CEDR Transnational Road Research Programme
Call 2013: Energy efficiency

funded by Austria, Germany, the Netherlands, Norway, Slovenia and the United Kingdom,

REETS: Realistic Energy Efficient Tunnel Solutions

Initial review of technologies

Deliverable 1.1
July, 2015

CEDR Call 2013: Energy efficiency
REETS
Realistic Energy Efficient Tunnel Solutions

Catalogue of energy reducing options

Due date of deliverable: 30/06/2015
Actual submission date: 31/07/2015

Start date of project: 01/01/2015 End date of project: 30/06/2016

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Version: final draft, 07.2015

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Executive summary

In terms of both construction and operation, tunnels are the most energy demanding of road infrastructure assets. The construction of a road tunnel is energy intensive due to the volume of excavation required and the energy embodied in the materials that form the structure of the tunnel. In operating a tunnel, energy is consumed to provide lighting, signage and ventilation for drivers, and to maintain drainage systems. A good deal of equipment is also installed to deal with emergency situations. With a tunnel's operational lifetime typically in excess of 100 years, energy usage through operation can soon outweigh that due to construction and therefore the former provided the focus for this project. The Realistic Energy Efficient Tunnel Solutions (REETS) project aims to enhance the energy efficiency of road tunnel operation, through the assessment, promotion and implementation of appropriate technologies.

REETS commenced with a wide-ranging review of energy-efficient technologies, considering those designed for tunnels, which could perhaps benefit from wider adoption, and those designed for other applications that have proved effective and which could be adapted for use in tunnels. Technologies were considered for each of the main services that together maintain the functionality of a tunnel, including: lighting, ventilation, drainage, and temperature regulation, with emphasis placed on the more energy demanding services. The review included technologies that reduce energy consumption, those that address energy provision and storage, and driver-oriented ones that help manage traffic flow. Such technologies might be implemented during the construction of the tunnel or be retrofitted in existing tunnels. Selection of the technologies for review was based on their capability and a consideration of whether they would maintain or enhance the current levels of safety and comfort experienced by drivers using tunnels on national road networks.

This document presents the findings of the review, as one-page technology descriptions, and describes the subsequent shortlisting process that was used to identify the most promising technologies. This was undertaken by an expert group at a workshop held on 2nd June 2015 at TRL, Crowthorne, UK. Experts were asked for their perspectives on the technologies identified and were invited to augment the list. A shortlisting exercise was then undertaken at the workshop, based on an evaluation of energy efficiency benefit *versus* risk (a composite indicator of readiness to market, applicability, safety and cost). Shortlisting yielded five technologies to take forward to in-depth assessment, two of which were combinations that had been evaluated separately:

- L03 Reducing threshold luminance
- L02 + L05 LED Lighting system and with adaptive controls
- DR02 Tunnel monitoring systems
- EP02 Supply voltage - high voltage distribution incorporating voltage optimisation, dynamic UPS and avoiding dynamic oscillation
- SM01 incentivising energy efficiency

1 Introduction

REETS is a project funded under the sixth transnational road programme of the Conference of European Road Directors (CEDR). The sixth programme, first initiated in 2013, funded five themes: Ageing Infrastructure Management, Traffic Management, Safety, Energy Efficiency and Roads & Wildlife. REETS falls under the Energy Efficiency theme and will conclude mid-2016.

1.1 Objectives of REETS

REETS set out to meet the following objectives:

i. Identify solutions, or combinations of solutions, that would reduce overall energy consumption - considering the whole environment of tunnels and their operation;
ii. Assess the feasibility of these solutions, considering cost and carbon emissions associated with their installation and operation, as well as the effect on user safety and comfort;
iii. Perform theoretical case studies to evaluate the costs and benefits that would result from implementation;
iv. Carry out the groundwork that NRAs can use as the basis of a business case for trialling the most promising option(s).

This deliverable set out largely to meet the requirements of objective (i). The remainder of project will address objectives (ii) to (iv).

1.2 Initial identification of technologies

The project commenced by identifying technologies that could improve operational energy efficiency in road tunnels. These might improve the energy efficiency of any particular service, such as lighting, ventilation, drainage or emergency services. The efficiency of energy provision itself was also considered, as were 'driver-based' technologies aimed at improving traffic flow, whether sited in the tunnel or vehicle. The scope extended to technologies deployed during initial construction, and through retrofitting works during the operation of a tunnel. Technologies were identified by literature review or, in most cases, from the expert knowledge of the project consortium. A one-page summary was produced for each technology; the reviews are presented in Section 2.

The technologies were grouped into four categories to aid the review process. The number of technologies in each category is indicated:

- Energy provision & miscellaneous (10)
- Lighting (7)
- Ventilation & air quality (10)
- Automotive / driver-based technologies (10)

1.3 Considerations

In compiling the one-page summaries, five considerations were addressed - as described below.

1.3.1 Description

A short description of the technology.

1.3.2 Energy efficiency benefits

An initial assessment of potential energy efficiency benefits: Whenever possible, a quantitative assessment was made. Where relevant, the number of tonnes of carbon dioxide saved in a given timescale was related to a percentage saving against a baseline. A qualitative assessment was made when quantitative data was not available.

1.3.3 Safety considerations

Safety levels have to be at least maintained for a technology to warrant further consideration. Any potential positives or negatives in relation to safety were noted.

1.3.4 Driver considerations

Driver comfort or the ‘overall driving experience’ is an important consideration. There is potential for crossover between driver and safety aspects, but elements such as ride quality and lighting transitions (rather than lighting levels required for safety) are deemed to fall within the ‘driver considerations’ category. Any positive or negative issues in relation to these aspects were noted.

1.3.5 Technological readiness level (TRL)

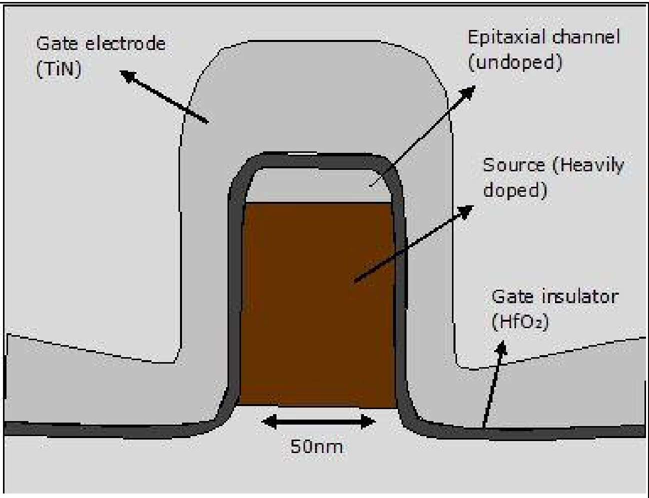
The closeness of a technology to widespread deployment in both the general marketplace and in road tunnels was assessed by assigning a technological readiness level (TRL). TRL was assessed using a scale of 0-9, where 9 is fully proven and in widespread use and 0 is embryonic. The levels are defined in the Horizon 2020 Work Programme (Schild, 2014) and are reproduced in Table 1-1.

Table 1-1: Technological Readiness Levels

TRL 0	**Idea**. Unproven concept, no testing has been performed.
TRL 1	**Basic research.** Principles postulated and observed but no experimental proof available.
TRL 2	**Technology formulation**. Concept and application have been formulated.
TRL 3	**Applied research**. First laboratory tests completed; proof of concept.
TRL 4	**Small scale prototype.** built in a laboratory environment ("ugly" prototype).
TRL 5	**Large scale prototype.** tested in intended environment.
TRL 6	**Prototype system.** tested in intended environment close to expected performance.
TRL 7	**Demonstration system.** operating in operational environment at pre-commercial scale.
TRL 8	**First of a kind commercial system**. Manufacturing issues solved.
TRL 9	**Full commercial application.** Technology available for consumers.

2 Technology summary reviews

EP01 Energy provision: Tunnel field effect transistors



Adapted from Nanowerk (2013)

Description
Tunnel field-effect transistors (TFETs) are energy efficient devices that can essentially switch on/off at lower voltages than the operation voltage of the regulation metal oxide semiconductor field effect transistor (MOSFET).
Energy efficiency benefit(s)
These devices promote energy efficiency by exploiting strained SiGe/Ge and III-V platforms, with CMOS technological compatibility. TFETs outperform other FETs when the voltage drops to 0.5 V in terms of both energy and delay metrics. Since 2011, GNC has been developing a TFET with the goal of reducing power consumption of LSIs to between 1 and 10 % of conventional transistors.
Safety considerations
One disadvantage of a TFET is that the current passing through it is smaller than that through the MOSFET. To obtain a higher current, it is important to apply a stronger electric field to the tunnel junction. The work described in Nanowerk (2013) used a new channel and electrode structure to achieve a stronger electric field.
Driver considerations
-

Technological readiness level (in relation to)	
General marketplace	TRL 9
Road tunnels	TRL 7

References/links

E2 Switch (Energy efficient tunnel FET switches and circuits) (2014) – http://www.e2switch.org/

Mukundrajan *et al.* (n.d.) – Ultra low power circuit design using tunnel FETs

Nanowerk (2013) – TFET architecture shows potential for performance improvements (http://www.nanowerk.com/news2/newsid=31881.php)

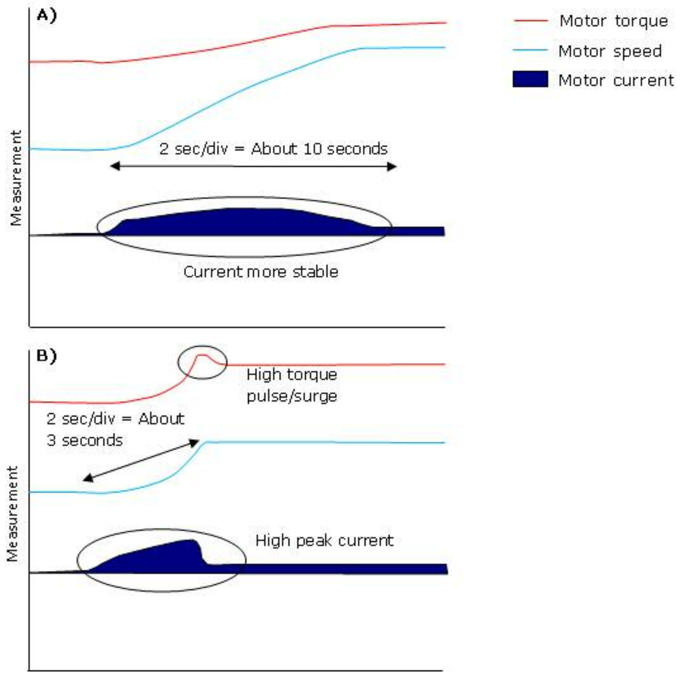
EP02 Energy provision: Higher supply voltage cable distribution system	

Description
An increase in the nominal voltage of serving power distribution for booster fans (for ventilation) can be beneficial in long tunnels and increase energy efficiency. This is because using long cables is expensive and can result in excessive voltage drops.
Energy efficiency benefit(s)
Projects in Hong Kong, India and Singapore have used tunnel booster fans with increased voltage of 660 V/690 V. Results have shown increased costs for voltage, but superior savings for reductions in the use of power cables for fans. Cheung and Lai (2014) compared low and high voltage schemes, and found total cost savings of $112,000 by using the high voltage scheme. To further improve energy efficiency savings, variable-voltage, variable-frequency (VVVF) drives can be considered for fan installations to achieve a steady current ramping for different fan speeds.
Safety considerations
Additional effort may be required to design and construct upgraded equipment, especially if voltage classifications and certifications cannot be met by off-the-shelf units.
Driver considerations
-

Technological readiness level (in relation to)	
General marketplace	TRL 9
Road tunnels	TRL 9

References/links
Cheung and Lai (2014) – Cost effective power scheme for tunnel booster fans

EP03 Energy provision: Soft start technology for jet fan motors and pumps



A) Soft start technology against B) linear technology for centrifugal pump load (Adapted from Rockwell Automation, 2012)

Description

Soft starters can be used in jet fan motors and pumps to allow gradual motor speed acceleration. This takes advantage of the fact that when the motor voltage is low, so are the starting current and the torque. Soft starters have thyristors in the main circuit and the motor voltage is regulated with a printed circuit board.

Energy efficiency benefit(s)

Soft starters can help to reduce maintenance and energy costs. Energy efficiency is improved by limiting the in-rush currents, which helps to meet power restrictions and lower peak demand charges.

Safety considerations

By reducing the starting torques and current, soft starters can reduce the long-term damage to the mechanical system and reduce problems with the electrical system, therefore extending the system life.

Driver considerations

-

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels	TRL 7

References/links

Modiri and Noferesti (n.d.) – Tehran Reselat tunnel innovations (http://lampx.tugraz.at/~tunnel2014/history/Tunnel_2010_CD/pdf_Dateien/13_Modiri.pdf)

Rockwell Automation (2012) – PowerPoint presentation on soft starters

EP04 Energy provision: Surface treatments and coatings to pumps

Description

Surface treatments and coatings can be applied to drainage pumps during their refurbishment to maintain and improve their efficiency. Polymer and epoxy-based coatings have been designed to reduce friction, and resist erosion and corrosion through their hydrophobic properties and low surface energy. This can help to reduce internal turbulence and improve hydraulic efficiency over a wide range of flow rates.

Energy efficiency benefit(s)

Pumps use electricity and typically, a surface treatment or coating will improve the energy efficiency of a pump by about 3 % compared to an untreated pump. Refurbished pumps may have efficiencies higher than new pumps that do not have surface treatments or coatings. Small efficiency gains can have a big impact on operating costs. A case study was presented by Xia (2002) from Alabama where four pumps were coated with a polymeric coating. A 12 % decrease in electrical usage from 100 to 88 amps was witnessed, which equated to savings of roughly $28,000 within a year. Therefore, payback period are often quite short.

Safety considerations

Polymer coatings can help to protect new pumps from erosion and corrosion.

Driver considerations

-

Technological readiness level (in relation to)

General marketplace	TRL 7
Road tunnels	TRL 6

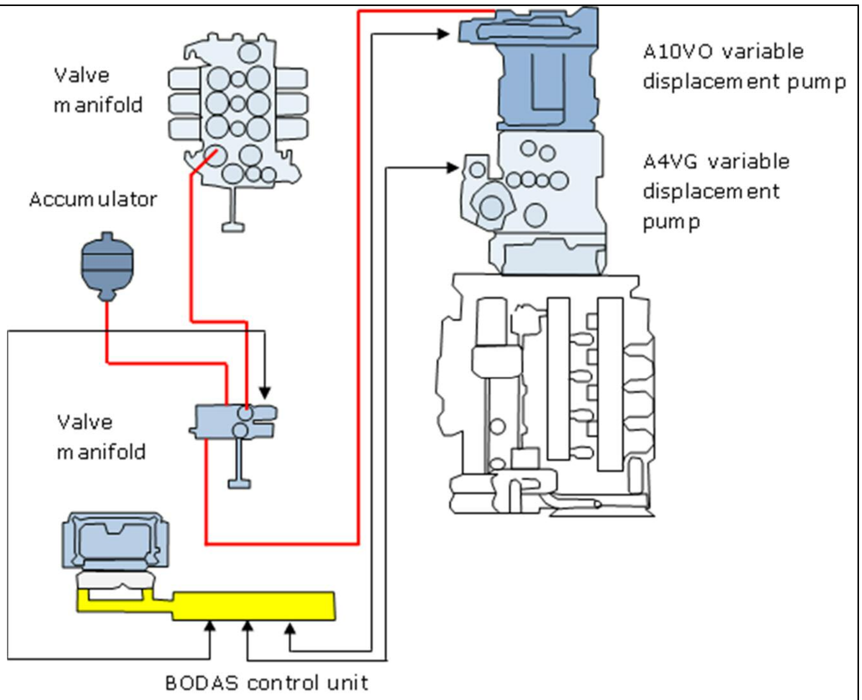
References/links

Industrial Equipment News (n.d.) – Anticorrosion coating for improving efficiency

Robertson Technology (n.d.) – Energy efficiency of pumps

Xia (2002) – Polymeric coatings for pumps

EP05 Energy provision: Start-stop technology for starter motors and pumps



Adapted from Gabriel and Weyhausen, 2015

Description

Start-stop technology can be used to improve the efficiency of motors and pumps so that they automatically switch off when not in use. Recent advances have included start-stop technology in hydraulics for construction machinery.

Energy efficiency benefit(s)

Start-stop technology can reduce fuel consumption and CO_2 output. It has been widely used in car engines with up to 8 % CO_2 emission reductions witnessed in city driving. The hydraulic system has the potential to save almost 2,000 litres of diesel over a vehicle's expected lifespan (Gabriel and Weyhausen, 2015)

Safety considerations

-

Driver considerations

-

Technological readiness level (in relation to)	
General marketplace	TRL 9
Road tunnels	TRL 7

References/links

BOSCH (n.d.) – Stop/start technology for cars

Gabriel and Weyhausen (2015) – Stop/start technology using hydraulics

Rexroth BOSCH Group (2013) – Stop/start technology for construction machines

EP06 Energy provision: Solar roofed tunnels using photovoltaic systems

Description

Photovoltaic systems, which produce electricity, can be constructed on tunnel roofs. An example is a project in Belgium where 16,000 solar panels were constructed on a two mile stretch of tunnel between Paris and Amsterdam in 2011. The tunnel was originally constructed to protect the rail line from falling trees. In the UK, Blackfriars bridge has been equipped with over 4,400 solar panels.

Energy efficiency benefit(s)

Photovoltaic systems use no fuel, and can produce electricity and reduce carbon emissions. The road tunnel in Belgium was anticipated to produce 3300 MWh of electricity per year, which is equivalent to that needed to power all trains in Belgium for one day per year and also help power Antwerp station. This project was also estimated to provide CO_2 emission reductions of 2400 tonnes of per year.

Safety considerations

Solar panels offer no obstructions and are relatively easy to install. The construction of the solar panels in Belgium took 12 weeks. They last between 30 to 40 years with the efficiency tailing off after 20 years. Recycling plans are necessary for dealing with the panels at the end of their life-cycle.

Driver considerations

-

Technological readiness level (in relation to)	
General marketplace	TRL 9
Road tunnels	TRL 8

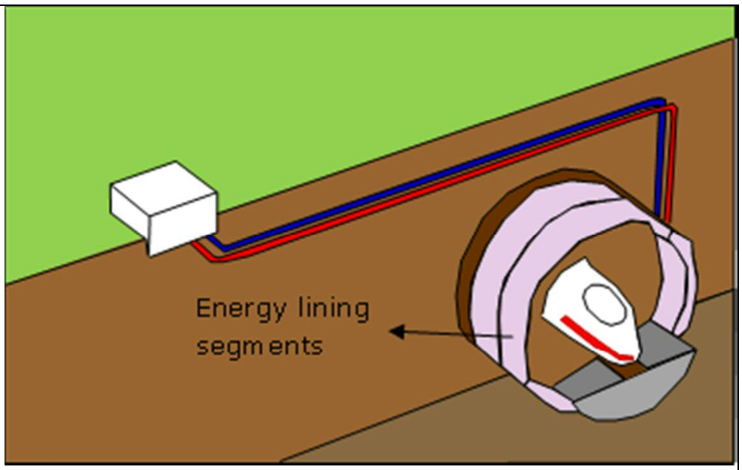
References/links

Carrington (2011) – News article about solar roofed tunnel in Belgium

BUILD (n.d.) – payback time of solar panels

Solar Century (n.d.) – Information about Blackfriars solar roof

EP07 Energy provision: Geothermal tunnel energy lining



Adapted from REHAU (n.d.)

Description

Geothermal tunnel energy lining has the advantages of being able to harvest ground source energy, heat and cool connected buildings, and potentially cool the tunnel in case of heat build-up through tunnel operation. Thermal activation of walls can be achieved by implementing an energy lining segment with the insertion of absorber pipes made of high pressure, cross-linked polyethylene, which can be utilised for heat exchange. The pipes are connected to a heat pump at the surface.

Energy efficiency benefit(s)

Extracted energy can be supplied for above ground use offering carbon savings for buildings being supplied with the heat energy. For example, Nicholson *et al.* (2014) found that 10 W/m^2 tunnel heat extraction provides enough heat to supply a continuous summer low temperature demand of 250 kW achieving carbon savings of over 40 %. In terms of energy use, there is a 50 Ka pressure drop for pipe fittings and 100 Ka pressure drop for the heat exchanger. Implementing geothermal plants when constructing new underground tunnels produces few additional costs with increases of just 2 %.

Safety considerations

The absorber pipes are robust against notches, scratches and punctual loads during production and installation. The durability of the pipes is in line with the design life of tunnels (about 120 years).

Driver considerations

-

Technological readiness level (in relation to)

General marketplace	TRL 7
Road tunnels	TRL 7

References/links

BINE Information Services (2013) Geothermics in tunnels

DETAIL (2011) Pilot geothermal project in Jenbach, Austria

Nicholson *et al.* (2014) Thermal tunnel energy segments for Crossrail, UK

EP08 Energy provision: Hybrid power solutions for emergency lighting of tunnels	

Description

Back-up systems for emergency lighting can utilise hybrid power supplied from renewable sources of energy. The system is designed so that when the batteries are fully charged, power can be supplied directly to the grid. The combination of wind and solar energy works well because solar energy is most pronounced in the summer and generally, wind energy more so in the winter, therefore complementing each other.

Energy efficiency benefit(s)

Dzhusupova (2012) noted that the average cost of wind turbines for the generation of wind power is between 900 and 1150 €/kW, and the average cost of photovoltaic panels for the generation of solar power is between 1500 and 3000 €/kWp. The payback period for wind turbines is between 8 and 10 years, while it is much higher for photovoltaic panels at between 18.5 and 54.6 years, depending on the investment cost.

Safety considerations

Wind turbines used for generation of wind energy can impact visually.

Driver considerations

-

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels	TRL 7

References/links

Dzhusupova (2012) – Wind and solar energy for energy use in tunnels

Mišák *et al.* (2011) – Power solutions for emergency lighting

EP09 Energy provision: Optidrive VTC

Description

The Optidrive VTC drive provides energy efficient pumping through a range of measures such as advanced sleep and wake functions, eco vector operation and pump blockage detection. It is specifically designed for variable torque applications. Optidrive VTC drives have been used in Dublin Port tunnel to evacuate potential stormwater incidents.

Energy efficiency benefit(s)

Optidrive VTC drives can optimise energy savings in pumping applications, while also providing additional benefits such as reduced installation and maintenance costs. The sleep function, which automatically switches the drive off when not required, is one of the functions that contributes to the increased energy savings. Optidrive systems typically reduce energy consumption by 2-3 % compared to standard AC drives. Furthermore, the use of film capacitors can reduce losses and improve efficiency compared to standard AC drives.

Safety considerations

Particular functions on the Optidrive VTC systems allow the pumps to be started in a safely controlled manner to ensure consistent filling and, pressurisation of pipe work and systems. The drives also have a blockage detection system and can trigger a programmed cleaning cycle to clear them.

Driver considerations

-

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels	TRL 9

References/links

Invertek Drives (n.d.) – Eco Optidrive pump control systems

Invertek Drives (n.d.) – Case study from a tunnel in Ireland

EP10 Energy provision: Water mist technology	

Description

High pressure water mist technology has been used to provide tunnel fire protection. It comprises of a system of permanently open jets, which are divided into zones of roughly three metres in length. In the event of a fire, an electronic control activates the valves in the zone above the fire and the two neighbouring zones. The interaction of water mist technology with other systems such as ventilation and smoke evacuation systems are particularly crucial in the event of a fire.

Energy efficiency benefit(s)

Water mist technology can provide benefits over sprinkler technology such as superior cooling and heat blocking, and reduced water consumption. This is because in the event of a fire, only the designated zones use water. Furthermore, smaller drops for the water mist technology have a large specific surface compared to sprinkler technology. Water mist technology is made of high-grade stainless steel and can help to increase the system lifespan.

Safety considerations

Water mist technology needs regular testing and maintenance to meet the acceptable safety standards. An extinguishing system was tested under real conditions in the A86 tunnel in France when a car caught fire in 2010. The system performed as expected and the tunnel returned to normal operation 90 minutes later. However, the technology did not work as well in the Fløffjell tunnel in Norway where problems were encountered such as the formation of ice in winter months and a high number of false alarms.

Driver considerations

-

Technological readiness level (in relation to)

General marketplace	TRL 7
Road tunnels	TRL 7

References/links

German Ministry of Economics and Technology (n.d) – Safety of life in tunnels, Fixed fire fighting systems

Vuorisalo (2008) – Implementation of water mist systems in tunnels with project case studies.

L01 Lighting: Solar powered LED lighting	

Description

Solar panels contributing to the lighting and associated equipment power requirement.

Energy efficiency benefit(s)

With LED luminaires having an already low power requirement, sourcing power from a suitable solar panel array could contribute to total power requirement.

Solar power could be utilised to maintain any UPS system charge levels.

Efficacy dependent on tunnel location and suitability of site. As an estimate would envisage a 10 % saving on standard energy supply.

(Note this could perhaps be incorporated with Technology 10 Threshold Extension).

Safety considerations

If used for lighting source, any changeover in energy source requires being instant and indistinguishable to drivers.

Driver considerations

Drivers should be immune from any disturbances of the lighting scheme.

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels	TRL 8

References / links

Premier Construction (2011), Ridden (2011)

Comment:

Any interior lighting would be an appropriate candidate for solar power sourcing as it is lower power and energised 24/7 at consistent day/night levels.

L02 Lighting: LED lighting system

Description

Light-emitting diode (LED) luminaire system for both tunnel interior and boost lighting requirements with the ability to control the output to meet required lighting levels.

Energy efficiency benefit(s)

The use of LED tunnel luminaires significantly reduces energy consumption compared with traditional light sources employed (HID/Fluorescent). There are already many examples of the use of LED's in tunnels installed in recent years. With the continued development of LED's it would be expected that improved savings would continue to be made. Energy savings of up to 70 % over HID have been realised to date.

Controlled by an intelligent control system continuous dynamic dimming of the LED's is available to more closely match requirements. Power fail UPS systems can be of a reduced capacity due to the lower power requirement of an LED system.

Safety considerations

With an appropriate installed layout, LEDs provide good uniformity with the ability to dim to required stage levels for all tunnel zones as well as an 'instant-on' ability improving safety in the event of a power interruption. With sufficient lumen design headroom, lighting levels can be instantly increased in the event of an emergency. The utilisation of white light improves overall visibility and aids driver's visual task.

Driver considerations

LEDs improve driver's overall visibility potentially reducing response times for drivers due to the full spectrum light source better assisting in replicating the eyes photopic state.

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels (Presently being employed in almost all new & refurbished tunnels)	TRL 8

References / links

Dzhusupova et al. (2012), GE Lighting (2013), Guo et al. (2011), Traffic Wales (2015), Phillips (n.d.), Thorn (n.d.) Products: Philips / TRT Lighting (2015)

Projects: Traffic Wales (2014), Merseytravel (2015), Coventry (2015)

L03 Lighting: Transparent Structures

Description

Transparent tension structure extending threshold zone.

Energy efficiency benefit(s)

The threshold zone is the most power onerous zone of the tunnel, energised during the day to high levels where any use of natural lighting via transparent structures (or sun-tight screens) would significantly reduce the quantity of high power luminaires required in this zone. Energy savings of 100 % for any light source used in the Threshold Zone could be viable.

Reduces initial and lifetime costs of lighting scheme.

(Structure could potentially accommodate Solar panel Technology 7)

Safety considerations

Any structure should be secure and able to cater for all seasons, environment and location. Safe maintenance methodology required.

Driver considerations

Approaching a tunnel the driver will have a more ambient relative lighting perspective view of the portal (no 'Black-Hole' effect).

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels (sunlight screens used historically)	TRL 8

References / links

Sun-tight screens: Peña García et al. (2010), Gil-Martin et al. (2011)

Merseytravel: Kingsway tunnel with sun-tight screens. Screens provide for total requirement of the Threshold zone (except night/basic day lighting which is installed throughout the screen section). No reported issues of road icing beneath or of icicles forming on structure (reported perceived issues) for last 30 years. Only reported issue has been the deteriorating integrity of the concrete structure where there have been incidents of debris falling on to vehicles, mitigation measures have been employed.

Transparent tension structures:

International Conference on Renewable Energies and Power Quality (ICREPQ'10) Granada (Spain), 23rd to 25th March, 2010
Energy saving in road tunnels by means of transparent tension structures.

L04 Lighting: Tunnel lining panels

Description

Self-cleaning tunnel lining panels.

Energy efficiency benefit(s)

Tunnel walls need to be illuminated up to a height of 2 m at a percentage of the road levels dependent on tunnel class. Any improvement in diffuse reflective properties will aid wall performance and minimise luminaire requirements at design / build phase.

Do not anticipate any significant energy saving as the road performance is the key element. Should there be any rearrangement of luminaires in consideration of wall performance energy savings would be ~2.5 % at best.

Safety considerations

A good wall performance prevents drivers becoming ‘wall-shy’ thus utilising the full driving lane aiding correct lane discipline.

Driver considerations

Good wall performance enhances driver view of any potential hazards especially within a tunnel having road curvature by contrasting object(s) against the walls.

Technological readiness level (in relation to)	
General marketplace	TRL 9
Road tunnels (currently available and employed in fire protection initiatives)	TRL 8

References / links

Vitra Group (n.d.)

http://www.vitragroup.com/tunnel-lining-overview-2/

L05 Lighting: Active / adaptive lighting

Description

Close control of the lighting installation within the tunnel in accord with that of the approach ambient lighting levels.

Energy efficiency benefit(s)

Tunnel lighting levels are determined at design phase; current intelligent control systems are set-up to follow these fixed design levels. A closed logic feedback of what the actual lighting levels are within the tunnel would ensure actual levels are in accordance with requirements thereby not causing over/under lighting.

Energy saving could potentially be realised in the region of 10 % due to better matching and monitoring of required levels for primarily the boost lighting.

Constant light output (CLO) control gear would ensure no initial over lighting occurs by accommodating constant maintenance factor (MF) against life profile of light source.

Safety considerations

Employing closed loop feedback would ensure the correct lighting levels are attained at all times.

Driver considerations

Original lighting design maintained throughout lifetime of installation aiding driver's visual task.

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels (tunnel interior sensors of luminance or illuminance need to be applied; CLO technology currently available.	TRL 8

References / links

Arnold and Hoyland (2011); Ceriotti et al. (2011)

Internal meters could be luminance or illuminance meters with pros/cons for each being assessed.

Fixed sensors have been tabled for some time as well as should they be luminance meters or illuminance meters (cheaper) correlated to road luminance values. Luminance meters would also consider road condition, new / old etc. however, illuminance meters would purely sense luminaire output.

L06 Lighting: Fuzzy algorithm lighting

Description

Vehicle detection and throughput statistics.

Energy efficiency benefit(s)

For less trafficked tunnels, lighting would be at a low standby level until an approaching vehicle is detected when lighting (LED) would be increased to an appropriate level for the time of day and for the duration of transiting traffic, reverting to standby levels where there is no traffic detected.

Dependent on the traffic volume energy savings in excess of 50 % could be achieved.

Safety considerations

Standby levels to make drivers aware of tunnel ahead. Triggering of functional level to be established in advance of the vehicles sight stopping distance (SSD) from the entrance portal.

Driver considerations

Design lighting levels to be achieved before driver enters the tunnel and maintained during transit.

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels (only considered viable for very low trafficked tunnels; technology available for application)	TRL 8

References / links

Zeng et al. (2011)

Navada & Adiga (2015) Applications of Fuzzy-FPGA systems and Lighting Control systems – A Review

L07 Lighting: Metal halide lamps	

Description	
Use of Metal Halide lamps in conjunction with photo catalytic paint.	
Energy efficiency benefit(s)	
Would question any energy benefits over LED. It would be anticipated that energy usage (Over LED) would increase at least 5 fold due to lamp technology used and indirect lighting distribution.	
Safety considerations	
Question if sufficient road luminance is produced from such indirect lighting.	
Driver considerations	
Report does show a good uniformity albeit at low levels.	
Technological readiness level (in relation to)	
General marketplace	TRL 9
Road tunnels (consider this style of lighting more akin to aesthetic lighting requirements)	TRL 8

References / links
disano illuminaxione (2007)

DR01 Driver technology: Intelligent road studs

(source: Astucia Traffic Safety Systems, 2014)

Description

Hardwired Intelligent Road Studs aid traffic management by providing guidance and warnings to drivers, thus giving them time to react accordingly. In the context of tunnels, they can be used for lane delineation. They use LED technology and are effective in all lighting conditions with up to 90-900 meters visibility.

Energy efficiency benefit(s)

This technology, using low energy consumption LEDs, requires low maintenance and improves visibility for drivers navigating the tunnel.

Intelligent Road Studs facilitate dynamic lane marking, both at the entrances and within the bores of the tunnels, giving operators the flexibility to maximize the continuous flow of traffic to increase road capacity. This leads to easing congesting, smoothing traffic flow and reducing pollution that would results from queuing traffic. Therefore an energy efficiency benefit would come from the decrease in ventilation rate.

Safety considerations

Studs can be used to enhance lane delineation and make the tunnel more clearly defined and allow for contra-flow arrangements in tunnels. In addition, the system can be used to provide advance warning of incidents. Other safety considerations include: brighter, more clearly defined path of light guiding drivers through the tunnel, reduced congestion and reduced collision potential.

Driver considerations

Intelligent Road Studs help the driver by increasing visibility of lane delineation.
Studies also show an increase in preview time of 3 to 4 seconds, when vehicle traveling at 60 mph.
Reduced congestion, road rage and collision potential.

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels	TRL 8

References / links

Astucia Traffic Safety Systems (2014). IRS2 Hardwired Intelligent Road Studs

Astucia (2010). Case Study – Astucia Hardwired Bi-Directional Studs installed in the Hinhead Tunnel

Astucia (2010). Case Study – Astucia IRS1 Intelligent Hardwired Road Studs installed to create contra-flow at Blackwall Tunnel

DR02 Driver technology: SmartMobility™ tunnel

(source: Schneider Electric, 2012)

Description

SmartMobility Tunnel provides operators with a comprehensive set of tools to manage and secure tunnel and bridge sites, such as:

- Control traffic in real time, by real time collection of data from intelligent field devices that can be incorporated in existing hardware platforms. Dedicated sensors can scan and detect smoke, fire, dangerous gas levels, etc.
- Back-up monitoring also checks that power, lighting and ventilation are working properly.
- Automated incident detection is also included.

This integrated management tool automates repetitive daily tasks. Moreover, it provides an easy interface that provides the most relevant information to key personnel, simplifying operations while increasing safety and security.

Energy efficiency benefit(s)

This tool can reduce maintenance budgeting and operations by delivering in-depth data on repair and failure rates. It assures long-term reliability and reduced maintenance cost. The maintenance modules (included in the system) help schedule preventive maintenance, manage real-time equipment status, and plan follow-up corrective maintenance actions that will ensure long-term infrastructure reliability.

Safety considerations

With real-time, centralized control of traffic and tunnel field devices and subsystems, tunnel operators can identify potential incidents within the infrastructure and respond quickly, efficiently and in a coordinated manner.

Driver considerations

The system has no direct interface with the driver. However, the driver benefits from this system, e.g. automated incident detection.

Technological readiness level (in relation to)	
General marketplace	-
Road tunnels	TRL 8

References / links

Schneider Electric (2012). SmartMobility Tunnel & Bridge

DR03 Driver technology: Vehicle platooning

(source: Jootel et al, 2013)

Description

A vehicle platoon, also called road train, is led by a vehicle, which is driven by a professional driver, while the following vehicles are under automated longitudinal and lateral control. However, persons in the following vehicles should still be able to take back manual control in the event of a controlled or unforeseen dissolving of the platoon. The system is realised by using environment sensors and vehicle-to-vehicle communication to electronically couple the vehicles. The main goal is to reduce headway distances and hence increase a road's capacity. It could be used both for HGV and passenger cars.

Energy efficiency benefit(s)

Studies showed that the effects on energy efficiency are diverse: On the one hand, harmonised speed and traffic flow would result in reduced emissions and lower headway distances (i.e. 8m gap) achieve fuel savings from 7 to 15%. On the other hand, platoons would increase the capacity of a road, i.e. the vehicle density would be increased, which affects the ventilation demand of a tunnel.

Safety considerations

There is little research on the safety impacts of platooning. Due to automation, the risk of rear-end collisions can be reduced for the vehicles in the platoon, but aspects such as unexpected behaviour of other drivers (e.g. lane change before motorway exits) and safe procedures for handing over control must be considered.

Driver considerations

Drivers travelling in a following vehicle can use the time to work or take a rest. A reliable and safe handover procedure must be implemented if the platoon is being dissolved.

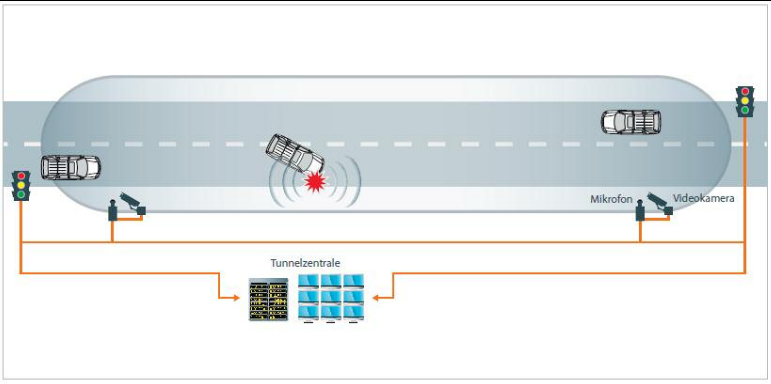
Technological readiness level (in relation to)	
General marketplace	TRL 5/6
Road tunnels	TRL 5/6

References / links

Jootel *et al.* (2013). SARTRE Project (2009 – 2012)

ERTRAC Automated Driving Roadmap (2015)

DR04 Driver technology: Audio incident detection



(source: ASFINAG, 2010)

Description

Audio incident detection system for road tunnels (AKUT) – monitors for differences in the ambient sound (e.g. tire blow out, collision with the tunnel wall, etc.). It uses dedicated microphones installed at every 150 meters in the tunnel. The microphones communicate over fibre optic system via a small local signal converter and can be easily mounted into existing tunnel infrastructure. The system uses a "learning" process first, to understand the ambient sound of the tunnel, for the definition of an abnormal event. When an abnormality is detected, the tunnel control centre can then receive the corresponding video surveillance by the detecting microphone.

Energy efficiency benefit(s)

Analysis performed at Austrian tunnels, where the AKUT system was installed, showed that when a real incident happened, in all cases, they have been detected first with AKUT. Impressive results in detection and time of response show the advantages of this system. This could results in energy efficiency, as early detection and response could mean less ventilation needed, less repairs, less energy. The microphones require minimal maintenance.

Safety considerations

Analysis performed at tunnels where the AKUT system was installed showed that when a real incident happened, in all cases, they have been detected first with AKUT. Impressive results in detection and time of response for taking the appropriate measures show the advantages of this system.

Driver considerations

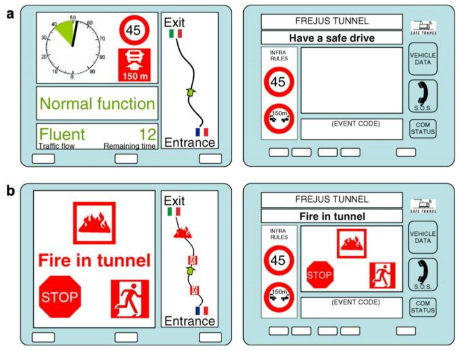
Although the driver doesn't interact directly with the system, AKUT can provide high benefits in case of an incident. Apart from quick detection and response time, the system can be used to detect whether persons are still in the tunnel (e.g. in case of an accident) or how far the rescue teams have advanced.

Technological readiness level (in relation to)	
General marketplace	-
Road tunnels	TRL 8

References / links

ASFINAG (2010). Acoustic tunnel monitoring (AKUT)

DR05 Driver technology: In-vehicle tunnel information system



(source: Vashitz et al, 2007)

Description

An in-vehicle tunnel info system was developed as part of the EU SAFE-TUNNEL project that can provide visual information and warnings to drivers, through on-board devices. A visual map presents the vehicle status, traffic flow, remaining time to exit and the relative location in the tunnel. Also speed information and speed warnings are given. In an emergency event (such as an accident or fire), an alert is presented using icons that indicate what happened, where and what should the driver do. Nearby emergency exists are also presented on the visual map.

Energy efficiency benefit(s)

The system can increase safety, traffic flow and decrease congestion, as well speed up the action of an emergency rescue/event. This could lead to an energy benefit, through less ventilation and less repairs/maintenance.

Safety considerations

In-vehicle information systems have been studied in depth, in terms of the effects on safety – relative to Human Machine Interface (HMI) – specific distraction. Within SAFE-TUNNEL project, it was concluded that the in-vehicle info system increased driving safety, through more information, as long as it doesn't create superfluous distraction. An interference with lane stability was observed during the study.

Driver considerations

The study showed that drivers responded well to the HMI and were content with having more information in the context of tunnel driving, as it builds certainty and sense of control and can reduce anxiety.

Technological readiness level (in relation to)

General marketplace	-
Road tunnels	TRL 5

References / links

Renault Vehicule Industrielle *et al.* (2005). SAFE-TUNNEL project (2001-2005)

Vaschitz *et al.* (2007). In-vehicle information systems to improve traffic safety in road tunnels

DR06 Driver technology: In-vehicle signage

(source: Malone, 2014)

Description

A vehicle-infrastructure link is used to provide information or a warning to a driver of the content of an upcoming road sign. This can be extended to inform drivers about other oncoming features of the road such as curves, roundabouts, traffic calming installations and road markings such as segregated cycle lanes or bus lanes. This application is often referred to as visibility enhancement - giving the driver information about situations beyond or outside the direct line-of-sight.

Energy efficiency benefit(s)

In-Vehicle Signage has a positive impact on the environment, due to lower speeds and management of traffic flow. Implicitly, this may lead to a decrease in fuel consumption and emissions. Quantitative evaluation is complex and depends on the level of service and information given to the driver (speed, curve warning etc.). The in-vehicle signage system itself does not cause additional energy costs to be borne by the tunnel operator.

Safety considerations

By providing speed information, the driver will decrease his speed and become more aware that there is a disruption in the traffic ahead, which plays a crucial role when approaching or driving in a tunnel. In the project COBRA, a literature synthesis resulted in a reduced number of fatalities by -7.2 % and a reduced number of injuries by -4.8 %.

Driver considerations

In general, in-vehicle signage is expected to have mainly positive effects on driver behaviour due to its support in perceiving road signs. However, issues such as diminished attention when the system is not active, over-confidence and hence insufficient observation of real-time circumstances must be taken into account when assessing the system's effectiveness.

Technological readiness level (in relation to)	
General marketplace	TRL 8
Road tunnels	TRL 8

References / links

Malone (2014). Drive C2X project (2011-2014)

Mocanu *et al.* (2012). COBRA project (2011-2013)

Kulmala *et al.* (2008). CODIA project (2007-2008)

DR07 Driver technology: Automatic headlights	 (source: Ruane, 2009)

Description

Automatic headlights use various sensors (e.g. ambient photoelectric sensor located at the base of the windscreen / top of the windshield) to detect the brightness of the environment, the road curvature or other vehicles and can automatically turn on, shade or rotate.

Energy efficiency benefit(s)

Automatic Headlights improve visibility in tunnels and aid the driver to navigate. This could lead to smoother traffic, less congestion, etc. However, until all concerns regarding the headlights activation thresholds, the drivers will either turn on the lights manually, or slow down at the beginning of the tunnel, waiting for the automatic system to turn on.

Safety considerations

Many vehicle manufacturers express that automatic headlights are designed to immediately turn on the position lights and headlights in a tunnel. However, there is concern that the system may not react in time, but after 50-200 m (depending on vehicle's speed), due to the fact that the sensor threshold may not be met immediately. This could lead to potential safety issues, due to poor visibility.

Driver considerations

The driver could rely on the vehicle's automatic headlight system for turning on the lights. If this happens with a delay, then the driver may feel insecure and unsafe.

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels	TRL 9

References / links

Sensata Technologies (2012). Automatic headlight control

DR08 Driver technology: Forward collision avoidance

(source: Raphael, 2011)

Description

Rear-end collisions are the most frequent collision types in uni-directional tunnels, mainly due to wrong human behaviour (e.g. insufficient distance) and inattention. Forward collision warning and avoidance systems (also often called Automated Emergency Braking systems) were developed to reduce crash risk by either warning the driver of a potential hazard (e.g. sudden braking of the front car) or by recognizing an upcoming impact and intervening immediately. Collision avoidance is realised by environment sensors (Lidar, computer vision, Radar etc.) coupled with car-to-car communication technologies.

Energy efficiency benefit(s)

Besides its safety impacts, this technology is predicted to have a positive effect on traffic flow harmonization and hence fuel consumption and emissions. Studies in this field are limited, but regarding energy efficiency in tunnels, forward collision avoidance is expected to reduce ventilation rate as well as energy costs, which incur due to crash response activities.

Safety considerations

Forward collision avoidance technologies that sense other road users and intervene when a collision is imminent are likely to produce large reductions in the number of crashes. Even allowing for a moderate level of unreliability, up to 30 % of all fatal crashes and up to 40 % of all injury crashes could be prevented in vehicles that are equipped with such systems. The greatest benefit is predicted to result from systems that combine a long-range detection system with a short-range, wide-angle system.

Driver considerations

For drivers, forward collision avoidance systems bring advanced assistance for fulfilling the driving task. Risks due to human error and inattention can be minimized and driving comfort is increased. Possible drawbacks of this technology include diminished attention when the system is not active, over-confidence and hence insufficient observation of real-time circumstances.

Technological readiness level (in relation to)	
General marketplace	TRL 5*/8
Road tunnels	TRL 5*/8

References / links

Anderson *et al.* (2012). Potential benefits of forward collision avoidance technology

* Cooperative collision avoidance has a lower TRL.

DR09 Driver technology: Intelligent speed adaptation (ISA)

(source: Schulze, 2014)

Description

ISA is a system that monitors a vehicle's speed and the speed limit on the road being used and intervenes if the vehicle is detected exceeding the speed limit. An ISA can have additional features to influence driver's behaviour by e.g. haptic gas pedal. Three types of ISA can be distinguished:

1. Informative - case in which the driver receives information about the speed limit and various types of warning signals (audio, video).
2. Warning – where the driver is alerted of exceeding the speed limit through an active warning, e.g. haptic accelerator pedal.
3. Intervening – in case of exceeding speed, the system takes over and limits the speed through automated braking.

Energy efficiency benefit(s)

A positive impact of ISA is the potential of decreasing congestion by aiding traffic flow. Implicitly this may lead to a decrease in fuel consumption and emissions. Various studies (ITS test beds, SafeCar etc.) estimate an average reduction of 1.5 % to 3.1 % in CO_2, approx. 2 % in NO_x and 2 % in fuel consumption. With regards to tunnels, this would result in a decreased ventilation rate. The ISA system itself does not cause additional energy costs to be borne by the tunnel operator.

Safety considerations

By providing information regarding the speed limits and warning the driver through various methods, the risk associated with speeding will be decreased. Several studies have been conducted to assess the reduction of accidents and injury, resulting in an average potential of -5.5 % fatalities and -4.6 % injury accidents. Less speeding will result in a more harmonized traffic flow, which is particularly relevant for tunnel safety.

Driver considerations

ISA supports drivers' compliance with the speed limit. The informative ISA warns the driver and lets her/him decide whether or not to slow down. By using a warning/haptic ISA, maintaining the speed is possible, but less comfortable because of the counter pressure. In the case of an intervening ISA, drivers may choose to switch the system on or off. However, some negative effects revealed by experiments include diminished attention or compensation by driving faster when the system is not active, over-confidence and hence insufficient observation of real-time circumstances.

Technological readiness level (in relation to)

General marketplace	TRL 9
Road tunnels	TRL 9

References / links

Driscoll *et al.* (2007). LAVIA project

Regan *et al.* (2006). Final Results of the TAC SafeCar Project

Lai (2012). How much benefit does Intelligent Speed Adaptation deliver: An analysis of its potential contribution to safety and environment

DR10 Driver technology: Eco-driving support

(source: Hunter, 2009)

Description

Electronic systems can control engines more effectively than people, but overall fuel consumption and emissions still depend on the driver's right foot. In an eco-driving support system, the driver can be recommended a strategy for minimising emissions and fuel consumption without affecting journey time. By doing so, the engine can be kept in its optimal operational zone. There is a variety of driver assistance systems available to support the driver in driving more efficiently. These assistance systems support drivers before their trip, during the trip or provide information or advice after the trip. The eco-driving support systems do not have to be integrated into a vehicle but can also be available as applications for mobile or nomadic devices.

Energy efficiency benefit(s)

Due to the system's overall aim to minimise emissions, a benefit for tunnels could be reduced ventilation. In total, the system can achieve fuel savings of up to 12 %. Since the system's recommendations to the driver also depend on the vehicle environment and geographic features, it can be modified for efficient driving in tunnels.

Safety considerations

Eco-driving facilitates more responsible driving, hence leading to more safety. Primarily, the safer driving behaviour results from an anticipating driving style, maintaining a steady speed, less speeding, less overtaking and less aggressiveness.

Driver considerations

In the last decades, engine technology and performance of cars has improved rapidly, while most drivers have not adapted their driving style. There are many smart and safe driving techniques, which may lead to behavioural adaptations, but at the end of the day, it is still the driver who must be trained for eco-driving and must be aware of its effects.

Technological readiness level (in relation to)

General marketplace	TRL 5-6*/9
Road tunnels	TRL 5-6*/9

References / links

Trommer and Holt (2011). eCoMove project (2010 – 2014)

Hibberd *et al.* (2014). ecoDriver project (2011 – 2015)

*Applicable for cooperative technology

VA01 Ventilation & air quality: Visibility and air quality control sensors	
Description	
Tunnel sensors can be integrated into an air quality management system to trigger ventilation systems when high concentrations of pollutants and/or poor visibility levels are experienced within a tunnel. Sensors monitor key parameters such as CO, NO levels and visibility.	
Energy efficiency benefit(s)	
Tunnel sensors provide energy and cost savings because they limit ventilation control to only when it is necessary, which reduces electrical energy consumption compared to ventilations systems that are running continuously. Maintenance and operation costs are limited with cleaning required annually. Operation costs are low because there is no air aspiration system and no test gases/ambient air required.	
Safety considerations	
Control systems are designed to withstand the harsh environments within road tunnels. Measurements are able to ensure high operational safety and a checking system is available for the purpose of monitoring the visibility measurements.	
Driver considerations	
-	
Technological readiness level (in relation to)	
General marketplace	TRL 9
Road tunnels	TRL 9

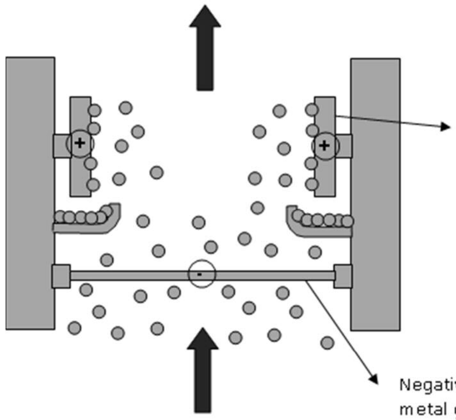
References/links
Dzhusupova (2012) – Visibility control systems SICK Sensor Intelligence (n.d) – Air quality tunnel sensors in road tunnels

VA02 Ventilation & air quality: Passive ventilation with vertical shafts	

Description
By-pass type installation is used to provide longitudinal ventilation in long tunnels. Polluted exhaust air is extracted out of the tunnel and fresh air is re-injected into the tunnel. Fans are used to supplement the input of fresh air (discussed in jet fans one-pager – VA07).
Energy efficiency benefit(s)
Passive ventilation utilises naturally existing air currents to refresh air – gradients in air pressure are not artificially produced through the use of fans or other suction devices. The use of electrical energy is avoided as a result.
Safety considerations
The extraction of polluted exhaust air can impact negatively on the outside environment. The question remains as to whether passive ventilation can solely be used to refresh air to the levels required, or whether it needs to be used in conjunction with more active air quality management systems.
Driver considerations
-

Technological readiness level (in relation to)	
General marketplace	TRL 9
Road tunnels	TRL 9

References/links
CETU (2010) – Bypass-type installations

VA03 Ventilation & air quality: Electrostatic precipitators	 Adapted from BBC, 2014

Description

Electrostatic precipitators are units designed to trap and remove dust particles from a gas exhaust stream by applying a high-voltage electrostatic charge. Particles are captured on metal plates with opposite charges as the air moves between the plates.

Energy efficiency benefit(s)

Electrostatic precipitators use electricity; Curran (2001) estimated that they consume 1 GWh per year assuming full usage. It was stated that they can provide significant energy savings compared to unfiltered tunnels (estimated at 32 GWh per annum by RTA). Electrostatic precipitators require maintenance as the plates should be cleaned after between 50 and 200 hours of operation to maintain efficient operation. The dust that is collected also needs to be disposed of. Curran (2001) estimated that a tunnel serving 70-80,000 vehicles per day would accumulate between 0.7 and 1 cubic metres of waste per month and weighing approximately 1.2 tonnes.

Safety considerations

The primary aim of electrostatic precipitators is to improve visibility in tunnels by removing soot in the air. They also remove harmful pollutants from the air. Efficiency is high for large particles (>10 μm in size), but it is much lower for smaller particles (<2.5 μm) with an efficiency range between 54 and 91 %. Examples where efficiency has not been as good were linked to high airflow rates where particles group together and can be dislodged back into the airstream.

Driver considerations

Electrostatic precipitators help to improve visibility for drivers in tunnels.

Technological readiness level (in relation to)

General marketplace	TRL 8
Road tunnels	TRL 8

References/links

Curran (2001)

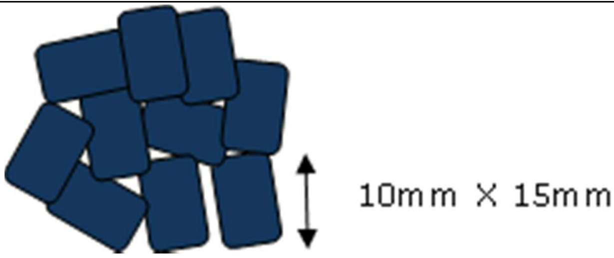
Dzhusupova (2012)

Fuji Electric Global (n.d.)

<table>
<tr><td>VA04 Ventilation & air quality: Pulsed corona air purifying system</td><td></td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">Pulsed corona technology utilises “cold” plasma to convert exhaust gases into harmless ones. A corona is a field (plasma) of active particles, electrons and free radicals that essentially create ‘mini thunderbolts’ capable of removing NO_X and SO_2 from flue gas. This technique is often used in combination with mechanical filters.</td></tr>
<tr><td colspan="2">Energy efficiency benefit(s)</td></tr>
<tr><td colspan="2">The technology is more energy efficient than non-pulsed cold plasma purifiers as it has the ability to chemically destroy NOx. It utilises electric energy but requires hardly any processing water or additional chemicals. Dzhusupova (2012) noted that one corona plasma unit is estimated to consume between 75 and 150 kW of electricity with a cost of between €150k and €200k. Active coal beds are required to remove ozone created from the corona reactor and this increases energy use with a pressure drop of 250 Pa (technology with a higher pressure drop will consume more energy). Operation and maintenance costs start at €50k per year for a 3 unit corona plasma reactor at 30 kW.</td></tr>
<tr><td colspan="2">Safety considerations</td></tr>
<tr><td colspan="2">Pulsed corona technology can remove up to 90 % of $PM_{2.5}$ – PM_{10}. The efficiency reduces to 60 % when the particle size is less than 1 µm. Studies on the application of this technology found no detrimental impacts on the health of tunnel users.</td></tr>
<tr><td colspan="2">Driver considerations</td></tr>
<tr><td colspan="2">This technology can help to improve visibility for drivers in tunnels.</td></tr>
<tr><td colspan="2">Technological readiness level (in relation to)</td></tr>
<tr><td>General marketplace</td><td>TRL 3</td></tr>
<tr><td>Road tunnels</td><td>TRL 3</td></tr>
</table>

References/links
Dzhusupova (2012) HMVT (n.d.) HMVT (n.d.) – Pilot project in Eindhoven PlasTEP (n.d.)

VA05 Ventilation & air quality: Denitrification by adsorption method



Adsorbent pellets (Adapted from PIARC, 2008)

Description

Denitrification by adsorption describes a process where air pollutants are adsorbed to a bed of absorbents and then desorbed. Adsorbent agents include active carbon, zeolite and polymers or a combination. In order to make the process continuous, adsorbents may be installed in a rotating drum with different working sections. They can also be in pellet form where they are packaged in a tank made of fibreglass-reinforced plastic.

Energy efficiency benefit(s)

For denitrification by adsorption using zeolite, Abromaitis *et al.* (2011) estimated the consumption of 1.3 kWh of electricity and 2.772 kgCO_2 equiv. for GWP. Contrasting figures for the pressure drop have been reported; CETU (2010) reported less than 600 Pa, while Dzhusupova (2012) noted 250 Pa when active coal is used. The performance capacity of the system is not as efficient as the absorption method; when pellets are used, frequent regeneration is required every 12 days using a sodium sulphate solution in situ.

Safety considerations

Denitrification removes harmful NO_2 emissions from the environment with removal rates often in excess of 90 %. The usage and/or disposal of zeolite contributed to relatively high contributions for ozone layer depletion (2.930 kg R11 equiv.), acidification (6.499 kg SO_2 equiv.) and human toxicity (712.025 kg DCB equiv.) compared to other air cleaning technologies such as biofiltration.

Driver considerations

-

Technological readiness level (in relation to)

General marketplace	TRL 6
Road tunnels	TRL 6

References / links

Abromaitis *et al.* (2011) – LCA about denitrification by adsorption

CETU (2010)

Dzhusupova (2012)

Panasonic (n.d.) – (http://panasonic.net/ecosolutions/air/tunnel/denitrification.html)

PIARC (2008)

VA06 Ventilation & air quality: Mechanical filters with nano-fibre technology

Description

Mechanical filters utilising nano-fibre technology (Ultra-web®) can efficiently remove particulate matter less than 1 micron. These filters can work alone or with other technology such as electrostatic precipitators or corona plasma technology.

Energy efficiency benefit(s)

Mechanical filters have high filtration efficiency and dust holding capacity. They have low pressure drop characteristics (roughly 75 Pa) compared to other air cleaning systems, thus reducing energy consumption. Dzhusupova (2012) noted that mechanical filters with nano-fibre technology have a lifetime of about 6,000 hours.

Safety considerations

Mechanical filters with nano-fibre technology are effective in the loading and trapping of sub-micron particulates (e.g. exhaust soot) and larger dust particles. They are composed of glass free material and do not contain Boron.

Driver considerations

-

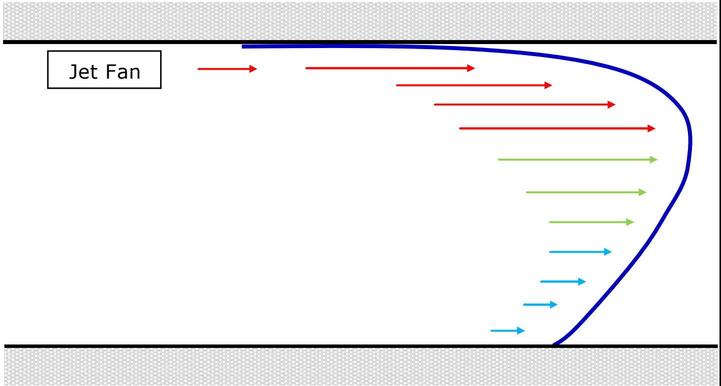
Technological readiness level (in relation to)	
General marketplace	TRL 8
Road tunnels	TRL 5-6

References/links

Donaldson Filtration Solutions (n.d.) – Information about nano fibre technology (http://www2.donaldson.com/toritdce/en-gb/replacement-parts-services/pages/filter-media/ultra-web.aspx)

Dzhusupova (2012)

Elmarco (n.d.)

VA07 Ventilation & air quality: Jet fans	 Jet fan velocity profile (Adapted from SCS Group, n.d.)

Description	
Jet fans discharge high velocity jets (as high as 40 ms^{-1}) to induce longitudinal air flow in tunnels. Jet fans utilise the concept of momentum exchange whereby faster moving jets of air discharged from a fan exchange momentum with the slower moving surrounding airstream. This creates a pressure rise and therefore, causes it to accelerate.	
Energy efficiency benefit(s)	
Jet fans cost less than a comparable ducted system and when combined with CO detection, can reduce running unnecessarily, therefore increasing potential energy savings. Furthermore, jet fans do not have to compensate for losses of pressure in ducts.	
Safety considerations	
Jet fans take up less space compared to axial fans as they are grouped side by side in "banks" spaced at regular intervals. This also reduces cabling costs. Jet fans require fewer ancillary components such as connecting ductwork and dampers.	
Driver considerations	
Jet fans can be fitted with silencers to reduce noise.	
Technological readiness level (in relation to)	
General marketplace	TRL 9
Road tunnels	TRL 9

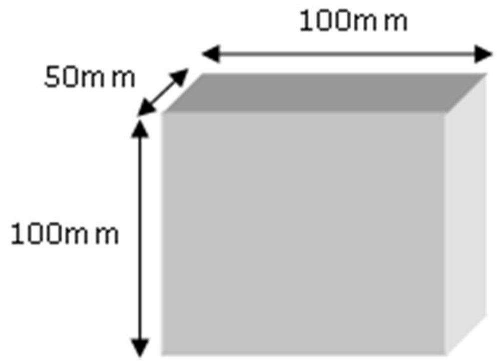
References/links

Panasonic (n.d.) – http://panasonic.net/ecosolutions/air/tunnel/jetfan.html

Ray et al. (2008) – Application of jet fans in ventilation shafts

Tarada (n.d.) - http://www.ansys.com/About+ANSYS/ANSYS+Advantage+Magazine/Energy-Efficient+Tunnel+Ventilation

VA08 Ventilation & air quality: Denitrification by absorption method



Absorbents for NO_2 removal (Adapted from PIARC, 2008)

Description

Denitrification by absorption utilises the process of sorption where NO_2 particles undergo chemical change. A number of absorbents can be used to facilitate this process such as activated carbon (NO_2 converted to NO, N_2 and CO_2) and potassium hydroxide (NO_2 converted to KNO_2 and KNO_3).

Energy efficiency benefit(s)

Denitrification systems work best when the air has already been treated by electrostatic precipitation; thus this should be should be factored into energy analyses. CETU (2010) reports that the pressure drop is less than 460 Pa. Absorbents need replacing every eight to ten months when removal efficiency begins to decline. This requires transporting the absorbents in their metal cubes and regenerating them by water washing, drying, covering in a potassium hydroxide solution and then drying again.

Safety considerations

Denitrification removes harmful NO_2 emissions from the environment with removal rates often in excess of 90 %. The regenerating solution used in the denitrification absorption method is not harmful to humans or the environment.

Driver considerations

-

Technological readiness level (in relation to)

General marketplace	TRL 8
Road tunnels	TRL 8

References / links

AMOG (2012) – Filtration trial including denitrification in Australia

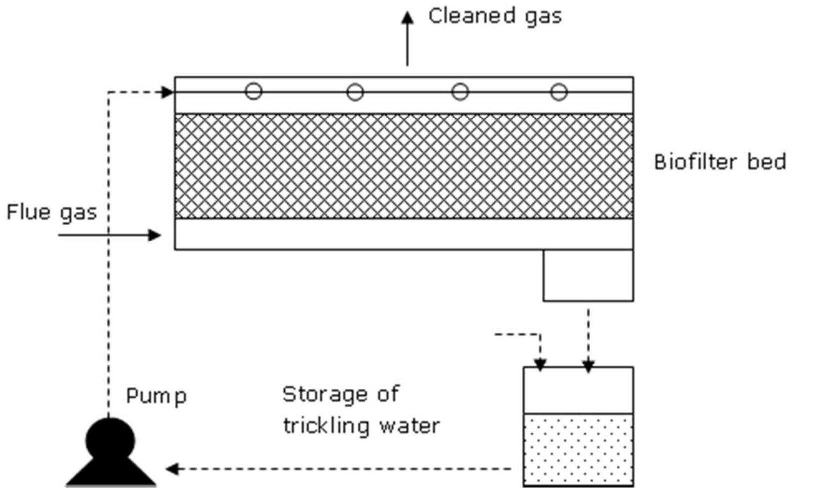
CETU (2010)

Nishimatsu Construction (2011) – Air purification system including denitrification in Japan (http://www.nishimatsu.co.jp/eng/solution/tech/kankyou/kankyouhozen.html

Panasonic (n.d.) – (http://panasonic.net/ecosolutions/air/tunnel/denitrification.html)

PIARC (2008)

VA09 Ventilation & air quality: Biofiltration



(Adapted from Abromaitis *et al.*, 2011)

Description

Exhaust air can be treated through a filter bed (e.g. compost, soil, peat, lava rock), which carries a thin film of water which supports micro-organisms. The pollutants in the gas stream are retained by adsorption and absorption, and are then degraded by the micro-organisms.

Energy efficiency benefit(s)

Compared to other types of ventilation systems, biofiltration has low energy and operating costs. This is because the oxidation of pollutants takes place at ambient temperatures, therefore reducing energy consumption normally associated with combustion. Energy use is primarily determined by the ventilator, which has to compensate for the pressure drop (e.g. 500 Pa for compost filter). Abromaitis *et al.* (2011) conducted an LCA study on biofiltration and found similar contributions to GWP (2.612 kg CO_2 equiv.) to other air cleaning technologies.

Safety considerations

Biofiltration can remove air pollutants and produce cleaner air; various studies have shown efficiency rates between 75 and 85 % for the degradation of air pollutants. Biofiltration ranked high in terms of eutrophication potential (0.068 kg Phosphate equiv.) compared to other air cleaning technologies due to wastewater treatment process emissions. Maintenance of the biofilter bed is crucial; issues such as moisture content, pH and the growth of micro-organisms need to be addressed.

Driver considerations

-

Technological readiness level (in relation to)

General marketplace	TRL 5
Road tunnels	TRL 3

References/links

Abromaitis *et al.* (2011) – LCA study on biofiltration

Jin *et al.* (2009) – Biofilters used to treat CO polluted air

PPC Industries, Air Pollution Control Systems (2008) – General information about biofiltration (http://www.ppcair.com/biofilter.php)

VA10 Ventilation & air quality: Photo catalysis

Description

Photo catalytic paints for tunnel walls or photo catalytic concrete for the pavement can be used to improve the air quality within tunnels. In the presence of UV light, the photocatalytically active form of TiO_2 present at the surface is activated, enabling the abatement of pollutants (NO_x, SO_x, CO, C_6H_6 etc) in the air.

Energy efficiency benefit(s)

Photo catalysis is regarded as energy efficient because TiO_2 is not consumed in the process and the conversion of pollutants can take place as long as there is light. The pollutants can be removed from the surface by rain or washing with water every month. This reduces the need for traditional brush cleaning of walls which can be costly. Ravesloot (2012) conducted a CBA for the use of photocatalytic paint in the tunnel tubes in combination with improved lighting, and found that the return on investment would happen in four years due to less cleaning required.

Safety considerations

Photocatalytic applications can result in local reductions in the concentration of air pollutants from vehicles. Reductions of NO_2 in the order of 20 % have been witnessed. The effectiveness of photocatalytic applications has been affected in some studies by the following factors: deactivation of the photocatalytic material, UV light below targeted levels, high wind speed and high relative humidity.

Driver considerations

The utilisation of the photocatalytic paint/concrete with the UV light can lead to more favourable optimal characteristics of the tunnel walls for drivers.

Technological readiness level (in relation to)

General marketplace	TRL 8
Road tunnels	TRL 8

References/links

Booden and Beeldens (2014), Gallus *et al.* (2015) – Pilot project in Belgium

KNOxOUT (2015) – Pilot project in the Netherlands (http://aircleaningpaint.com/home.do)

Ravesloot (2012) – CBA of study in the Netherlands

3 Shortlisting process

The aim of the selection process was to reduce the 37 technologies identified from the wide-ranging review to four or five of the most promising ones for further analysis in WP2. This was achieved with the assistance of a group of tunnel experts from NRAs and operating companies during a day-long workshop held at TRL. A list of the attendees to the workshop is provided in Annex A.

3.1 Workshop format

The workshop agenda provided is in Box 3-1.

In the morning presentations, an introduction to the project was provided in presented together context with (a) the type and characteristics of the tunnels on the European TEN-T network and (b) relative energy use for the life cycle of a tunnel (initial construction and operation). Then the technologies that had been identified in the review were each described individually by the project team and discussed by the experts. The afternoon sessions consisted of exercises to produce a shortlist of technologies to take forward to an in-depth analysis later in the project.

Box 3-1 REETS WP1 workshop agenda

1000: Introductions

1010: Project overview and objectives for the day

1020: Tunnels & the energy efficiency context

1040: Group 1 technologies – energy provision (TRL)

1100: Brief discussion / feedback on Group 1

1105: Coffee break

1125: Group 2 technologies – lighting (DfL)

1145: Brief discussion / feedback on Group 2

1150: Group 3 technologies – driver technology (AIT)

1220: Brief discussion / feedback on Group 3

1225: Group 4 technologies – ventilation & air quality (TRL)

1245: Brief discussion / feedback on Group 4 / additions to the overall list

1300: Lunch

1340: Shortlisting exercise

1500: The project going forwards

1520: AOB

1530: *Close* (further discussion by project partners until 1600)

3.2 Selection process

The selection process was threefold. Firstly, the reviewer for each group of technologies proposed a shortlist of three technologies based on their analysis. This produced the following list of technologies:

- EP06 – Solar roofed tunnels
- EP07 – Geothermal tunnel energy lining
- EP02 – Higher supply voltage cable distribution system
- L02 – LED lighting system
- L03 – Transparent structures (for reducing threshold luminance)
- L08 – Road surface materials
- DR02 – Smart mobility tunnel
- DR04 – Audio incident detection
- DR09 – Intelligent speed adaptation
- VA01 – Visibility air quality control systems
- VA07 – Jet fans
- VA10 – Photo catalysis

Each of these reviewer shortlists were then discussed at the workshop. Through discussion a consensus was reached and the shortlist modified. At the end of the morning session, the following list of ten technologies had been elicited:

- EP02 supply voltage – high voltage distribution incorporating voltage optimisation, dynamic UPS and avoiding dynamic oscillation
- EP06 + EP08 – renewables (solar, wind & water)
- EP03 + EP05 – stop/start technology including soft start
- L02 + L05 LED lighting system and with adaptive controls
- L03 Reducing threshold luminance
- L08 Road surface materials
- DR02 Tunnel monitoring systems
- DR04 Audio incident detection systems
- SM01 Incentivising energy efficiency
- VA11 Jet fans (reduced used thereof – e.g. by better control, trigger levels, sensor reaction, mist systems etc.)

Some entries on the list (EP06 + EP08; EP03 + EP05; and L02 + L05) were pairs of technologies that had previously been treated individually. It was logical to combine these together, as they addressed the same fraction of overall energy consumption. Also, as a result of discussion, two technologies were added to the shortlist (VA11 and SM01).

Workshop attendees were split into three sessions and asked to rate each of the ten technologies based on a matrix of perceived energy efficiency benefit *versus* risk. Risk was defined as a composite indicator that took account of:

- Cost: to deploy the technology. Would significant investment be required and at what risk?
- Applicability: To have widespread applicability, the technology should have the potential to be retrofitted to the existing tunnels rather than just new-build tunnels, as risk would be diluted by widespread application.
- Readiness to market: Is the technology readily deployable and proven, or is it only an idea or prototype that has the potential to hit snags before widespread deployment can proceed?

- Safety. Are there any doubts about the level of safety associated with the introduction of the technology?

Photographs of the three resultant matrices are presented in Annex A. Following discussion the three matrices were consolidated into a 'master' matrix to provide an agreed shortlist.

3.3 Shortlist of technologies to take forward

The five technologies identified to be taken forward to the next stage of assessment are:

- Reducing threshold luminance (L03) - The aim of this initiative is to reduce the required lighting level in the threshold zone which, in turn, determines subsequent lighting levels in other zones. Feasible means might include: sun-tight screens, taut structures, darkening structure, and landscaping - such as tree planting over portal. In essence this includes any means to darkened and/or reduce the percentage of sky and bright objects in a 20 degree field of view, as viewed from the stopping distance. The intention is to provide a lower L_{20} measurement - where this parameter forms the basis of the total lighting requirements.
- LED Lighting system and with adaptive controls (L02 + L05) - This constitutes close control of the LED lighting system for the whole tunnel. LEDs are already widely deployed, and this further enhancement would mean that LEDs could be dimmed and switched instantly (or nearly so) thus allowing closer control. A point tabled at the workshop was a closed-loop control philosophy (currently control systems have no feedback loop) would allow for 'instant' adjustment to the outside ambient lighting conditions. The use of vehicle sensing could be explored as a closely-related application for low use 'mountain' tunnels.
- Tunnel monitoring systems (DR02) – Systems are available for monitoring the environmental conditions within a tunnel; such as air quality, lighting, sump levels, and incidents. These systems can improve the level of safety and optimize the day-to-day operation and maintenance of a tunnel. Through exploitation of the data produced, tunnels can be operated more efficiently and thereby lower energy consumption. Monitoring systems can detect early performance degradation, and thereby reduce the risk and consequences of unexpected and/or undetected failures of systems and components that could compromise the safe operation of the tunnel.
- High voltage distribution incorporating voltage optimisation, dynamic UPS and avoiding dynamic oscillation (EP02) - The use of high voltage distribution systems can provide energy savings, but there is no direct interface with the user. The use of efficient UPS systems enables tunnel safety systems to operate in the event of a major power failure and also provide a limited amount of tunnel lighting.
- SM01 incentivising energy efficiency – Through procurement policy and contractual conditions, NRAs can incentivise the efficient use of energy in assets operated by contractors. A stepwise approach to lower overall energy use is often desired. Such an approach can be promoted by encouraging suppliers to avoid unnecessary energy use and/or switch to more energy efficient technologies by offering financial incentives and/or through the tender assessment process.

4 Conclusions and next steps

This document provides details of the process undertaken to derive a shortlist of technologies that could improve operational energy efficiency in tunnels. It documents a wide-ranging review of potential technologies that could be used in tunnels, and can be used as a point of reference.

The next stage of this Project is to assess the shortlisted technologies. This will be achieved by considering the following:

- Full description: expand the short descriptions of the technologies provided so far. Document the scope of their use and evidence of deployment to date, in tunnel applications or otherwise. Determine operational characteristics, energy demand, and on/off cycles.
- Carbon reduction potential: assess this potential through measurement against an established baseline, across a typical tunnel lifetimes. To establish a current baseline, use will be made of data provided by NRAs on consumption attributed to different tunnel functions. A reduction potential will be derived for each technology.
- Cost: the cost of deployment will be determined by direct comparison to conventional technologies.
- Safety and user comfort: to check that current levels of these two essential characteristics are maintained or exceeded when a new technology is implemented, bespoke methodologies have been developed to assess these characteristics based on an objective and a subjective analysis respectively.

Following completion of the in-depth assessment, each shortlisted technology will be re-appraised for its suitability for deployment through a series of theoretical case studies based on actual tunnels.

5 Acknowledgement

The research presented in this report was carried out as part of the CEDR Transnational Road Research Programme Call 2013. The funding for the research was provided by the national road administrations of Austria, Germany, the Netherlands, Norway, Slovenia and the United Kingdom.

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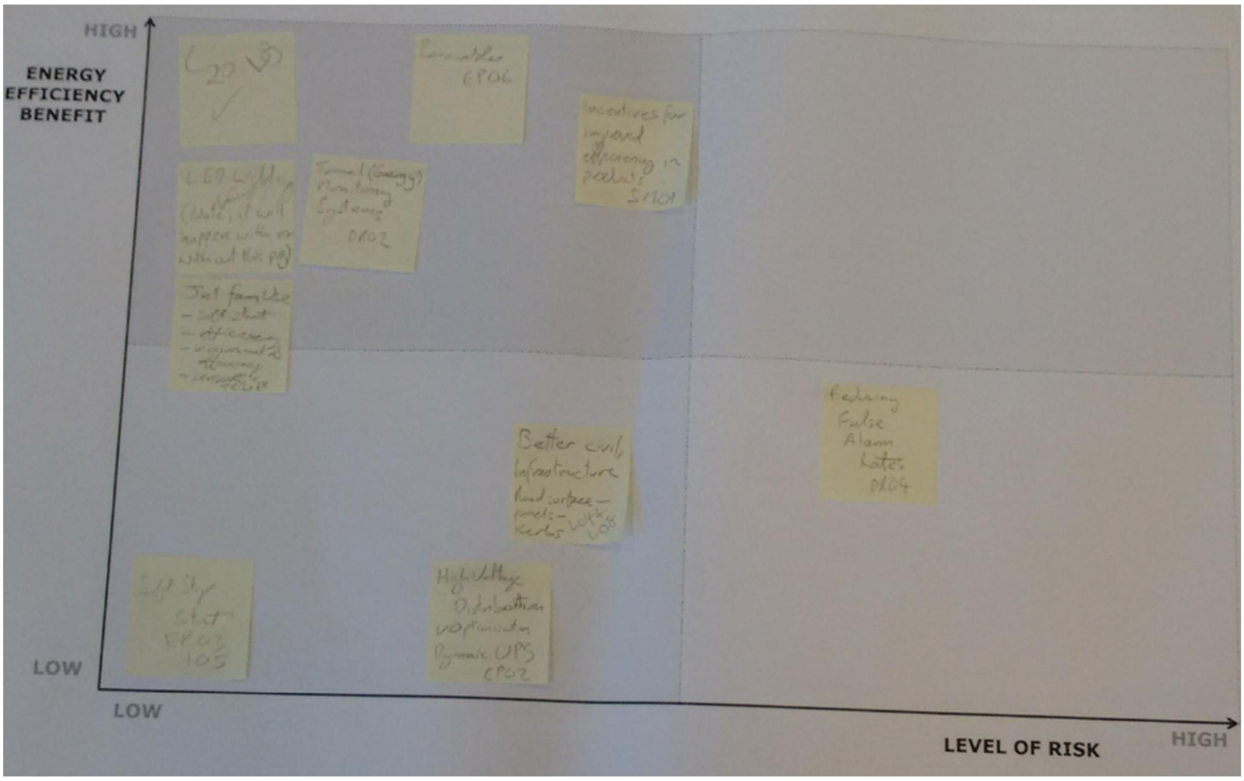
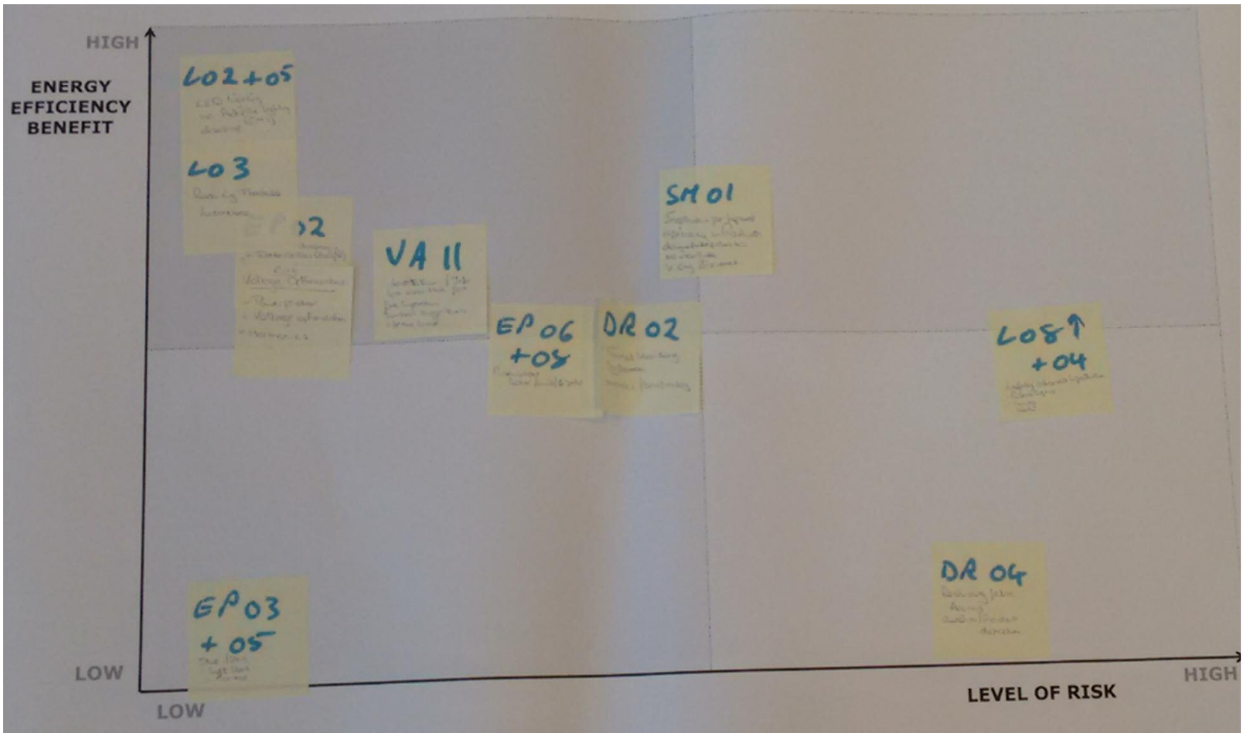
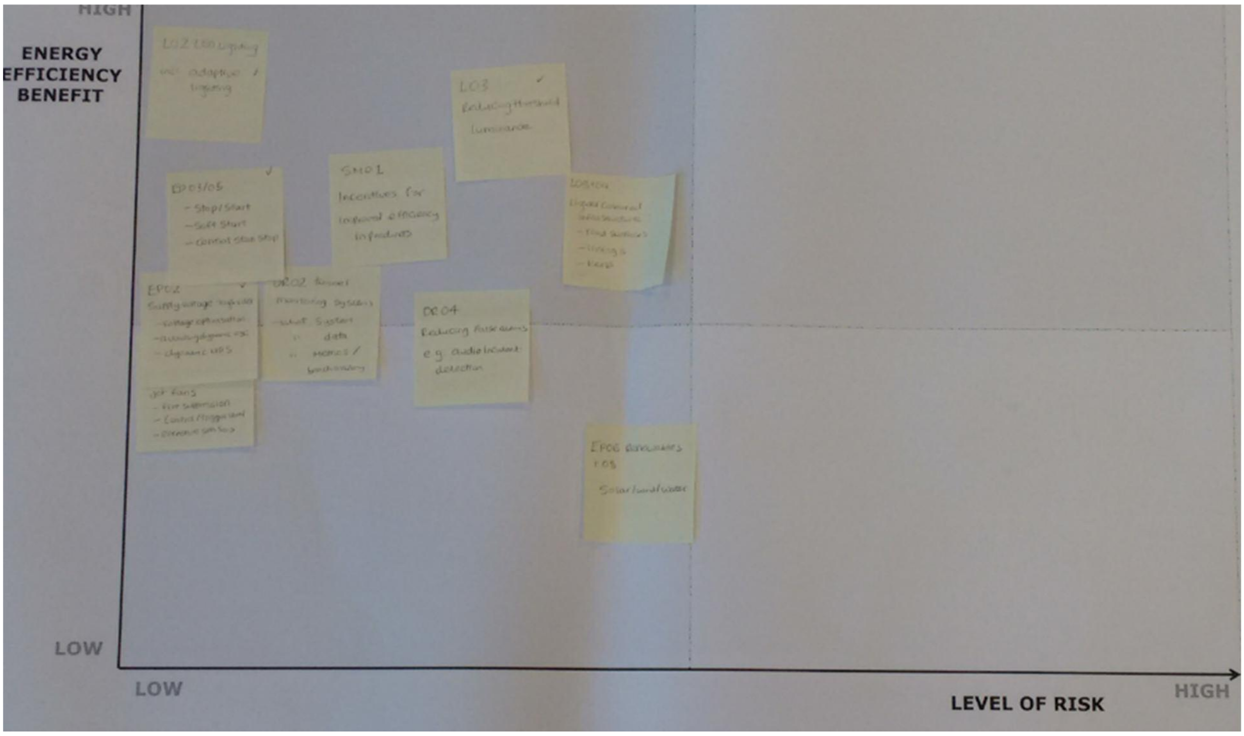
Annex A: Workshop attendees

Name	Affiliation
Stuart Beale	Highways England
Kiran Desai	Connect Plus
Gerhard Eberl	ASFINAG
Andy Mack	Connect Plus
Isabela Mocanu	AIT
Johan Naber	Rijkswaterstaat
Philippe Nitsche	AIT
James Peeling	TRL
John Potter	Mouchel
John Rands	Designs for Lighting
Sarah Reeves	TRL
Steve Ryan	Transport for London
Helen Viner	TRL
Matt Wayman	TRL
Russell Williams	Highways England

Annex B: Matrices from the selection process






HIGH
ENERGY
EFFICIENCY
BENEFIT
LOW
LOW
LEVEL OF RISK
HIGH