable Tunnel Ventilation – Standards and Practice

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1 INTRODUCTION

There is increasing interest in the application of sustainability concepts to tunnel ventilation design, installation and operation. This is due to the need to reduce energy consumption as a means of minimising carbon footprint, the commercial imperative to reduce costs at all stages of the infrastructure life-cycle, and the requirement to enhance equipment availability.

The World Road Association (PIARC) is about to publish a report on “Recommendations for Sustainable Road Tunnel Operation” [Ref. 1], which contains a survey of existing frameworks for sustainability, including various national regulations and guidelines. The report also includes chapters on identifying and reducing costs associated with tunnel civil works and equipment. This paper includes a summary of the PIARC report in the areas pertinent to tunnel ventilation.

Three case studies are provided to illustrate the application of sustainability concepts to tunnel ventilation design and operation. The case studies comprise: a twin-tube unidirectional urban road tunnel, a single-tube bidirectional urban road tunnel, and a twin-tube airport road tunnel. In all of these case studies, a significant reduction in power consumption was obtained by changing the tunnel ventilation operating philosophy and/or installing energy-efficient equipment.

2 SUSTAINABILITY CONCEPTS

[Ref. 1] provides an overview of sustainability concepts and their application to tunnel design, construction and operation. The "sustainable development" concept may have a slightly different meaning from one country to another, and its scope may vary. Nevertheless the Brundtland Report [Ref. 2] and the 1992 Rio Summit [Ref. 3] have provided the first rules, set a general framework, and established globally-recognised principles.

According to the Brundtland Report [Ref. 2], sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The sustainable development concept is based on three main pillars:

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

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

Contrary to certain common beliefs, the concept of sustainable development does not solely rest on the objective of preserving the environment. It also aims to meet social needs and economic requirements. It is thus generally represented by three pillars which should roughly have the same weight (Fig. 1).

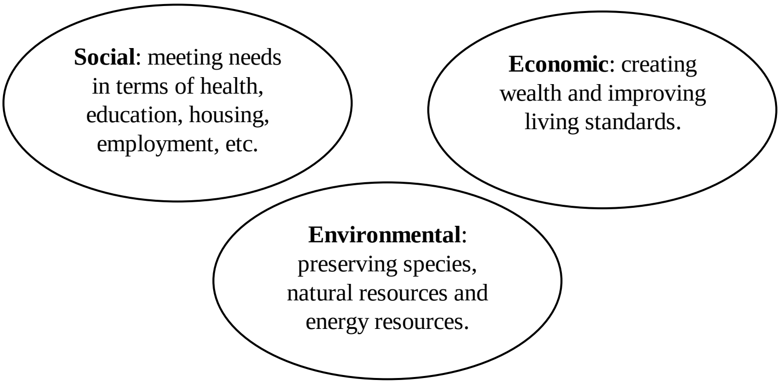

Fig. 1: Pillars of Sustainable Development [Ref. 1]

Sustainable development represents a holistic approach of the whole life-cycle of a project, and requires a balance to be struck between economic, social and environmental objectives. A sustainable design must recognise the integrated nature of human activities and must therefore include a commitment to coordinate planning and design amongst all relevant sectors, disciplines and groups.

With regards to safety, consideration must be given to the three pillars: social (in terms of human aspects), economic (cost of mitigation measures as well as the impact of accidents) and environmental (environmental damage due to pollution).

3 TUNNEL LIFE-CYCLE

The operation of a road tunnel is highly dependent on the design and construction phases which preceded the commissioning of the work. More precisely, it is necessary to take account of the effect of solutions opted for during a project's design phase on operating conditions. If the selected design solution is not ideal, it will be very difficult to improve the tunnel’s sustainability throughout its life cycle.

The World Road Association has provided an estimate of the impact of the various phases of a tunnel project on operating costs [Ref. 4]. The data is presented in Table 1 below, and highlights the importance of good design to minimise operating costs.

Project phase	**Estimated impact**
Design / study	60 – 80%
Build / construction	10 – 30%
Operate / tunnel lifespan	10 – 30%

Table 1: Impact of project phases on operating costs [Ref. 4]

The relationship between the project phases and the level of influence exercised on operating costs is shown diagrammatically in Fig. 2. The planning phase (study/design) is normally 3 to 10 years, the building/construction phase 2-3 years while the operation phase may be from 5 to 20 years for installations/equipment and 80 to 100 years for the tunnel structure. This does not account for possible refurbishment work undertaken on the tunnel.

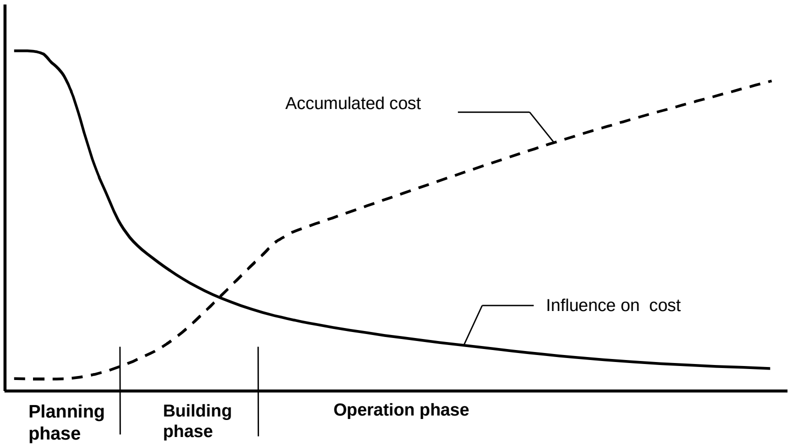

Fig. 2: Accumulated costs as a function of tunnel life-cycle [Ref. 4]

The impact of the upstream phases, especially the design phase, on accumulated costs is extremely important. Since cost-effectiveness is an integral part of any sustainability consideration, any worthwhile study of tunnel sustainability must focus on the design phase of the project, while still accounting for the construction and operation phases.

4 APPLICATION OF SUSTAINABILITY CONCEPTS TO TUNNELS

The starting point of this section is that a decision has been taken to build a new tunnel, or that a review of the sustainability of an existing tunnel is required. The issue of whether a new tunnel should be built at all is outside the scope of this paper.

A balance between sustainability and cost-effectiveness must be struck. Ideally, the measures taken by the tunnel manager are both sustainable and cost-effective (not only on a societal level, but also for the tunnel itself). However, in most cases a compromise has to be found, balancing the three pillars of sustainability on the one hand, and cost-effectiveness on the other hand.

The minimum requirement for a measure to be called “sustainable” should be that the total effect on all the three pillars is better than, or at least equal to, the present situation (see the definition below). For a measure to be called “cost-effective”, the life cycle costs of the measure should lower, or at least be equal to the life cycle costs in the present situation.

Thus, for the consideration of measures supporting sustainability, the decision matrix in Table 2 could be applied.

		Cost effective measure?	
		No	Yes
Sustainable measure?	No	Don’t implement the measure	Consider if the cost effectiveness weighs up to loss of sustainability, according to the applicable tunnel operations policy, and determine whether or not to implement the measure.
	Yes	Consider if the sustainability weighs up to loss of cost effectiveness, according to the applicable tunnel operations policy, and determine whether or not to implement the measure.	Implement the measure

Table 2: Decision matrix for sustainability measures [Ref. 1]

Table 3 below summarises the results which may be expected in three situations:

- New tunnels for which the sustainability concept may be applied at the earliest stages and cover all components: the tunnel itself and its equipment, operating procedures and employees (including training and raising the awareness of employees regarding sustainability);
- Existing tunnels in which a large-scale refurbishment or upgrading programme will be implemented. The scope offered is not as broad as for a new tunnel. However, a sustainable development approach can be used for the equipment to be renovated. This renovation may have an impact on several pillars: impact on the economic pillar

(maintenance cost), impacts on the social pillar (e.g. the new equipment may reduce noise nuisance) and the environmental pillar (through the use of equipment which consumes less energy while providing the same or improved service);

- Existing tunnels where no major refurbishment is envisaged. The only options will comprise optimising operating parameters, and possibly raising employee awareness regarding sustainable operations.

Pillar	Issue	Tunnels in project stage	Tunnels to be refurbished or upgraded	Existing tunnels
Economic	Wealth creation	Strong	Moderate to low	Very low
	Improvement of living standards	Strong	Moderate to low	Very low
	Reduction in operating costs	Strong	Moderate to low	Moderate to low
Social	Impact on housing	Strong	Moderate to low	Low
	Impact on human health	Strong	Moderate to low	Low
	Impact on employment during construction (or refurbishment)	Strong	Moderate	Not applicable
	Impact on employment during operation	Not applicable	Strong	Strong
	Economic attractiveness	Strong	Low	Very low
Environmental	Preservation of species	Strong	Moderate to low	Low
	Preservation of natural resources	Strong	Moderate to low	Very low
	Preservation of energy resources	Strong	Moderate to low	Moderate to low

Table 3: Impacts of a sustainable development approach [Ref. 1]

5 EXISTING FRAMEWORKS FOR SUSTAINABILTY

According to the survey undertaken in Ref. 1, there are no consistent frameworks with regards to the development of sustainable development of tunnels across different countries. Certain countries which have general regulations have no specific application to tunnels; conversely, other countries, which may not have general regulations, have set specific requirements for tunnels (regulatory texts, recommendations, etc.). In most cases, existing requirements do not specifically apply to tunnels. Instead, they usually apply to road projects or infrastructure construction projects.

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

- In Greece, all tunnelling projects must have an environmental license according to the environmental law. The Greek Ministry for Infrastructure, Transport and Networks has drawn up the “Guidelines for Design of Tunnel Electromechanical Installations” (2002, lighting, ventilation system, power supply, water supply, fire detection and fire-fighting system, traffic management system, communication, SCADA, etc.). Furthermore, in 2004 the “Guidelines for ordinary maintenance of electromechanical tunnel installations” were adopted. Risk analysis methodologies have been adopted at the national level in order to support decision making for safety measures and arrangements.
- In Japan, “The Environment Impact Assessment Law” was enacted in 1997. According to this law, the corporation which carries out a large-scale project, including the construction of a long road tunnel, has to predict and evaluate the impact on the environment. If the predicted impact is significant, the project must be improved to be more environmentally friendly, or stopped.
- The Spanish Ministry of Public Works has produced several documents concerning tunnel lighting in particular, such as “Recommendations for road and tunnel lighting (1999)” and “Standard for energy efficiency in public lighting (2008)”, along with several technical reports.
- In the Netherlands, the availability demands for the tunnel are documented in the Rijkswaterstaat Tunnel Standard that was developed during the past 2-3 years. Parts of the Tunnel Standard (regarding the prescribed tunnel equipment) are included in the legislation (ministerial regulation under the “Law on Additional Rules for the Safety of Road Tunnels or “Warvw”) for state owned road tunnels. However, the availability demands will not be part of the legislation, since it is out of the scope of the Warvw and the European directive. Also, the availability of the state owned road network is already the responsibility of the Minister of Infrastructure and the Environment, thus making additional legislation in this field unnecessary.
- In Italy, the ANAS "Linee Guida per la progettazione della sicurezza nelle Gallerie Stradali" are general guidelines applied to design M&E systems and safety issue for the road tunnel owned directly by ANAS. The guidelines, which have general technical validity, suggest requirements for the installations on the basis of safety and environmental aspects and include a methodological proposal to approach the risk assessment to support decision making for the Tunnel Operating Body.
- In South Korea, the “Act on environmental impact assessment” was established in 1977. Large-scale projects such as urban development, industrial estates, energy, harbours, railroads, roads, airports, etc. should evaluate their impact on the environment, during and after the construction of the project. For road tunnels, the impact of excavation during the construction and air pollution during the operation are frequent issues.
- In Singapore, environmental impact assessment studies are conducted for large scale infrastructure projects including long road tunnels. The National Environmental Agency (NEA) of Singapore sets targets and guidelines for ambient air quality and noise in Singapore.

A number of different evaluation methodologies have been developed across different countries and regions:

- In 2003, the Federal Roads Office (FEDRO) in Switzerland established a method to evaluate road infrastructure projects while taking account of sustainable development objectives (NISTRA). NISTRA is a general methodology applicable for tunnels.
- In the Netherlands, the Rijkswaterstaat (a public institution managing traffic by road and water throughout the Netherlands) uses the DuboCalc calculation module to evaluate the sustainability of materials and energy for construction projects in civil engineering.
- In North America, the Leadership in Energy and Environmental Design (LEED) is a standardisation system for high-performance green buildings created by the US Green Building Council in 1998.
- In Great Britain, the Building Research Establishment Environmental Assessment Method (BREEAM) was created in 1990 as a method of assessing the environmental performance of buildings. It was developed by the Building Research Establishment (BRE), a UK research entity.
- In Italy, UNI (Entre Nazionale Italiano di Unificazione) has defined the Standard for Tunnel Lighting, based on the CIE 88-1990 and CIE 140-2000, combining safety standards with energy consumption requirements. The UNI standard has become a national standard with ordinance dated 14th September 2005.

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

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

Of the three pillars which constitute the concept of sustainable development, the environmental pillar is often the one that is handled the best, particularly in relation to aspects concerning the preservation of natural and energy resources. The economic pillar is also handled fairly well, in particular the creation of wealth. The social pillar is not always dealt with as well as the other two pillars.

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

However, despite regulations which, with regards to operation, are not, at this moment in time, either very comprehensive or restrictive, many tunnel managers or tunnel operators have taken the initiative. These initiatives are consistent with a sustainable development approach. Although their origins are rooted in the concept itself, they are rarely carried out as part of a global strategy and they only address one of the three pillars. It is suggested that a global strategy would comprise addressing all three pillars at the same level of detail.

By considering these three pillars and the same themes as before, Table 4 below identifies initiatives that a tunnel manager or a tunnel operator may take in relation to an existing structure.

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

Table 4: Possible initiatives for a tunnel manager or tunnel operator [Ref. 1]

6 OPERATING COST REDUCTION

[Ref. 1] addresses the issue of operating cost reduction in tunnels. Almost all of the equipment installed in a tunnel requires electrical energy which is usually bought from a supplier. Depending on the power required to guarantee the smooth running of equipment, power supply may be high-voltage or low-voltage. Generally, it is high-voltage if the tunnel is equipped with a ventilation system.

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

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

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

The respective share of each of these energy-consuming systems varies greatly, depending on the specific characteristics of the tunnel: length, gradient, water ingress, etc. For example, a short tunnel would not normally be mechanically ventilated (therefore the power consumption related to ventilation element is removed), but it will be lit with entrance zones covering almost its entire length and, due to its short length; lighting will thus be a major energy consumption factor. In contrast, for very long tunnels, the energy-consumption of lighting will be low compared with the energy consumption of the ventilation system. In terms of optimisation, ventilation and lighting systems usually deserve special attention because the potential gains can be high.

Table 5 below summarises the impact of broad families of equipment (with the exception of smoke extraction in case of fire) in terms of electrical consumption, according to the length and type of structure (unidirectional or bidirectional). The information provided should be considered as a general trend as the specific characteristics of a particular structure may lead to different findings. Air exhaust to avoid portal discharge is not considered in this table.

	L ≤ 300 m	300 m < L ≤ 3 000 m		L > 3000 m	
	uni- and bi-directional	uni-directional	bi-directional	uni-directional	bi-directional
Lighting	Very major	Major	Average	Average	Minor
Ventilation	No impact	Very minor	Average	Minor	Major
Safety equipment	Very minor	Minor	Minor	Average	Average
Auxiliaries and miscellaneous losses	Very minor	Minor	Minor	Average	Average
Pumping	Minor	Minor	Minor	Minor	Minor
Note: The information above only has comparative value within the same column (for instance, electrical energy consumed by lighting is greater when the length of the tunnel increases, but its relative share within the total consumption decreases).					

Table 5: Relative impact of equipment on electrical consumption (adapted from Ref. 1 on the basis of NFPA 502, 2014 edition)

In relation to energy expenditure, the first thing that an operator can do for any given energy requirement is to play competitors off against each other by consulting several suppliers that provide the kind of electricity to be used. This approach assumes that the installation is optimised in terms of the power installed and the operating times of the various pieces of equipment.

In effect, energy expenditure is closely linked to two factors: the power installed per family of equipment and each family of equipment's operating time.

For each family of equipment, the installed power is assessed during the study phase and is fixed during the implementation phase. Once the structure is operational, the installed power can only be changed during renovation. At that point in time, the installed power may be decreased if the applicable standards and regulations allow such a reduction, and if the energy performance of the replacement equipment has improved. It may be increased if regulations have become stricter (for example, if greater smoke extraction capacities are specified).

If an operator wishes to reduce its expenditure on electricity without renovating the tunnel, it can only do so by optimising the operating times of the installed equipment.

7 PRACTICAL EXAMPLES

As indicated above, comprehensive sustainability analyses are rarely undertaken for tunnels. However, some practical examples related to good sustainability practices are given below, focusing on energy conservation for existing tunnels.

7.1 Unidirectional river-crossing tunnel

The energy consumption of an existing unidirectional river-crossing urban road tunnel has been critically assessed, with a view of optimising the tunnel ventilation operation.

The tunnel consists of twin bores, each of which is approximately 2.2km long and carries a two-lane carriageway. The tunnel is ventilated in a semi-transverse manner from two ventilation stations on either side of the river. These stations contain supply fans intended to supply clean air to the tunnel via the invert entering the bore via cut-outs in the walkways and extract fans to remove vitiated air from the bore. The arched approach section at the east of the tunnel is ventilated separately by eight extract fans installed in the crown of the structure.

The ventilation system currently operates constantly but with the configuration being modified during the day to suit the anticipated traffic conditions (such as morning and evening rush-hours). If the carbon monoxide (CO) levels increase or visibility is reduced, alarms are triggered and system flow rates are increased manually; if necessary, the tunnel is closed.

In the event of high CO levels, the control room engineers increase the fan speeds to maximum and start up banks of jet fans in sequence until all are in use. If levels were to continue to rise then the short-term tunnel closures may be required.

A similar approach is taken in case of poor visibility: fan speeds are progressively increased to maximum and the banks of jet fans are started up in sequence. If necessary, the tunnel would be subject to short-term closure.

Air quality simulations were undertaken using IDA [Ref. 5] to compare measured air quality values under the current ventilation regime with the calculated values. While there were some detail differences between the measured pollutant levels and those predicted by the computer model, there was reasonable agreement on the peak concentrations of NO_2 within each bore for typical tunnel operation (Table 7).

	Measured (mid-river)	Predicted maxima (occur on exit ramps)
North Bore	1.5ppm	5.2ppm
South Bore	3.5ppm	6.2ppm

Table 6: In-Tunnel Maximum CO Concentrations Weekdays

	Measured (Mid-River)	Predicted maxima (occur on exit ramps)
North Bore	0.2ppm	0.16ppm
South Bore	0.3ppm	0.26ppm

Table 7: In-Tunnel Maximum NO_2 Concentrations Weekdays

Measurements of visibility in the tunnel were not available. However the computer simulations predict maximum extinction values of 0.0012 in the north bore and 0.0016 in the south bore during peak daily traffic. These equate to maximum 'K' values of 1.2 and 1.6.

On this basis it is proposed that any new ventilation control regime for the tunnel should not allow CO concentrations of greater than 6ppm, NO2 concentrations in excess of 0.3ppm or extinction 'K' values of any greater than 1.6.

The energy efficiency benefits of using closed-loop controllers for the tunnel ventilation have been assessed on the basis of the IDA model. The model was run over a 24-hour period using measured traffic data, and the overall power consumption was integrated over time.

The model includes 'sensors' at three locations per bore in the tunnel. There are separate sensors at each location reading CO, NO_2 and the extinction coefficient. The outputs for each sensor type are compared and the highest value for each pollutant is forwarded to its respective proportional controller.

There are three proportional control modules, one for each pollutant. The input to each controller is the maximum pollution value detected by the sensors along the tunnel; this is compared with the setpoint value for the pollutant and an output signal between 0% and 100% is forwarded to the Proportional/Integral (PI) comparison module for the tunnel bore. The gain and time constants for each pollutant have been set separately. These values have not been optimised but do seem to give a reasonable response while avoiding ‘hunting’.

The two bores of the tunnel have separate control systems. For each bore, the three outputs from the proportional controllers are compared and the largest value is forwarded to the fan controllers for each ventilation station.

Each fan station receives a signal of between 0% and 100% from the PI comparison unit. The fan flow rate is set so that the 100% signal delivers the maximum flow from the fan. The maximum values assumed are those measured during fan tests. The fans will only operate if they are allowed to by the timer and logic switches that set the ventilation mode.

Electricity is assumed to cost GBP 0.097 per kWh at 2013 prices. It is estimated that for this idealised typical weekday that using closed loop control the tunnel fans would consume approximately 170 kWh per day. This is equivalent to approximately GBP 5900 per annum. This compares very favourably with the GBP 342 500 estimated for the current ventilation regime.

This is considered to be an over-optimistic assessment of the savings that might be achieved, assuming as it does that the traffic in the tunnel is free flowing at a speed of 40 mph every day for an entire year. Under slower moving conditions the air demand will increase and the north (eastbound) bore system will be required to operate.

Our IDA calculations indicated that for normal weekday operation with uncongested one way traffic, the tunnel is usually self-ventilating and requires no mechanical ventilation. Prior to the installation of a feedback control system, the tunnel operator therefore decided to use a simple strategy of switching off the fans during normal operation. The air quality continued to be monitored continuously, with the option of switching the fans on should the need arise.

At the time of writing this paper, the tunnel operator had reported significant reductions in power consumption using their manual control method, although no definitive measurements of the savings had been recorded yet.

7.2 Bi-directional river-crossing tunnel

The energy consumption of an existing bi-directional river-crossing urban road tunnel has been analysed, with a view of optimising the tunnel ventilation operation.

The tunnel consists of a main single bore tunnel carrying two lanes of traffic in both directions beneath the river. This main bore is approximately 3.2km long. In addition to the main tunnel there are two two-lane branch tunnels connected into the main bore.

The tunnel was originally ventilated in a semi-transverse manner from six ventilation stations along the length of the main bore and in the branch tunnels. The ventilation stations contain supply fans intended to supply clean air to the tunnel via the invert walkways and extract fans to remove vitiated air. Five of the ventilation stations remain in operation, while the sixth station has been decommissioned.

The ventilation system currently operates constantly but with the configuration being modified during the day to suit the anticipated traffic conditions (such as morning and evening rush-hours). If CO levels increase or visibility is reduced, alarms are triggered and system flow rates are increased manually and if necessary the tunnel is closed.

In the event of high CO levels, the control room engineers increase the fan speeds to third speed and then to maximum. If levels continue to rise then short-term tunnel closures may be required. A similar approach is taken in case of poor visibility: fan speeds are progressively increased to maximum. If necessary the tunnel would be subject to short-term closure.

The tunnel has recently had its pollution/visibility monitoring systems upgraded with eight units that monitor CO, visibility and NOx.

The air quality simulations considered conditions in the tunnel under the current ventilation regime. While there were some detail differences between the measured pollutant levels and those predicted by the computer model there was broad agreement on the peak concentrations of CO and NO_2 within each bore for typical tunnel operation (Table 8).

	Measured (any tunnel location)	Predicted maximum (any tunnel location)
CO	5.5ppm	4.7ppm
NO_2	0.26ppm	0.14ppm

Table 8: Tunnel Maximum CO and NO2 concentrations on weekdays

Measurements of visibility in the tunnel were not available. However the computer simulations reported in predict maximum extinction values in 0.0020 in the main bore. This equates to a maximum ‘K’ value of 2.0.

On this basis it is proposed that any new control regime for the tunnel should not allow CO concentrations greater than 5.5ppm, NO_2 concentrations in excess of 0.26ppm or extinction ‘K’ values of any greater than 2.0.

A closed-loop control system was modelled in the IDA software, in a manner similar to that adopted for the unidirectional tunnel (section 7.1). It is estimated that for an idealised typical weekday that using closed loop control the tunnel fans would consume approximately 710 kWhr per day. This is equivalent to approximately GBP 25 000 per annum. This compares favourably with the GBP 168 000 estimated for the current ventilation regime (at 2013 prices).

The traffic data showed that in the morning peak hours, 62% of the traffic in the tunnel is heading eastwards, while during the evening peak hours, 63% of the vehicles heading towards the west. Our calculations indicated that this asymmetry of traffic flow was sufficient for the tunnel to be self-ventilating during the peak morning and evening hours.
Prior to the installation of a feedback control system, the tunnel operator therefore decided to use a simple strategy of switching off the fans during the morning and evening rush hours, in order to save energy consumption. The air quality continued to be monitored continuously, with the option of switching the fans on should the need arise.

At the time of writing this paper, the tunnel operator had reported significant reductions in power consumption using their manual control method, although no definitive measurements of the savings had been recorded yet.

7.3 Airport Tunnel

In another case, an approximately 0.6km long dual tube road tunnel at a major international airport required significant refurbishment. The original specifications for the refurbishment called for 710 mm internal diameter conventional jet fans with two-pole motors. It was anticipated that this installation would be noisy, take up a lot of space, and possibly require increased safety precautions due to high jet velocities required for effective operation.

A redesign of the proposed ventilation system used 800 mm internal diameter MoJets, an innovative type of jetfan which feature shaped nozzles [Ref. 6]. The shaped nozzles reduce the Coanda effect, which is the tendency of the air steam produced by each jet fan to be drawn to nearby walls, leading to increased friction and significantly increasing the energy required to move the air. This effect occurs because the jet flow close to the wall decelerates, creating a pressure difference across the jet that reinforces its attachment to the wall, even at high velocities. The reduction of the Coanda effect was confirmed by the use of 3D CFD calculations (Fig. 3).

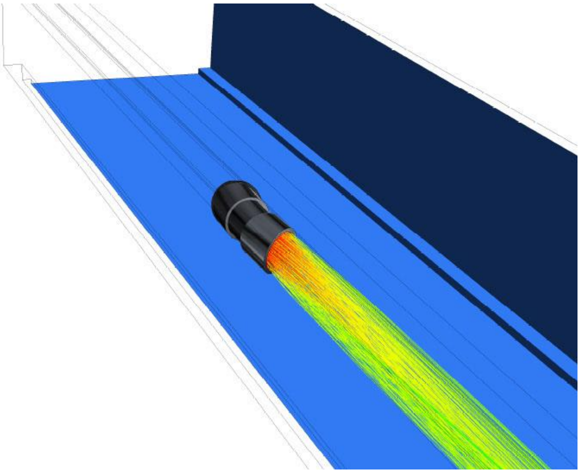

Fig. 3: 3D CFD particle tracks coloured by air velocity

Four-pole motors were selected that run at half the speed of equivalent two-pole motors were selected for the design. The result was a 30 percent reduction in power consumption and a 7 dB reduction in sound pressure level in the tunnel, along with significantly reduced jet air velocity. In addition, the innovative jetfans could be installed much closer to tunnel walls and at reduced distances along the tunnel, reducing construction and cabling costs.

8 CONCLUSIONS

A robust approach to achieving sustainability requires the simultaneous consideration of the social, economic and environmental impacts of any design and operation proposals throughout a tunnel's life-cycle. Statutory requirements, technical guidelines and frameworks should all be considered in formulating holistic strategies for the design and operation of tunnels. The application of such holistic considerations is very challenging, but progress can nevertheless be made through focusing on certain aspects of sustainability, such as reducing operating costs and reducing sound emissions. Tunnel ventilation provides a significant opportunity for sustainability improvements, particularly for long tunnels which can absorb significant amounts of power.

Although the initial design of a tunnel has the greatest impact on a tunnel's subsequent sustainability, it is still possible to achieve significant improvements based on improved operations and through the subsequent installation of innovative technology, as demonstrated through the three projects presented in this paper. It is hoped that this paper will encourage additional research and field trials to promote sustainable tunnel design.

9 REFERENCES

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