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DISTANCE

State-of-the-art on secondary functions for pavements and noise screens

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Developing Innovative Solutions for TrAffic Noise Control in Europe

Partners:

BRRC (Belgian Road Research Laboratory) [Belgium]

TRL (Transport Research Laboratory) [UK]

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CEDR Call2012: Noise: Integrating strategic noise management into the operation and maintenance of national road networks

DISTANCE: Developing Innovative Solutions for TrAffic Noise Control in Europe

State-of-the-art on secondary functions for noise barriers and road surfaces

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Executive summary

The objective of the DISTANCE project is to provide NRAs with information and guidance on a wide range of topics to assist them in planning and implementing future noise mitigation measures on their road networks. In the current economic climate, budgetary restrictions mean that NRAs must strive to ensure that implemented measures are fit for purpose and durable whilst keeping costs as low as possible. Noise mitigation measures that provide additional benefits beyond simple noise reduction may therefore be an attractive proposition to NRAs if they can be achieved with relatively little additional expenditure or if whole life costs are favourable.

Work Package 3 of the DISTANCE project has sought to investigate how primary NRA assets such as road surfaces and noise barriers might be enhanced to provide additional benefits, referred to here as 'secondary functions'. Options have been identified and assessed in terms of their known or anticipated (whichever is applicable given the technical readiness of the option) advantages, disadvantages, and likely costs (relative to conventional measures); the level of technical readiness, i.e. how ready they are for commercial application, has also been identified.

From the different options reviewed the following are considered as being presently available and offering the most useful benefits to NRAs with respect to secondary functions:

For noise barriers with secondary functions:

- Noise barriers with photovoltaics
- Integrated noise and safety barriers
- Enhanced visual aesthetics (including the use of transparency)
- Green barriers

For road surfaces with secondary functions

- Use of recycled materials (recycled asphalts)

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1 Introduction

Traffic noise is a huge burden in Europe today, both in terms of human health and wellbeing as in term of economic damage. It is unlikely that the problem will disappear or even diminish by itself. On the contrary, traffic volumes continue to increase year by year: in the EU-27 freight traffic increased by on average 1,5 % per annum in the period 2000-2010 and passenger traffic by 1,4 % per annum in the period 1995-2009 (ERF, 2013). It is therefore increasingly important that noise mitigation measures selected and implemented by National Road Authorities (NRAs) are and remain for as long as possible fit for purpose.

The objective of the DISTANCE project is to provide NRAs with information and guidance on the state-of-the-art in practical noise mitigation measures, data requirements for future action noise mapping and action planning, future potential traffic scenarios and improving public perception, awareness and acceptance of noise mitigation. This additional knowledge will assist them in planning and implementing future noise mitigation measures on their road networks.

In the current economic climate, budgetary restrictions mean that NRAs must strive to ensure that implemented measures are fit for purpose and durable whilst keeping costs as low as possible. Noise mitigation measures that provide additional benefits beyond simple noise reduction may therefore be an attractive proposition to NRAs if they can be achieved with relatively little additional expenditure or if whole life costs are favourable. These benefits may be categorised as being physical, economic, environmental or social.
Physical benefits, e.g. solar power generation, may well have a greater positive influence on public acceptance in circumstances where the introduction of a mitigation measure might be perceived to have a negative impact on the local landscape/visual aesthetics of an area.

Work Package 3 of the DISTANCE project seeks to investigate how primary NRA assets such as road surfaces and noise barriers might be enhanced to provide additional benefits, referred to here as 'secondary functions'.
This report presents the findings from the Work Package, grouped by function and highlighting the related advantages and drawbacks. Where evidence of practical implementation has been identified, details are provided; where no evidence is available, the report outlines the concept only.

1.1 Definition of 'secondary functions' for noise barriers and low-noise road surfaces

Within this Work Package of the DISTANCE project, secondary functions for noise barriers and low-noise road surfaces are considered as functions or benefits provided by the noise mitigation option which are in addition to the primary noise mitigation function.

It is considered the secondary functions can be broadly categorised into two types:

- **'Designed' secondary functions:** This is where the noise barrier or road surface is **physically modified** either by

- integrating additional elements **within** the structure of a conventional barrier or surface, or
- 'retrofitting'/mounting additional elements **onto** the structure of a conventional barrier/surface structure.

so that it provides a **physical (non-acoustic) function** that would not be provided by a conventional noise barrier or surface. This physical benefit is the primary reason for the modification of the barrier/surface and is embedded and/or integrated in it. However, additional non-acoustic benefits may potentially also be realised; these can be categorised as **social, environmental and economic functions**, examples of which are presented in the bullet point below.

Physical functions/benefits are considered as being those not normally associated with conventional noise barriers, such as energy generation, increased road user safety, reduced land uptake, etc. For example, a noise barrier fitted with photovoltaic cells will generate electricity as its secondary physical function. The photovoltaic cells might be directly integrated into the surface of the acoustic elements on the noise barrier or separately mounted onto the façade of the barrier in the form of solar panels.

- **'Bonus' secondary functions:** These are additional non-acoustic benefits that are realised even where **no physical modifications** are made to the barrier or road surface. As above these can be categorised as **social, environmental and economic functions**, as follows.

  <u>Social functions</u>: These are considered most likely to be benefits associated with public perception and associated subjective responses/viewpoints, and public interaction with the barrier. As such, they are most likely to be associated with the aesthetics of the barrier/road surface, obscuration of the local environment, etc. These may be associated with physical secondary benefits or may be independent as in the case of constructing noise barriers from different materials.

  <u>Environmental functions</u>: These will be benefits associated with an improvement of the local environment in the vicinity of the road or noise barrier.

  <u>Economic functions</u>: These are benefits which might result from changes to whole life costs or where additional monetary benefits might arise due to the need for a separate/previously unrelated solution being reduced or eliminated. For example, energy generation through the use of photovoltaic cells or panels might result in a reduction in energy produced from traditional sources such as power stations and reduced energy bills for residents connected to the photovoltaic system.

  For example, a noise barrier constructed out of recycled materials can be considered to have 'bonus' secondary functions since the barrier that does not perform a secondary physical function but contributes towards a reduction in materials being sent to landfill.

Designed and bonus functions can each be broken down into two further sub-categories as follows:

- **'Demonstrated' secondary functions**: This is where documented evidence of the barrier/surface with the secondary function has been identified, for example, as part of research trials or prototype demonstrations or, in the case of more developed solutions, where the system is in routine use on public road networks.
- **Concept' secondary functions:** This is where no documented evidence has been identified. This means that the barrier/surface with that secondary function might be presently untried/untested or a completely new concept.

Figure 1.1 on the following page presents the relationship between these different functions and benefits in a schematic form.

1.2 Overview of considered secondary functions

The secondary functions for noise barriers and road surfaces considered within this report are summarised within Table 1.1 on page 5. These were identified based on a combination of the project team's expert knowledge in the field of noise mitigation and experience of plausible or demonstrated secondary functions, and an open discussion of ideas.

More detailed descriptions of these secondary functions are presented in Chapters 2 and 3; these descriptions also present the following information:

- The **potential benefits** offered by implementation of the measure in question.

- The **potential drawbacks** or disadvantages of the measure in question.

- A high-level indication of the **likely costs of implementation** of these measures, if such an indication can be supported. Due to a lack of information on the costs of noise barriers and road surfaces that can be routinely applied across all European Member States, all cost estimates have been made qualitatively.

  For **noise barriers**, an average cost has been defined by the CEDR Project Group Road Noise (Milford et al, 2013) as €400 per square metre (derived from the average cost of €1,600 per linear metre for a 4 m high noise barrier; the same report records that the annual cost for noise barrier maintenance is €77 per linear metre). Using this as the benchmark, the following cost bands have then been defined within this Work Package:

  - *Cost band '-'*: The noise barrier with the secondary function is expected to be less expensive than an average noise barrier.
  - *Cost band '='*: The noise barrier with the secondary function is expected to be comparable in cost to an average noise barrier.
  - *Cost band '+':* The noise barrier with the secondary function is expected to be more expensive than an average noise barrier.
  - *Cost band '++':* The noise barrier with the secondary function is expected to be considerably more expensive than an average noise barrier.

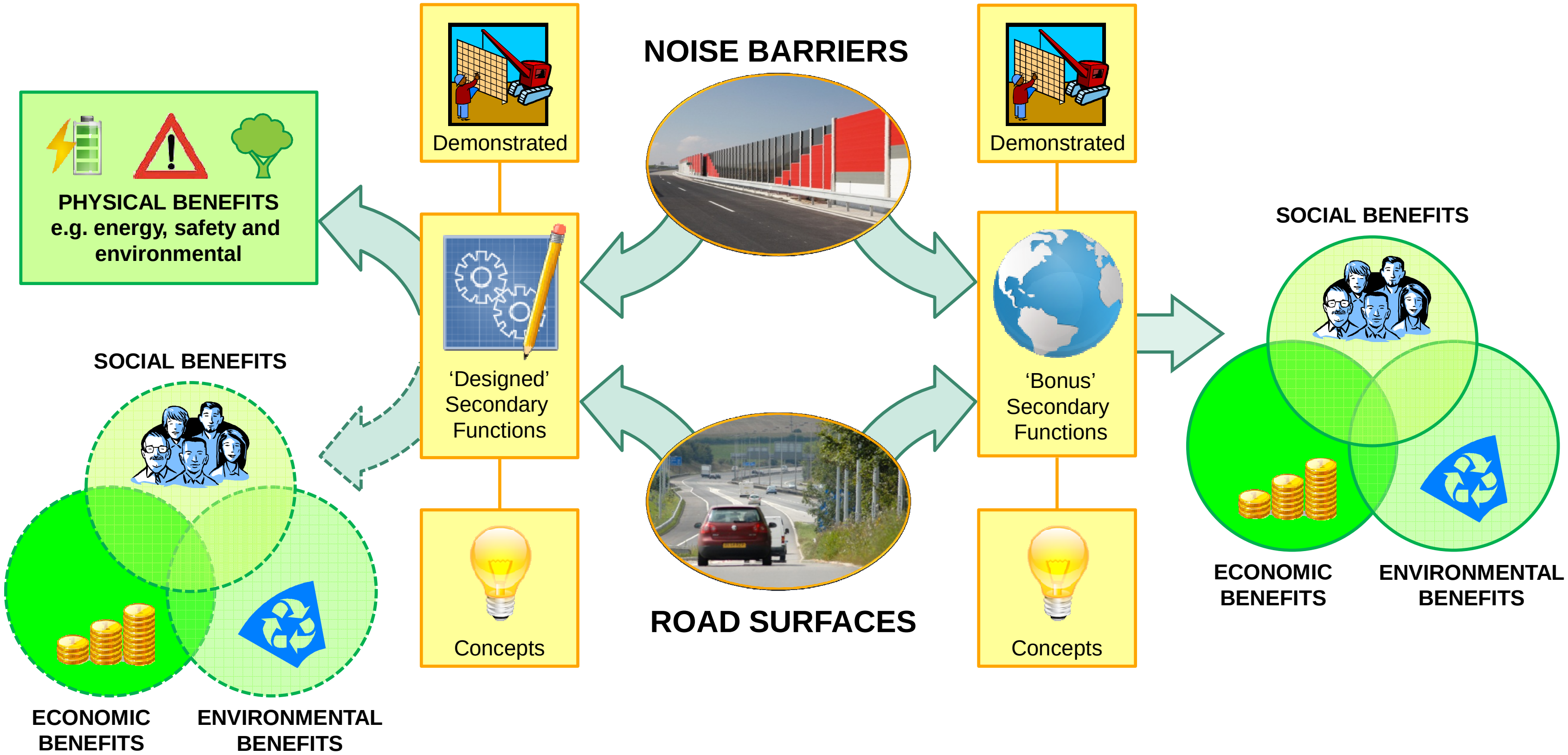


Figure 1.1: Definition of 'secondary functions within DISTANCE Work Package 3

Table 1.1: Summary of secondary functions considered in the report

Noise barriers		Road surfaces	
Designed (Demonstrated)	**Bonus (Demonstrated)**	**Designed (Demonstrated)**	**Bonus (Demonstrated)**
Integrated noise/safety barriers	Green (vegetative) barriers	Dynamic road markings	Use of recycled materials
Solar energy collection via PV cells	Transparent noise barriers	Inductive charging	
Air pollutant capture using TiO_2 coatings	Use of recycled materials for noise barrier elements	Heat generation/storage	
Fine dust capture using electrostatic concepts	Enhanced visual aesthetics	Modular pavements	
	Added devices to enhance acoustic performance	Self-healing road surfaces	
		Air pollutant capture using TiO_2 coatings	
		Energy generation via vibration	
Designed (Concept)	**Bonus (Concept)**	**Designed (Concept)**	**Bonus (Concept)**
Integrated lighting			
Advertising displays			
Information displays			
Rainwater harvesting			

Conférence Européenne des Directeurs des Routes
Conference of European Directors of Roads

For **road surfaces**, the CEDR report considers a reference pavement as an 11 mm Dense Asphalt Concrete (DAC11), but does not state average costs for surfacing and maintenance; instead it presents the costs for other surfaces in terms of the increase or decrease in cost relative to DAC11 for those activities.

Defining average costs for installation and maintenance of surfaces is very difficult since they will vary depending on the type of surface, traffic loads, climate, bearing capacity etc. Within the OPTHINAL project (Kragh et al, 2011), as part of a life-cycle cost analysis, an attempt was made to present the average cost for a conventional asphalt surface, which was reported as being €9.7 per square metre. Using this as figure as a benchmark, the following cost bands have then been defined within this Work Package:

- *Cost band '-'*: The road surface with the secondary function is expected to be less expensive than a conventional surface
- *Cost band '='*: The road surface with the secondary function is expected to be comparable in cost to a conventional surface.
- *Cost band '+':* The road surface with the secondary function is expected to be more expensive than a conventional surface.

- **The state of technology readiness of the measure in question:** This provides an indication to whether the measure is already available on the market or, if not, the maturity level of the measure in terms of its development/research status.

  A number of existing different scales were investigated for defining the technology readiness, such as the Technology Readiness Levels (TRL) implemented by NASA (NASA 2014) and within HORIZON 2020 (the EU Research and Innovation programme, which runs from 2014-2020; European Commission, 2014). However, with 9 levels on these scales, they were considered overly complex for the current study. The project team therefore devised a simpler 4-point feasibility scale, as follows:

Technical feasibility	Description
1	Initial identification of new concept knowledge and/or technology
2	Demonstration of prototype measure in the laboratory/trial conditions
3	Initial demonstration of measure on public roads
4	Concept routinely available on the commercial market

- The overall expert appreciation towards **potential for use by NRA**, based on the assessment from all previous criteria, ranging from readily implemented and suitable for widespread use on an NRA road network, over means readily implemented and suitable for restricted use on an NRA road network, to 'not ready for implementation' or 'suitable for very restricted use on an NRA road network'

2 Noise barriers with secondary functions

Noise barriers with secondary functions are more widely used than road surfaces with secondary functions (see Chapter 3). Several types are already in routine use across European road networks and the benefits are widely recognised. Examples of such measures include photovoltaic noise barriers, noise barriers using vegetation in their construction (green barriers), noise screens integrating safety elements with acoustic panels and noise barriers with TiO_2 coating to neutralise NO_x molecules.

In the remainder of this chapter, the most interesting examples of multifunctional noise barriers are described and analysed in terms of their benefits, potential; disadvantages, state of technology readiness and, where possible, indicative top-level costs. The main features of the most promising solutions are finally summarised to highlight and promote their potential use around Europe.

2.1 Designed (demonstrated) secondary functions

2.1.1 Integrated noise and safety barriers

For the protection of road users, vehicle restraint systems (safety barriers) are generally installed in front of noise barriers to prevent vehicles crashing into them and debris breaking away from the barrier, causing risks to road users and/or residents. Safety barriers are usually mounted at a distance sufficiently far from the noise barrier so as to allow them to deform in case of impact without affecting the noise barrier. This approach requires space between the barrier and the edge of the carriageway which may not always be available, so for new road schemes or road improvements the situation can be addressed through the use of systems where the noise barrier and safety barrier are integrated into a single structure.

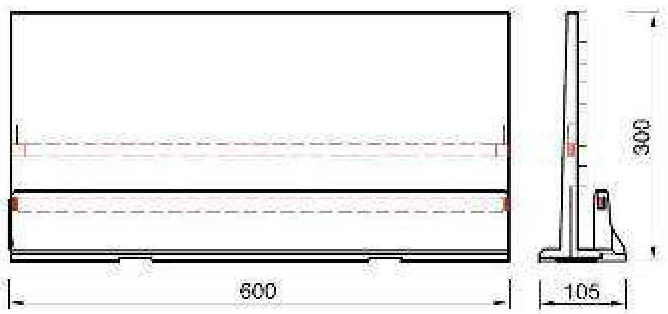
Integrated noise and safety barriers are noise barriers equipped with safety components, i.e. metal guard rails and/or concrete safety barriers (e.g. new jersey type or F-shape); in some cases, the systems are freestanding so that no foundations are necessary for their installation. Examples of this type of integrated barrier are shown in Figure 2.1 and Figure 2.2.

Potential Advantages: Integrated noise and safety barriers offer a number of strongly innovative features: first of all, the installation of a single integrated noise and safety barrier moves beyond the usual dual installation of safety barrier and conventional noise barrier by enabling installation of the noise barrier directly at the edge of the pavement.

This characteristic makes the integrated noise-safety barrier more effective compared to a standard noise barrier of the same height since the position of the leading diffracting edge is moved closer to the road. In other words, integrated barriers with a lower overall height can be used to reduce noise to the same extent, thus providing some material saving. Furthermore, a lower operating width is needed for their installation, thus resulting in land and money saving. For instance, a 4m high noise barrier at 3 m from the source to secure the working space of a safety barrier in case of impact, can be lowered by about 0,5 m if positioned on the edge of the road.

Figure 2.1: Integrated noise and safety barrier with metal guardrail
(*minimal depth 125cm to 165cm, height 2m to 5m)*

(Images reproduced with permission of Paver S.p.A.)



- *Minimised depth from 105 cm to 125 cm*
- *Different final heights (from 300 cm up to 450 cm)*

Figure 2.2: Integrated noise and safety barrier with new jersey elements(Images reproduced with permission of CIR S.p.A.)

Thanks to the rapid assembly of free-standing noise-safety integrated barriers (no foundations or anchor to the soil are required), the time required for their installation is also reduced, making this application cost-effective.
This type of system also offers the potential for more easily introducing noise barriers into the central reservation.

Integrated noise and safety barriers, using both concrete and steel guard rails as the vehicle restraint component, have also shown positive response on safety issues by passing crash tests for safety barriers carried out according to EN 1317-1 (CEN, 2010a) and EN 1317-2 (CEN, 2010b), even though the separation of the noise barrier and the vehicle restraint is limited; this means that the barriers would comply with the safety in collision requirements within EN 1794-1 (CEN, 2011a).

Figure 2.3: Integrated noise and safety barrier with metal guardrail crash tests

(Images reproduced with permission of Paver S.p.A.)

Potential Disadvantages: The maximum tested noise-safety barrier height is 5.00 m with metal guardrail and 4 m with concrete safety barriers. This solution is not applicable when the height needed is more than 5 m or 4 m respectively.

Technical Feasibility: Level 4. The concept has been proven in real-world applications and products are already commercially available.

Indicative Cost Band: Band '+' (more expensive than an average noise barrier). When total cost of safety and noise barriers are considered, combining both might be more economical than separate safety barriers and NB.

Potential for use by NRAs: The concept is proven and is therefore one that could be readily implemented by road administrations on their networks, especially since combined barrier heights of 4.0-5.0 m are, depending upon the precise design, feasible. It will not be suited to all situations where noise barriers are/can be used since noise barriers are not always located at the edge of the carriageway. It is considered that the concept could be applied for both new road schemes and barrier replacement schemes since in the latter case, it would not require the introduction of replacement foundations closer to the carriageway.

2.1.2 Photovoltaic noise barriers

Photovoltaic noise barriers (PVNB) allow the simultaneous abatement of noise and the production of renewable energy, by converting solar energy into electricity, thus limiting the production of greenhouse gas emissions into the atmosphere; Figure 2.3 - Figure 2.4 show examples of such barriers. Photovoltaic modules can be directly integrated within the surface of the barrier or 'retrofitted'/mounted onto the barrier in the form of solar panels.

Figure 2.3: A photovoltaic noise barrier installed in Vallese di Oppeano (Italy) - first stretch.

Figure 2.4: Photovoltaic noise barrier installed alongside the motorway A22 Brennero (Italy).

The position of the photovoltaic modules inside/on the barriers depends on the orientation and geometry of the barrier surfaces, which are defined by the sound abatement specifications: vertical barriers are most commonly used, coupled with an additional tilted surface on the top of the barrier or with other anti-diffraction elements; sometimes, in order to reach the requirements specified by the design, the road is partially or totally enclosed using a tunnel configuration.

PVNB have been trialled since 1989 (first installation along the A13 motorway in Switzerland) in a range of countries across Europe (pvresources.com, 2013) including Switzerland, Germany, Italy, the Netherlands (van der Borg and Jansen, 2001) and the UK (Carder and

Barker, 2006) with Germany and, to a lesser extent, Italy having installed the greatest quantity. Installation costs for large PV systems vary between €1,500 to €2,500 per kW. (Corfield, 2012) currently most likely lower as prices have dropped dramatically last years. A number of commercially produced systems are currently available. Several positive effects can be ascribed to PVNB application from the economic, environmental and social perspective.

Several test sections and studies give variations in life-cycle costs for PVNB. (e.g. Bellucci and La Monica, 2012) and state that PVNB can reduce the life cycle cost of noise reducing devices by up to 30%, based on current case histories, by selling the generated electricity. However this figure depends upon the price, level of public funding for renewable energies, the amount of mounted PV cells and on the PVNB being installed in appropriate climate conditions such as those in Southern Europe,
In contrast, results from a pilot project in the UK on the M27 in 2004, resulted in a far less positive message (Carder and Barker, 2006; Carder et al 2007).

No proof has been found that driver safety is affected by the presence of the PV cells, or that acoustic nuisance caused by sound reflection on installed PV cells is increased significantly.

A feasibility study on PVNB in Belgium (De Schepper et al, 2012) monetized not only economical (so also including the subsidies for green energy) but also ecological benefits, as taking the latter into account is important to have a positive cost-benefit assessment. It stated that in the case of a decision for a noise barrier, PVNB could form an alternative to promote public-private partnership where government, private investors and residents could all benefit.

Potential Advantages: Generally, the literature states that the overall gain of generating energy by PV cells mounted on noise barriers is limited with respect to the investment and maintenance cost. However subsidies could make PVNB worthwhile in some conditions although the latter only means a cost reallocation.
The remunerative nature of PVNB could result in a drain on private and public financial resources. Therefore, the costs of PVNB could potentially be shared funding the PV solution/part of the PVNB from the private sector and the basic noise barrier from public expenditure. The possibility of earning money from the production of renewable energy, makes it particularly interesting for the private sector. This is the case, for example, with PV noise barriers built in Italy, which have been constructed with the financial support of private investors.

Another advantage of using PV cells mounted on noise barriers is that no supplementary land consumption is needed. Integrating this secondary function with noise barriers could also speed up the decision process for the provision of noise abatement measures, and so have a direct social benefit.

The use of PVNB also increases awareness of renewable energy sources for all stakeholders.
Last, but not least, the production of renewable energy reduces the amount of CO_2 in the atmosphere.

Potential Disadvantages: Maintenance needs and maintenance costs are an important drawback to the use of PVNB. Modules, inverter and other components should be maintained, repaired or replaced, as far as is practicable and depending upon the design, without destroying/removing the noise barrier and with minimum traffic disruption. Cleaning of PV surfaces is a costly operation and as such, not often carried out

Theft and vandalism could be also a problem; the high price of modules makes PV components appealing for thieves, while their large and visible surfaces could be an easy target for vandalism or graffiti. Nevertheless, these problems can be solved with appropriate design strategies (e.g. ensuring robustness, the use of anti-theft bolts, the use of materials which are easily cleaned, etc.) and protecting the barrier location through installation of security fences, cameras, etc. (although any requirement for such security measures may count against the use of PNVB barriers in the design/selection phase).

Technical Feasibility: Level 4. The concept has been proven in real-world applications and products are already commercially available

Indicative Cost Band: Band '=' to Band '-' (comparable to or less expensive than an average noise barrier) when considered in terms of whole-life costs. Initial investment costs are high, but the sale of energy produced can drastically reduce the costs of the barrier, although this is likely to depend on the barriers being installed in locations where energy production is favourable. Experiences have demonstrated that in favourable conditions then without incentives the cost of the photovoltaic modules is recouped within the service life of the modules whilst with incentives the costs can be recouped in 15 years.

Potential for use by NRAs: The concept is proven and one that could therefore be readily implemented by road administrations. However, it will not be suited to all situations where noise barriers are/can be used since the efficiency and scale of energy generated by the PV cells will be dependent upon the orientation of the barrier, number of PV cells and the climate (amount of sunshine) and the potential use for the energy. If the barrier is low in height, the investment and benefits may be insufficient. The financial benefits of the generated energy must be carefully weighed up against the cost of energy storage/transfer infrastructure.

2.1.3 Noise barriers with TiO_2 coating

Vehicle emissions are one of the greatest sources of air pollution and, under certain conditions, contribute to smog formation. Smog has a detrimental effect on the environment and on human health. Whilst treating the problem at source (i.e. directly on the vehicles) is clearly the most preferable, this is not an option available to National Road Administrations, so measures which could assist in controlling the dispersal of emissions away from the roadside are likely to be considered positively if they can be proven to be effective.

Various studies have looked at the impact of noise barriers on the dilution and dispersion of air pollution. For example, Brechler and Fuka (2014) reported that noise barriers reduce concentrations of nitrogen oxides (NO_x) and airborne particulates along motorways. Also research into the performance of using photocatalytic coatings on noise barriers to reduce NO_x is ongoing.

Photocatalytic pollution abatement has been a subject of interest for some time, as it is an easily adaptable option for a variety of applications on existing infrastructure, such as roadways, tunnels, the surfaces of parking lots and also for noise barriers. The mechanism

relies on a photocatalytic coating, made of titanium dioxide (TiO_2), which breaks down pollutants such as nitrogen oxides (NO_x) in the presence of UV light (e.g. from sunlight) into non-harmful compounds that can then be easily washed away with rain.
TiO_2, is commonly used as a white pigment, photocatalytic coating. Figure 2.5 presents a an overview of the overall photocatalytic process

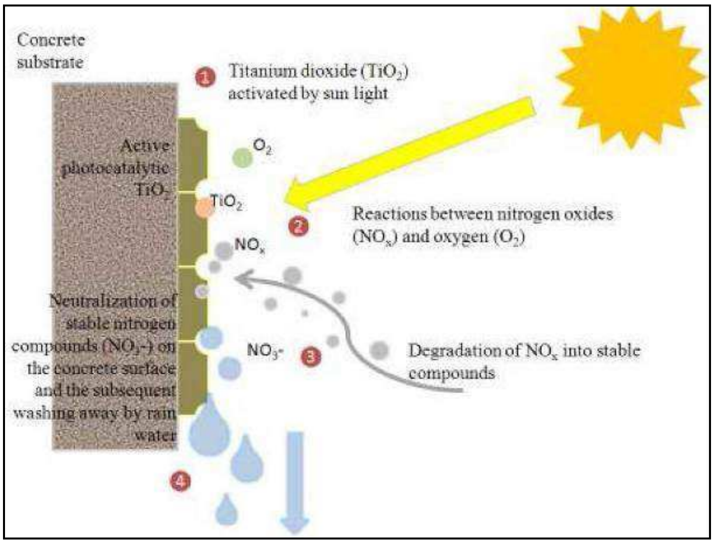


Figure 2.5: Overview of the photocatalytic process, adapted from figure by Ontario Ministry of Transportation (2011)

Recent studies (Blaschke, 2011; Chusid, 2010; Churchill and Panesar, 2013) have shown that there are several factors affecting the rate of NO_x removal, including porosity, particle size, irradiation time, atmospheric exposure and pollutant concentration.

Examples of practical trials on noise barriers incorporating TiO_2 coatings, e.g. the Dutch Air Quality Innovation Programme (Hooghwerff et al, 2009), UK trials on the M60 motorway and field trials in Wuppertal, Germany (Ifang, 2012) have met with limited success. Other studies have also been undertaken in Germany (for example, on the A1 near Osnabruck-North and on Krohnstieg in Hamburg; BAST, 2014) although no results from these studies have been identified. A new study in the UK is shortly to commence which will further investigate the issue using barriers installed specifically for air quality purposes (Highways Magazine, 2014). From a cost- benefit viewpoint, a high NO_x degradation rate is imperative (Cameron and Panesar, 2013). Trials in the Netherlands (Voogt, 2013) have demonstrated that proving that an air cleaning barrier works is very hard in real life circumstances.

Potential Advantages: On a sunny day, ideally 75% of the pollutant gases that come into contact with the TiO_2 coating can be eliminated (Eurovia Vinci, 2013). On a cloudy day, there is enough light to maintain the product's effectiveness. Furthermore, an overall pollution reduction by 15% to 25% is estimated. On the other hand, many references mention the reduced effectiveness in less ideal conditions. The degradation rate can decrease significantly in real life circumstances such as high humidity, a lack of UV light, dust deposition, etc.

Potential Disadvantages: The manufacturing process of TiO_2 coating requires chemical procedures that generate pollutants that contribute to global warming and smog formation. Consequently, the expected benefits from the TiO_2 coating could not outweigh the environmental burdens incurred through the manufacturing process.

Technical Feasibility: Level 3. The concept has been demonstrated in a large number of trials on public roads, but has yet to reach a stage where it is ready for wider implementation.

Indicative Cost Band: Band '++' (considerably more expensive than an average noise barrier).

Potential for use by NRAs: The concept still requires further development and proof of effectiveness before it would be ready for use as a recognised air pollution mitigation measure by road administrations. Based on the variation of reported effectiveness during trials, it is not considered that the technique will ever be appropriate for widespread use; however, public perception of such a measure may be favourable even if the effects are limited, since the road administration would be perceived as taking action to improve air quality.

2.1.4 Electrostatic fine dust collection

Whilst the noise barrier concepts discussed in the previous section addressed vehicle emissions such as NO_x, other concepts have been identified that address the capture of larger particle sizes, i.e. dust particles. In this instance, the innovative principle is to remove fine dust particles out of the air around roads by making use of the electrostatic concept. Such a system is based upon the use of electrically charged wires which are mounted onto the surface of a wall/barrier. The electric field charges particles suspended in the air. These charged particles can then be caught by another set of electrically grounded metal screens.

Following a successful preliminary small scale test in which the concentration of dust particles was reduced by nearly 50%, the electrostatic concept has been applied in a trial project (de Neef, 2014) in the Netherlands in the 1.1km long, highway tunnel 'Thomassentunnel'. In this trial, the number of days where the 24h-limit concentration for dust particles was exceeded decreased by 1 to 2 per year. However, it is clear that a lot of improvements and optimisations are needed for the system to be feasible for use beyond trial projects.

In 2012 the same principle was successfully applied to noise walls in trials in the Netherlands, besides tests of other techniques to capture fine dust such as the use of filter cloths and lava stones. The trial showed that for a 4m high screen, reductions in fine dust concentrations of up to 32%, could be achieved, with an average net- effect on a yearly basis of 5%.(van Ratingen, 2012; van't Selfde and Zoeter, 2012). Again additional research and development is needed for the systems to be feasible beyond trial projects.

Potential Advantages: The concept has shown already from trial sections to have potential to reduce fine dust particles concentration.

Potential Disadvantages: More knowledge is needed on the inducement of the electrostatic field, the change of the state of charge of the particles, the transport of the loaded particles from the air to the screen, the influence of climatic conditions, etc.

Technical Feasibility: Level 2. Although the concepts have shown potential, they are not yet ready for full trials without further development.

Indicative Cost Band: Band '++'. It is expected that these barriers, if they were to pass beyond prototype stage would be considerably more expensive than an average noise barrier, however this is based on the judgement of the authors of this report in the absence of evidence.

Potential for use by NRAs: The concept still requires further development and proof of effectiveness before it will be ready for use routine by road administrations. It is not considered that the technique will ever be appropriate for widespread use.

2.2 Bonus (demonstrated) secondary functions

2.2.1 Green noise barriers

Traditional solutions to abate traffic noise make use of concrete and steel barriers. These barriers are obtrusive and often cause complaints about their appearance. While society desires more peaceful surroundings, they also desire an aesthetically pleasing environment. This desire has led to the development of green noise barriers.

A green noise barrier is an engineered structure that uses soil and vegetation to mitigate noise. Green noise barriers, such as earth berms and vegetative screens, are advantageous with respect to traditional concrete barriers in their ability to blend in with the natural environment. Through this bonus secondary function of improving the aesthetics of the barrier, these barriers improve the public perception of noise mitigation. Green noise barriers also provide equal or better noise reduction when compared to traditional noise barriers due to their ability to absorb noise especially at high frequencies and deflect sound rays in different directions. Green barriers are available in a variety of designs, depending on the type of vegetation used.

Figure 2.6: Vegetative barrier
http://ntl.bts.gov/lib/43000/43000/43080/134556_FR.pdf

As a further bonus second function, green barriers can provide CO_2 absorption, although this is likely to be rather limited. A square meter of vegetated surface can absorb 44 µg/s on average (Taiz & Zeiger, 2010). The amount of CO_2 absorption depends on the average annual solar exposure and on vegetation type. For example, in Italy the average annual solar exposure is 2.000 hours, corresponding to an annual absorption of 316 gr/m^2. Considering that a light vehicle emits 126 gr/km of CO_2, a 4 m high and 1 km long green barrier can absorb on average the equivalent CO_2 amount of 10.000 vehicles/year.

The following are examples of different types of green barrier that have been identified from the literature.

- **Living willow walls.** *These designs are where the barrier is effectively a small footprint earth bund, planted with willow.* The example shown in the pictures uses two wooden frames placed several feet apart to retain and support the willow trees and a soil core. The soil core provides noise reduction and moisture retention for the willow trees while the geotextile retains the soil and prevents erosion. The willow trees act as a façade to increase the aesthetics of the barrier. A drip irrigation system is installed during construction to provide moisture to the willow trees.

- **Willow panels.** These designs offer two types of green noise barrier and have a footprint comparable to a conventional panel-construction noise barrier; they are generally panel type systems installed between steel posts. The first type uses dry woven willow rods to create the façade of the noise barrier; similar systems have been identified which use bamboo or coconut fibres in place of the willow rods.

(a) living willow barrier
Photo reproduced with permission of Cheviot Trees Ltd

(b) living & woven willow barrier
Photo reproduced with permission of Cheviot Trees Ltd

(c) Coco-fibre barrier
Photo reproduced with permission of Kokosystems BV

Figure 2.7: Examples of living wall type barriers

The second type uses a combination of woven willow rods and live willow trees (the latter normally installed in the form of living willow rods planted into the ground; as such, the aesthetics of the barrier change as the planted willow becomes more established. The living willow also provides season-dependent aesthetics and helps the barrier blend in with the natural environment.

- **Barriers incorporating plants within the acoustic elements:** This type of barrier is constructed from panels or elements which have hollow sections which can be filled with earth/gravel or planted so as to allow vegetation to establish itself on the barrier façade.

Figure 2.8: Barrier with plants
http://ntl.bts.gov/lib/43000/43000/43080/134556_FR.pdf

A number of different designs of barrier of this type have been identified. The barrier shown in the photograph on the right uses concrete elements that are stacked in an interlocking grid. This structure provides for an empty space in the centre of each element of the grid that can be backfilled with soil to plant vegetation. The system offers excellent noise reduction features due to the property of concrete to reflect sound waves and the absorbing characteristics of soil.

Figure 2.9: Barrier with plants
http://ntl.bts.gov/lib/43000/43000/43080/134556_FR.pdf

The barrier shown in the photograph on the left uses a series of wooden panels that are stacked in an interlocking structure. This structure creates empty cells that can be backfilled with course aggregate. These cells can be used to host soil and plant vegetation. The course aggregate creates empty spaces that trap noise while the wooden elements absorb noise. Furthermore, the wooden elements provide increased aesthetics and the addition of vegetation can help these barriers to integrate in the environment.

The design shown in the photograph on the right uses precast concrete trays that are stacked on top of each other. These concrete trays have a flower box design that allows soil to be retained within the barrier. Additionally, the trays can be stacked to meet the required height to provide the desired noise reduction. These barriers provide good noise reduction, which can be attributed to the size of the barrier and the thickness of the concrete and soil.

Figure 2.10: Barrier with plants
http://ntl.bts.gov/lib/43000/43000/43080/134556_FR.pdf

The barrier shown on the right combines vertical supports and horizontal elements to retain the soil. These supports and elements are made of lightweight recycled plastic. The elements create a soil core that allows vegetation to grow on the face of the barrier. The combination of plastic and soil contributes to reflect and absorb the sound waves providing a better noise reduction with respect to traditional concrete noise barriers. Furthermore, the vegetated surface concurs to increase the aesthetics.

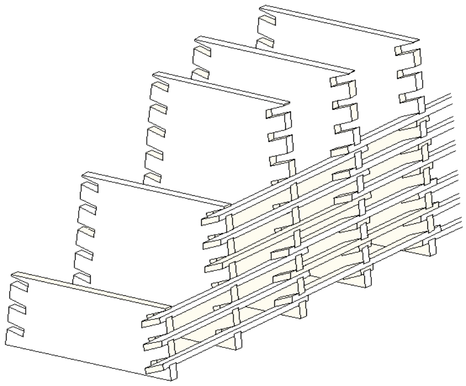


Figure 2.11: Barrier with plants
http://ntl.bts.gov/lib/43000/43000/43080/134556_FR.pdf

Potential Advantages: The main advantage relies in their environmental sustainability and their ability to blend in with the landscape, thus improving the public perception of noise mitigation, and depending upon whether the vegetation is included on the receiver side of the barrier as well as the source side, potentially improving the aesthetics of the barrier for residents living behind it.

Another advantage shown by some types of green barriers is that no foundation is needed.

Depending on the vegetation used, green barriers can offer a service life of up to 60 years. In addition, the combination of soil and vegetation can sometimes increase noise reduction when compared to traditional noise barriers due to their ability to absorb noise especially at high frequencies and deflect sound rays in different directions. Diffraction on the canopy of trees does not result in an increased total A-weighted sound pressure level due to the typical low-frequency spectrum of traffic noise (Van Renterghem, 2002).
More generally, the interaction between sound waves and vegetation, and design rules for vegetation and tree belts are studied in Chapter 4 (Acoustical characteristics of trees, shrubs, and hedges) and 5 (Designing vegetation and tree belts along roads) from the outcome handbook from European project HOSANNA (HOlistic and Sustainable Abatement of Noise by optimized combinations of Natural and Artificial means) (Nilsson, 2014).

Potential Disadvantages: The main disadvantage relies on the need for frequent maintenance operations and the availability of irrigation systems to guarantee sufficient amounts of moisture for vegetation. This leads to increased maintenance and labour costs.
The construction of green noise barriers are also labour intensive and require special skills, making these systems less interesting and cost-effective. Furthermore, green noise barriers that use a concrete structure skeleton may be susceptible to erosion from wind and rain, while those using plastic elements are subject to deformation under high and low temperatures and may deteriorate when exposed to direct sunlight.
In addition, more space is required by green noise barriers for their installation.

Technical Feasibility: Level 4. The concepts, particularly willow wall barriers, have been well demonstrated and products of this type are available on the market.

Indicative Cost Band: Band '=' to band '+' (comparable to or more expensive than an average noise barrier; the cost is likely to vary considerably depending upon the design that is installed).

Potential for use by NRAs: The concept is proven and one that could therefore be readily implemented by road administrations. However, it will not be suited to all situations where noise barriers are/can be used due to maintenance requirements and irrigation and spatial availability will affect the types of design available. If the objective is to enhance/disguise the appearance of the noise barrier for residents screened by the barrier, a more effective and manageable approach may be to use a conventional noise barrier and plant vegetation behind it.

2.2.2 Transparent noise barriers

Transparent acoustic elements are used to either provide a fully transparent barrier or are incorporated as components within an opaque barrier constructed from other materials. As such, their bonus secondary function is to reduce the visual impact that would result from the use of a conventional opaque barrier; they may allow drivers to view the surroundings beyond the road environment, allow residents a view across the road; and reduce unwanted shading on the receiver side. Where they are used as the upper acoustic elements on an opaque barrier, they reduce the perception of being 'enclosed'. The elements may be constructed from glass, acrylics, (coated) polycarbonate, polymethyl methacrylate, etc. Examples of this type of barrier are shown in Figure 2.12.

It has been found that human sensitivity to noise appears to be greater when the source of the noise cannot be seen (see, for example, Watts et al, 1999) meaning that the *perceived* noise level at the receiver is lower behind a transparent screen than behind an opaque screen with the same *actual* noise level behind the barrier; this has been further validated in other studies, e.g. Maffei et al (2013). This therefore suggests that opaque barriers may not provide the optimum protection for noise sensitive receivers. However, it is noted that research by Joynt and Kang (2010) looking at the perception of noise reduction for different noise barrier types based on preconceptions of the performance of different material contradicted this rationale.

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Figure 2.12: Examples of fully or partially transparent noise barriers

Transparent barriers are already used in many countries across Europe and many products are commercially available.

Potential Advantages: These barriers allow for the mitigation of noise to a similar extent as reflective opaque screens but with reduced/little obscuration of the local environment for both road users and residents behind the noise barrier. They can significantly change the aesthetics of the barrier.

Such barriers may be particularly beneficial where noise mitigation is required on bridges, flyovers, etc., as their use will not adversely affect the visual impact of the structure when viewed from ground level. However, consideration must be given as to how the barriers would behave if they were subject to vehicular impact, e.g. the safety risk posed by falling debris/acoustic elements from the barrier to road users/pedestrians beneath the bridge/flyover.

Potential Disadvantages: Depending upon the inclination of the barrier angle and the materials used, the barriers may require regular cleaning. Depending upon the materials used, there may be a tendency for the transparent components to become more opaque over time, although material developments make this less likely than when this type of barrier was first introduced. The barriers are more expensive than conventional opaque noise barriers and costs will vary depending on the type of transparent material.

There may be the possibility for light reflections from the transparent surfaces, either from reflections of the sun or headlights at night, which could cause issues for residents and/or road users and thereby affect safety. The barriers should be tested for light reflection in accordance with EN 1794-2 (CEN, 2011).

If transparent modules are incorporated within sound absorptive barriers (either as the upper most acoustic elements or as 'windows' in the barrier) this will reduce the sound absorption capabilities of the overall barrier. Therefore, in cases where there is either a barrier installed on the opposite side of the road or where there are large sound reflective structures (buildings) in close proximity on the other side of the road, the height of the barrier(s) might need to be increased to mitigate any increase in reflected sound due to the reduction in sound absorption. Alternatively, the problem can potentially be addressed by inclining the barriers away from the by a small angle, e.g. 10°, although this approach can be problematic for any high rise buildings located opposite the barriers.

Technical Feasibility: Level 4. The concept has been proven and there are a wide range of products commercially available.

Indicative Cost Band: Band '+' (more expensive than an average noise barrier; the cost will vary depending upon the material used and the percentage of the barrier installation that is transparent.

Potential for use by NRAs: The concept is proven and one that could therefore be readily implemented by road administrations. However, it will not be necessary in all situations where noise barriers are/can be. It is most likely to be used whether there is a need to reduce a perceived canyon effect (for drivers) when there are barriers on both sides of the road, or to reduce the perceived height/visual intrusion of the barrier (for residents) when barrier/residence separations are small.

2.2.3 Use of recycled materials

Noise barriers are just one area where end users are becoming more conscious of issues regarding sustainability of materials, carbon footprint, disposal and recycling at the end of the product life and consideration of whole life costs rather than simply the cost of the initial installation. The use of recycled materials for the construction of noise barrier acoustic elements is therefore a growing industry.
The bonus secondary function provided by these barriers is therefore primarily environmental, in that it reduces the amounts of material going into landfill and reduces the need for the extraction of 'fresh' materials such as timber, stone for aggregate, etc.

The most common use of recycled materials in noise barriers is through the use of recycled plastics. There are a number of commercially available products based on noise barrier acoustic elements of this type.

Other examples of barriers constructed wholly from recycled materials or which use recycled materials as a constituent material within their construction have also been identified within the literature. Whilst most of these are still prototype systems or undergoing on-road trials, some are already commercially available.
One area where there is an increasing interest is the use of tyre derived rubber materials (TDRM) from scrap/recycled tyres to create noise barriers with sound absorptive properties. Tischmak and Marcato (2011) reported investigations into a range of barriers constructed from TDRM. Barrier using these materials in some form, have also been demonstrated in a number of recent research projects and, in some cases have even reached the point of commercial application. Examples are as follows:

- **TDRM as a substitute for aggregate in concrete barriers.** This concept has been successfully demonstrated by Armtec (undated) and in projects such as RUCONBAR (www.ruconbar,com), a Croatian project which has developed a barrier where only the front façade of the barrier is sound absorptive, i.e. it is comprised of two layers – a back layer of conventional reinforced concrete and a front, absorbing layer of concrete mixed with TDRM (Lakušić et al, 2011; RUCONBAR, 2014). As of May 2014, construction commenced of a RUCONBAR barrier on a public road near Krk in Croatia.

(a) RUCONBAR noise barrier panels

Photo reproduced with permission from Prof. Stjepan Lakusic, Coordinator of EU project RUCONBAR University of Zagreb Faculty of Civil Engineering Zagreb, Croatia

(b) Whisper Wall barrier system

(from http://files.armtec.com/Downloads/Categories/Noise-Control/Whisper_Wall/Whisper_Wall_Brochure.pdf)

Figure 2.13: Examples of concrete noise barriers incorporating TDRM

Other examples where TDRM have been used in this form include the EKOPAN project (www.ekopan.eu).

- **TDRM as a replacement for conventional absorbers in modular systems**, Barriers of this type have been demonstrated by Carsonite (2010).

- **TDRM as a cladding material on other types of barrier**. Barriers of this type have been demonstrated by Štuliková and Šnajdr (2014); in this instance the TDRM was used to provide sound absorptive cladding on the front of a stone gabion noise barrier.

- **Barriers constructed solely from TDRM.** Barriers of this type, e.g. the Soniwall system produced by Sound Protection Solutions (2013; see photograph on right), can use very large quantities of TDRM in their manufacture, considerably greater than the amounts used as an aggregate substitute in concrete barriers. However, the weight of the acoustic elements is significantly greater than that of conventional barriers and may be a prohibitive factor.

Figure 2.14: Soniwall noise barrier system (from http://soundprotectionsolutions.com/our-products/acoustic-protection-system/usage/)

Other examples of where recycled materials have been included within acoustic elements for noise barriers include concrete waste, as reported by Krezel and McManus (2010); the barriers used in these trials were manufactured from recycled concrete (RC) aggregate and industrial by-products such as fly ash and reclaimed water and both sound reflective and sound absorptive designs have been investigated.

Potential Advantages: The use of recycled materials can reduce the amount of material such as plastics and tyres being sent to landfill. Depending upon the type of material used, they can introduce acoustic absorption properties to a noise barrier.

Potential Disadvantages: Depending upon the materials used, there may be considerable processing required to produce the forms suitable for inclusion as a constituent material within the acoustic elements of noise barriers, as is the case of TDRM, where the most common applications require waste tyres to be converted to tyre granulate (particles of rubber whose maximum dimension is between 1 mm and 10 mm).

Materials might not be as locally available for barrier manufacturers as conventional materials, meaning materials might have to be transported from further afield; this might increase the costs of the end products and affect the manufacturer's carbon footprint.

Depending upon how the materials are used within the manufacturing of acoustic elements and the quantities used, the end products may be heavier than conventional acoustic elements.

Specifiers/procurers must be aware of any adverse effects that the use of any recycled materials might have on the environment through the release of toxic constituents. All materials used and any physical/chemical conditions that might result in adverse environmental impacts should be declared in accordance with EN 1794-2 (CEN, 2011b). Increased fire risks might also be posed by the use of some recycled materials, including smoke hazards and toxic fumes; barriers should have been tested in accordance with the brushfire test in EN 1794-2 (it is noted that a new standard is in development (prEN 1793-4; CEN, 2014) which includes both that test and, for more stringent requirements, further tests for reaction to fire.

Technical feasibility: Level 2-4. Whilst some concepts have only reached demonstration stages within individual research projects, some types of noise barrier acoustic element incorporating recycled materials are already commercially available.

Indicative Cost Band: Band '=' to Band '+'. Where recycled materials are used as substitutes for other materials in the construction of acoustic elements, it is considered that the costs may be or are comparable to those elements constructed without the recycled materials. The use of recycled materials might increase the costs of the products.

Potential for use by NRAs: Depending upon the materials used, the concept ranges from under development to proven and is not necessarily one that could therefore be readily implemented by road administrations. The use of such materials will depend upon the design requirements of the barrier and may not be a characteristic or requirement that is directly specified by a road authority during the procurement process

2.2.4 Enhanced visual aesthetics

The level of consideration of the aesthetics of environmental noise barriers and how they sit within the visual character and architecture of their location varies. Since functionality is the primary concern and since they are most commonly installed using standard, off-the-shelf components, the same designs of barrier, with little visual appeal, can be seen installed in many locations.

However, sometimes it is preferable to make a feature of or a strong visual statement with the noise barrier or to disguise its presence/purpose. This may be to match the character of the area being protected or to improve public perception/acceptance of the measure which, whilst improving acoustic quality, might otherwise be seen as a blight on the local landscape. In such cases, this can be achieved through careful consideration and design of the appearance of the noise barrier and the materials/colour palette used.

The improvement in aesthetics is therefore defined as being the bonus secondary feature, albeit that to describe it as such might be perceived as tenuous.

There are many different ways in which making a strong visual statement with the barrier can be achieved, as shown in the examples in Figure 2.15. This is more the responsibility of the designers and architects taking care of the non-acoustic design aspects of the noise barrier and the overall aesthetics of the road scheme, although it will still be necessary to ensure that the noise barrier is of the appropriate type, i.e. sound reflective or sound absorptive, and that its height and position are adequate to provide the expected levels of acoustic screening at noise sensitive receivers behind the barrier. As such, the approach does not necessarily involve the use of additional, specialist materials and can include the following:

- Changing the colour of the noise barrier or the design of the façade, e.g. through the use of digital printing on metal cartridge panels, or through casting patterns on the façade. Clearly the ability to achieve this will be dependent upon the types of materials used for the construction of the acoustic elements.

  An example of such an approach being applied in combination with public/resident participation is the 'barcode' noise barrier installed on the A40 at Bochum Wattenscheid in Germany (shown in Figure 2.15(a)). The final colour scheme was the result of a public competition in which over 1200 participants submitted design proposals. (Barcode A40, 2009).
  Other examples of barriers with distinct visual aesthetics are shown in images (b), (c), (d) and (g) of Figure 2.15

- Changing the profile of the noise barrier in either the vertical and/or horizontal plane. This might involve changing the profile of the top edge so that it is not horizontal, changing the vertical profile of the barrier so that it is no longer flat. An example of such a barrier is the concept to be used on the Waterview Connection project in New Zealand (www.nzta.govt.nz/projects/waterviewconnection/overview.html) shown in Figure 2.15(g).

- Using different combinations of materials within the same structure, e.g. concrete and transparent elements. An example of such a barrier is shown in Figure 2.15(e).

- Adding additional elements of design features to make the barrier look less like a barrier and more like a different structure. One such example, installed at Margarentengütel in Vienna Austria, is shown in Figure 2.15(f) where a high transparent noise barrier has been installed directly connected to the high sided buildings at either end of the barrier.

- The use of vegetation in the barrier design (see also Section 2.2.1 of this report).

(a) BARCODE Noise Barrier, A40, Germany (from www.planung-a40-b1.de/Sechsstreifiger-Ausbau-Bochum.208.0.html

(b) Peninsula Link, Australia (from http://ausplastics.com.au/)

(c) Reproduced with permission of Urban Fencing Ltd

(d) SILENCE noise barrier (from www.pircher.eu/en/barriere-antirumore)

(e)Combination barrier (from www.cir-ambiente.it)

(f)Transparent barrier, Margarentengütel in Vienna Austria (Architecture © TREUSCH architecture)

(g) Concept barriers for the Waterview Connection Project, New Zealand. Reproduced with permission of Well Connected Alliance

Figure 2.15: Examples of barriers with enhanced visual aesthetics

- Using standardised components. An approach developed within the Netherlands as part of the Dutch Noise Innovation Program (IPG) was the concept of using a 'toolkit' of standardised noise barrier components across the road network (Hallinga et al, 2004), examples of which are shown in Figure 2.16. The approach was derived from Dutch architecture policy which aimed to enhance the quality of public spaces by preventing the occurrence of architecturally untidy/cluttered highways. The performance and costs of the toolkit are known, thereby assisting planners and architects in reducing overall costs and improving the visual continuity between different barrier schemes. The IPG modular barrier toolkit comprised (free-standing) posts with heights from 2 up to 8 m, acoustically reflective (concrete and glass) and absorptive (rockwool) acoustic panels and mounting components (clamps, etc. for fitting the panels in between the posts). The potential for adding further elements to the toolkit, such as T-profile barrier caps, was also recognised.

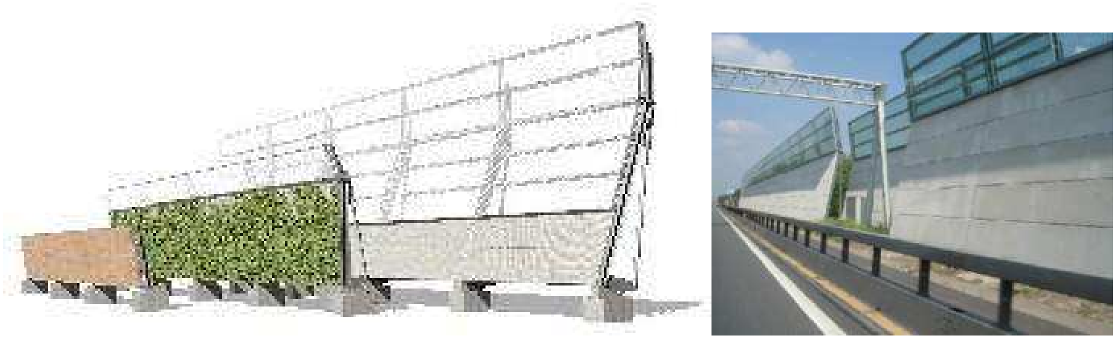

Figure 2.16: Examples of the IPG modular noise barrier toolkit and the construction alongside the A12 in the Netherlands (from Morgan, 2008)

Within the IPG programme, an 8 m high, 1.2 km long barrier was constructed on the A12 highway using the MNB toolkit (see Figure 2.16) and a modular T-profile barrier was constructed alongside the A28 highway.

Other examples of these different types of practice can be found in the review of European Best Practice by Huber et al (2013).

Potential Advantages: The use of improved aesthetics relative to conventional noise barriers is likely to enhance the acceptance of the noise barriers by the general public. It may also make the purpose of the noise barrier less obvious.

Potential Disadvantages: Depending upon the design and materials used, the barriers might be more expensive and construction/installation process may last longer than that for a conventional plane noise barrier and require additional staff/equipment.

Technical Feasibility: Level 4: Improving the visual statement of the barrier can be achieved through the use of existing products and is more a function of design.

Indicative Cost Band: Band '=' to Band '+'. The cost depends upon the method by which the strong visual statement is made. Merely changing the colour of a barrier will have little impact upon the cost, whereas changing the shape or profile of the barrier, for example, might require greater structural support, stronger foundations or the use of more materials than the implementation of a simple plane screen noise barrier.

Potential for use by NRAs: Since this is more about the design of the barrier rather than its performance, the concept is one that is readily implemented by road authorities, even if in the majority of cases it is deemed unnecessary or not considered, with 'off-the-shelf' products being routinely used. The importance of visual aesthetics will vary from scheme to scheme and will be a key consideration during the design stage if the introduction of a barrier is perceived by the general public to blight the surrounding location.

2.2.5 Added devices

Added devices are defined within CEN/TS 1793-4:2002 (CEN, 2003) as acoustic elements that are fitted on the top of conventional plane-screen noise barrier to enhance performance, serving primarily to affect diffracted sound energy. This is typically achieved with either no or a small increase in the height of the original noise barrier, and therefore offers potential for improving screening performance both during the initial design of new barrier installations or via retrofitting the devices to existing barriers. They work by moving the position of the leading diffracting edge closer to the noise source, adding additional diffracting edges, increasing the surface area of sound absorptive material at the top of the barrier or a combination of these effects.

From the perspective of what the devices offer with regards to bonus secondary functions, they change the aesthetics of the barrier.

Various research projects have studied the design of such added devices for use alongside roads and/or railways, using combinations of numerical modelling and full-scale testing, e.g. de Roo et al (2004). Considerable work has been undertaken on the performance of these devices in Japan; see, for example, the summary by Morgan (2004). Other studies where the performance of specific devices have been investigated include assessments of multiple-edge diffracting devices (Watts, 1996), interference devices (Watts and Morgan, 1996), T-profile devices (Kaptein et al, 2004), cylindrical caps (Asdrubali, 2007) and caps incorporating Helmholtz resonators (Bockstedte and Zaleski, 2011).. More recently, on-road trials of different devices have been reported by Kragh and Skov (2014).

Figure 2.17: Examples of added devices (from Morgan, 2008)

Such devices are presently not widely used across Europe; indeed, their use by National Road Administrations is presently limited to Italy and Poland, the devices typically being curved or octagonal-shaped devices.

Potential Advantages: The devices improve acoustic performance of a plane screen with no or little increase in height. They can change the aesthetics of the barrier from the perspective of both road users and residents living behind the barrier.

Potential Disadvantages: It is perceived to be a lack of data on their overall effectiveness, although the forthcoming issue of the full EN 1793-4 standard on diffraction performance provides a standard way of characterising performance and comparing the efficiency of different devices.

The ability to accurately model the acoustic behaviour of added devices within noise modelling software is restricted and in many cases unavailable.

It is considered that the devices are expensive in comparison to merely increasing the height of a plane screen.

Technical Feasibility: Level 3-4. Whilst some devices have not been demonstrated beyond roadside trials for research purposes, there are various added devices that are commercially available.

Indicative Cost Band: Band '=' to 'Band '+'. In this instance, the costs are considered relative to increasing the height of an existing screen. Depending upon the type of barrier onto which the device is to be fitted and the type of device to be implemented, the existing barrier might require some structural modification before the device can be installed.

Potential for use by NRAs It could be readily implemented by road administrations already. However, it will not be suited to all situations where noise barriers are/can be used since the acoustic efficiency is still questioned and studied, and from the perspective of aesthetics of the barrier, the secondary function, the gain is rather limited.

2.3 Designed (concept) secondary functions

2.3.1 Integrated lighting

Instead of mounting lights onto noise barriers, lighting elements could potentially be incorporated directly into the acoustic elements of noise barriers so that the upper section of the noise barrier could serve as street lighting. It is anticipated that such a measure would only be used in circumstances where there was no existing street lighting, and that there was a confirmed need at the individual location for lighting to be installed, e.g. to improve safety. No examples of this type of application have been identified.

Potential Advantages: This would eliminate the need for street lighting in the central reservation of the highway and potentially reduce light disturbance on the receiver side of the noise barrier due to the lights being below the top of the barrier.

Potential Disadvantages: It is expected that this approach would only be suitable for those barriers in close proximity to and at the same level as the road, otherwise there would most likely be insufficient illumination. The position of the lights might require regular maintenance to keep the lights clean etc. The quantity of integrated lighting installed would require careful consideration and design to ensure that, in providing adequate illumination, the energy consumption required would not exceed that for conventional street lighting appropriate to the road type/location in question; where no lighting is currently in place, the need for installing such lighting would need to be fully justified.

Technical Feasibility: Level 1 (no such systems have been identified from the literature review)

Indicative Cost Band: Band '++' if compared to conventional noise barriers alone, as not only would the acoustic elements incorporating the lights be more expensive, it would be necessary to install cabling and any other necessary associated systems so that the lights could be connected to the local power network. However, noise barriers with integrated street lighting might be more economical than the combined cost of a conventional barrier and street lights.

Potential for use by NRAs: No examples of this technology have been identified in the literature. Therefore there is no scope for NRA implementation without research and development work to investigate the feasibility and practicability of the concept.

2.3.2 Advertising displays

This secondary function would see noise barriers used to support advertising hoardings in some manner, such as being either mounted directly onto the barrier façade, or with the barrier serving as a base for advertising hoardings/displays to be mounted above the top of the main barrier.

It is assumed that adverts displayed below the top of the barrier would be mounted in the same plane as the noise barrier, i.e. flush with the barrier facade and not at an angle to the façade. Were advertisement hoardings/display to be mounted above the top of the noise barrier, it is assumed that these could be set at a different angle, although the height of the barrier would need to be such that the sign did not protrude into the emergency lane or, if none is present, the closest running lane.

An appropriate manner of mounting and ensuring the robustness of the advertisements would need to be identified, so that the risk of the advertisements breaking up and debris entering the road space would be eliminated. If the barriers are to be mounted above the top of the existing barrier, it would need to be ensured that the barrier foundations are sufficient to cope with the extra wind loading.

No examples have been found for this type of application. However, it is possible to digitally print onto the surfaces of metal cartridge noise barriers, so in principle, the display of permanent adverts on barrier facades that did not require to be replaced are already feasible.

Potential Advantages: The advertisements would be fitted onto an existing structure, so issues such as planning restrictions for the placement of new hoardings etc. might be eliminated, unless they were to extend above the height of the existing barrier. The length of barriers available on road networks potentially offers a significant increase in the capacity for advertisement placement.

Potential Disadvantages: There have been a number of studies looking at the optimum angle for advertisements when road users are the target audience. Mounting adverts onto the facades of noise barriers so that the adverts are displayed parallel to traffic would be mean that they are displayed at an inappropriate angle and may adversely affect driver behaviour due to distraction and the angle of view, causing safety risks for road users. In some countries e.g. Germany there are national laws forbidding advertisements near to highways because of safety issues.

If the advertisements were to become detached from the barrier, there is a risk that they could cause road accidents by interfering with the safe passage of drivers and may also pose a safety risk to pedestrians/residents at the rear of the barrier.

Technical Feasibility: Level 4 in the case of using digital printing to 'place' the advertisements. Level 1 for other options based on the lack of evidence of noise barriers being used for this purpose.

Indicative Cost Band: Band '=' in the case of using digital printing to place the other advertisements. No estimate is made for using other options for using noise barriers to display adverts.

Potential for use by NRAs: There appear to be no physical or technical difficulties that would potentially prohibit implementation of the concept; however, concerns arising from studies related to effects on driver behaviour/road user safety (based on the position/orientation of the signs relative to the carriageway) are such that there is considered to be little or no use for the approach by NRAs in practice. Existing legislation already prohibits the concept in some countries.

2.3.3 Informative displays

This secondary function would see noise barriers used to display road user information, e.g. for indicating the proximity of a car accident, traffic jams or slowing down traffic, through the use of digital matrix signs attached to the noise barrier. It is assumed that matrix signs installed below the top of the barrier would be displayed in the same plane as the noise barrier, i.e. flush with the barrier facade and not at an angle to the façade.

As with the advertising displays, it is assumed that matrix signs mounted above the top of the noise barrier could be set at a different angle, providing that they did not interfere with traffic.

Providing that wind loading issues could be resolved, the mounting of smaller temporary matrix signs such as those currently used in some countries for advance signing of road works, etc., on the top of a noise barrier, might be feasible, although it would not be possible to install these without a crane, meaning that such an application is unlikely.

Potential Advantages: Installation costs may be less than those for the installation of overhead gantries/matrix signs.

Potential Disadvantages: The issue of the angle of the displays relative to passing drivers posing safety risks is the same as for advertising displays, as discussed above. Depending upon the information displayed and the position relative to the on-road incident/issue, the matrix signs would not be visible from a sufficient distance to provide adequate warning for drivers.

Technical Feasibility: Level 1. Although matrix signs are routinely used on highways, there are no examples of their use in conjunction with noise barriers.

Indicative Cost Band: No estimate is made for using noise barriers for this purpose.

Potential for use by NRAs: There appear to be few physical or technical difficulties that would potentially prohibit implementation of the concept; however, the effectiveness of existing matrix sign technologies, the potentially late notification to drivers and concerns arising from studies related to effects on driver behaviour/road user safety (based on the position/orientation of the signs relative to the carriageway) are such that there is considered to be little or no use for the approach by NRAs in practice.

2.3.4 Rainwater harvesting

This secondary function could seek to overcome water shortages during extended dry periods or reduce general public water consumption from conventional sources by using noise barriers fitted with guttering type arrangements to collect rainwater which would then be stored in underground tanks. No examples have been found for this type of application.

A closely related trial project is ongoing in Denmark (de Neef, 2014), where water is not collected but instead slowly released. In this trial, the idea is to collect storm water run-off from nearby roofs and slowly release this over a period of three days, by way of evapotranspiration and the sewer system, to reduce peak discharge volumes during rain events. It will not be able to handle large volumes from cloudbursts, but can retain a fraction at least. For now the collected water is not foreseen for use by others purposes, but this could become an extension in the future, e.g. for nearby gardens. The level of water collected would be considerably greater than that collected by the proposed noise barrier application.

Potential Advantages: Local stored water supply for use by residents in times of drought or to supplement existing supplies

Potential Disadvantages: Collected water quantities are likely to be relatively low, since there are no run-off surfaces emptying into the guttering. The cost and spatial requirements for installing underground tanks are likely to be prohibitive and some form of pump system may also be required so that water within the storage tanks could be diverted into existing drainage systems. Drained water from roads could be polluted or at least not ideal for some kinds of use.

Technical Feasibility: Level 1. Whilst the idea is feasible, no evidence beyond the Danish trial has been identified

Indicative Cost Band: No estimate is made for using noise barriers for this purpose.

Potential for use by NRAs: The technique is considered unlikely to be implemented by NRAs.

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3 Low-noise pavements with secondary functions

Road surfaces with secondary functions are significantly less prevalent than noise barriers with secondary functions. Any move to introduce a secondary function must be achieved without adversely affecting primary performance factors associated with road surfaces, such as skidding resistance, noise emission, rolling resistance, etc. Since the inclusion of secondary functions may, depending upon the design, result in a more expensive pavement, it is also important that durability, both in terms of repair frequency and working lifetime should preferably be comparable to or better than that of conventional surfaces.

The review has identified a range of different technologies and concepts that have been applied to introduce secondary functions and which have undergone practical trials on various locations. These include dynamic road markings, inductive charging, heat capture/storage for various applications, modular pavements and the use of photocatalytic coatings.

3.1 Designed (demonstrated) secondary functions

3.1.1 Dynamic road markings

Beyond the use of conventional road traffic signs and, increasingly, LED-matrix type signals, raising the awareness of drivers on-road to current road and traffic conditions is largely outside of the control of National Road Authorities. Mechanisms such as the broadcast of information via radio and TV traffic/weather alerts or sat-nav traffic alerts may be useful but may only reach a small percentage of drivers.

However, recent developments in so-called dynamic road markings may offer a further option which would inform all drivers on the affected road. Dynamic road markings are those which react to local conditions to visually alert drivers of changes in physical conditions such as temperature and traffic flow.

Smart Highway (http://www.smarthighway.net/), a joint venture between Studio Roosegaarde and Heijmans Infrastructure (2014), is one such project developing new designs and technologies for future road schemes. These designs include concepts such as:

- Dynamic (luminescent) paints for road lane delineation, e.g. edge lines, which 'charge' during the daytime, enabling them to glow at night and thereby making lanes and road edges visible. Such markings are already in use in a pilot trial on the N329 in Oss, the Netherlands.

- Dynamic paints which show “ice crystal” symbols on the pavement which only appear when the temperature is close to or below 0°C.

- Dynamic road markings which can be used for 'real-time' traffic control, i.e. ‘turned on’ at certain times to indicate priority lanes for electric vehicles, car sharing, etc., or to control overtaking. The precise mechanism for controlling when the lanes are in operation for such purposes is not clear from the available literature.

For a wider application by NRAs beyond trials, information would be required from how far the road markings are visible, how skid resistant they are, how visible they are during the day and how they would perform in winter when there are fewer hours of daylight, but it is highly likely that there is insufficient energy stored in the winter season, hence the marking would not be visible during a significant part of the night, which is of course unacceptable. No information is available on the durability of the dynamic paints. Even if durability of the "ice crystal" markings would be comparable with conventional, state of the art road marking paints, there would be a durability problem as they suffer much more wheel passes than the edge and lane separation lines. It may be expected that they would disappear completely in the wheel tracks within a few months, if not weeks.


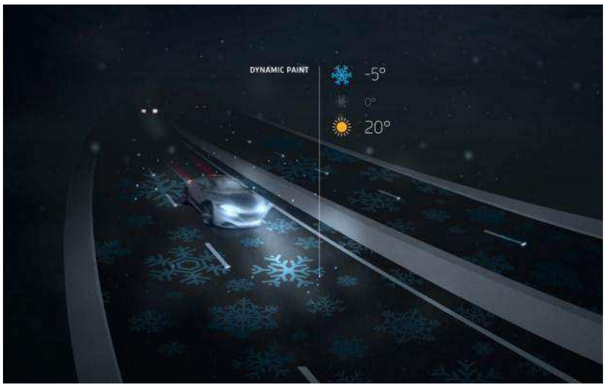

Figure 3.1: Examples of dynamic road marking concepts within the Smart Highway venture (Picture reproduced with permission of Studio Roosegaarde – awaiting permission mail@studioroosegaarde.net)

Potential Advantages: Apart from the aesthetic aspect and the "fun" factor, one can see little advantages for the concept of the "ice crystal" symbols. According to the authors this is more a "gadget" than a serious innovation for future road design. The luminescent lines could be interesting to enhance traffic safety, provided they are visible during the whole night, which is not the case. The current conventional method of making markings visible during the night, i.e. by making them retroreflective by adding glass beads, works well, but has the disadvantage that the glass beads gradually wear away. It is very unlikely that luminescent markings are a solution for that.

The use of such technologies for traffic control, e.g. to operate priority lanes or control overtaking could potentially be considerably less expensive than using conventional means such as over-lane gantry signals, however, this is assumed in the absence of any information on how such systems operate.

Potential Disadvantages: Too little energy storage in luminescent road markings and insufficient durability of systems constantly overrun by vehicles for the ice crystal concept.

There is also the consideration that their use to provide information on physical road conditions, e.g. low temperatures, icy conditions, etc. might merely reflect information that would be available to drivers through existing on-board vehicle technologies, particularly on new vehicles.

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Technical Feasibility Level 3 for dynamic road markings used for road lane delineation. Level 1 for dynamic road markings used for traffic control.

Indicative Cost Band: Band '=' for dynamic road markings used for road lane delineation, although this is based upon the best judgement of the authors of this report; the application of road markings will be a relatively small cost within a road scheme, so that whilst dynamic paints may be more expensive than those paints used for conventional road markings, it is still considered likely that such paints would be relatively inexpensive.
Indicative costs for using dynamic paints as part of dynamic traffic control cannot be estimated as the manner in which they would be controlled is unknown.

Potential for use by NRAs: Pilot trials of dynamic road markings have been undertaken with some success, but the need for further investigations to investigate performance factors mean that this concept is not yet ready for implementation. Proof would be required to demonstrate that the concept could perform better than other existing approaches. As such, no indication can be given as to the likely future scale of implementation.

3.1.2 Inductive charging

Based on current national government strategies and public attitudes towards energy efficient and sustainable transport, the use of electric vehicles across Europe is increasing and is expected to continue to do so. Many current technology fully-electric vehicles have a limited range and therefore the scope for performing longer journeys on roads typically controlled by NRAs, e.g. motorways, is limited unless charging points are readily available along the journey route.

This application consists of electric vehicle charging as a secondary function of road surfaces, by providing the infrastructure through which electric vehicles can be charged in a dynamic, as opposed to static, manner.

One project, FlandersDrive (undated; see also Perik 2013a, Perik 2013b) focussed on the actual transfer of charge to vehicles and their operation rather than on the generation of the power to be transferred. Inductive systems were successfully fitted to both a bus and a passenger car. From the perspective of dynamic charging, the work focused on the inductive charging of electric buses with charging systems trialled in both concrete and asphalt surfaces. The results showed that the technique is feasible, applicable and electrically safe. However the practicalities of whether an inductive system can be readily integrated into a road surface require further investigations, with the results suggesting that prefabricated, modular road sections may be preferable. The focus now is rather on static rather than on dynamic charging.

Elsewhere, Nguyen et al (2014) assessed different prefabricated concrete slabs with integrated electrical supply cables, designed to act as charging system for electric vehicles by induction. The study monitored the strains and displacements measured under a dual wheel load and revealed that joint deflections after one million passes of the wheel were minor and that horizontal strain loads were very small. The report concluded that the technology is a promising solution for powering electric vehicles in urban areas.

Inductive charging has been successfully implemented in Braunschweig, Germany by Bombardier Transportation for the static charging of buses since 2013.

Potential Advantages: The availability of dynamic inductive charging for electric vehicles in motion would favour the use of fully electric vehicles on NRA roads, both for short journeys as for trips which exceed the action radius of the electric vehicles, since routes would not need to be planned based upon the locations of static charging points, e.g. at motorway service stations.

Potential Disadvantages: The reliability of the technology has to be robustly demonstrated or require systems to be designed to ensure minimal maintenance. Faults should only affect small sections of the charging. for the system may be damaged during road maintenance activities.

The cost for installing dynamic induction charging surfaces might be significantly greater than for the installation of static charging points and a higher percentage of the fleet should consist of electric/hybrid vehicles for the investment to be justified.

Technical Feasibility: Level 2 for dynamic induction charging. The approach has been demonstrated at small scale and only for a limited vehicle selection. Level 3-4 for static induction charging.

Indicative Cost Band: Band '++', based on the judgement of the authors of this report; the published findings suggest that the technologies would be expensive, especially if one has to use prefabricated pavements.

Potential for use by NRAs: The concepts have been demonstrated, but require further development before they will be ready for use. The level of infrastructure required is likely to be prohibitive for the concept to be widely used on NRA roads unless national transport policies result in a high percentage of future fleets being electric vehicles.

3.1.3 Heat capture/storage

There are a number of potential applications for heat captured from road surfaces, as outlined below

(a) For provision of electrical power

The provision of energy capture via solar panels is becoming increasingly common and is a technology that is starting to be introduced as a secondary function on noise barriers. However, energy/heat capture through road surfaces is a concept that is much more in its infancy.

Heat capture through innovative pavement design can be achieved through a number of different technologies and used in different ways, as highlighted here and in section 3.1.4. This section focusses on heat generation for use in buildings and homes.

Work in the Netherlands (WinnerWay, undated) has been carried out towards obtaining renewable energy from infrastructure including the design of road structures and asphalt collectors for the extraction of heat and cold energy. The asphalt collectors were tested in 1998 and showed that 30 m^2 of asphalt was necessary to provide heat for a modern, well-insulated house for one year. The energy could also be stored through a heat pump for use in delivering hot tap water or heating other spaces such as car parks or airports. The asphalt collector is built into the pavement substructure and in summer heat is extracted from aquifers (60 to 100m below ground level) and transferred, via a heat exchanger, to a suitable energy storage system. This energy can be used as low-grade heat for buildings, up to around 24°C, although it is primarily used for heating road surfaces (see next Section).

A similar system has been used for the climate control of buildings for a number of years, such as the station buildings at Schiphol airport.

In the United States solar panels embedded within road surfaces have been installed in parking lots and funding is being sought to roll them out to highways (solarroadways.com; TrafficTechnologyToday.com, 2014). They consist of interlocking tempered glass hexagonal panels. The intention is for the stored heat to be transferred as energy supply for local buildings (see Section 3.1.4 for further details).

Potential Advantages: The systems would provide low-grade heat or electricity to buildings which could serve as an alternative to or complement the use of conventional solar panels (mounted either on buildings or as part of noise barrier installations).

Potential Disadvantages: The systems are likely to be complex and time intensive to install and may be difficult to maintain. They may also be affected by any routine surface maintenance or other service works (e.g. cable or water mains replacement) that might be required. For systems with solar cells one has to have (and maintain) a pavement which is at the same time very transparent and sufficiently skid resistant, which is in the current state of the technology not feasible according to the authors. Any kind of glass will be scratched and polished almost instantly by the action of tyres and the inevitable presence of sand and small stones on the pavement. One could avoid this by making the pavement from the very hard sapphire, which would resist much better to scratching and polishing due to its extreme hardness, but the price would be far above any reasonable limit. And even a very hard surface would become dirty, reducing the solar energy harvested by the solar cells.

Technical Feasibility: Level 2 for both asphalt collectors and in-road solar panels. None of these technologies have yet proceeded to being tested on public roads.

Indicative Cost Band: Band '++' based on the judgement of the authors of this report and the current state of development of the technologies.

Potential for use by NRAs: The concept still requires further development and proof of effectiveness before it will be ready for routine use by road administrations. It is not considered that the technique will ever be appropriate for widespread use due to the additional infrastructure required.

(b) For road de-icing

An alternative secondary function for capturing and storing heat energy via road surfaces is automatic road heating in winter conditions to reduce, if not eliminate, the need for roads to be gritted/salted. Various trials have been identified from a review of the literature.

The system tested in the Netherlands (WinnerWay, undated; see previous Section) was designed primarily to use the heat from the energy storage system to warm the road surface to a temperature of around 7°C. The system could also be used to cool the surface in the summer.

In Japan several demonstrations have been carried out to test the use of underground heat recovery and storage for the de-icing of roads in winter.

Fukuhara et al, (2002) describe two snow melting systems using ground heat, one being a reservoir heat collection system which includes two water tanks underground used for melting snow in a car parking area and the other being a borehole heat exchange system used for melting snow on a pedestrian pavement. Results are reported from tests carried out in the winter of 1999/2000. As with the Dutch work the systems could also be used to cool the pavement in summer to prevent rutting from heavy vehicles.

Tanaka et al (2003) evaluated results from the borehole heat exchange system described by Fukuhara et al. This system uses geothermal energy from 50 to 150m below ground for heat storage and melting of surface snow. Data shows that the road surface temperature using this system is of the order of 6°C higher than the corresponding air temperature. It was claimed that operating costs were of the order of 10-20 times cheaper than conventional electric heating or boiler systems. The extracted heat, over a year, was found to be around 8 times greater than the power consumption over that period.

The performance and development of a road heating system using electricity generated by wind power, installed at the entrance to a tunnel, has also been looked at (Ishida, 2002). Heating cables were installed at the base of a 4m layer underneath a semi-flexible pavement layer consisting of open graded asphalt concrete with a high void ratio. The heated sections of pavement at either end of the tunnel were found to be between 2 and 6°C warmer than the surface in the tunnel which was not heated.

In Europe, Eugster and Schatzmann (2002) reported on a Swiss system which collects excess heat from solar warming just below the road surface and stores it underground. The objective was to prevent ice formation on a highway bridge surface. The stored heat is used to control the temperature of the surface in winter and keep it just above 0°C. Benefits of the system were listed as a reduction in traffic accidents, more free flowing traffic, less maintenance work and an extended lifetime for the surface. In summer, approximately 140 MWh of energy was stored but around one third of that was lost to the surroundings prior to its use in winter, which is one demand. Depending on the severity of the winter conditions between 30 and 100 MWh of energy was needed to keep the surface above 6°C and prevent the formation of snow and ice. For the system to be adapted to other types of road, new approaches will be needed for laying down the heat exchangers and revised construction of the road surface (this could possibly be achieved using modular (prefabricated) road surfaces. Eugster reported in 2007 that the Swiss plant was still operational and that other studies on geothermal road/bridge heating were on going in Germany and Switzerland..

Potential Advantages: The systems would reduce, if not eliminate the need for the salting/gritting of roads in winter conditions; not only would this potentially offer cost savings to road authorities, but would also eliminate the impacts of sudden changes in weather conditions, when road gritters receive insufficient notice for roads to be treated in time. This would in turn increase the safety of driving conditions during the winter months and potentially keep roads open during adverse conditions.

Reduced salt application and the reduction in the clearing of snow using snow ploughs, etc. is likely to extend the lifetime of the surfaces.

Potential Disadvantages: The systems are likely to be costly, complex and time intensive to install and may be difficult to maintain. They may also be affected by any routine surface maintenance or other service works (e.g. cable or water mains replacement) that might be required. Gritting vehicles, with stand-by crews and a suitable supply of road salt might require to be maintained as a back-up in the event of the road heating systems failing.

Technical Feasibility: Level 3. Away from pedestrian areas, the main application for such systems to date has been to prevent ice formation on bridge structures. Systems have been shown to work on small sections of road in Japan but the techniques are unproven on different pavement types.

Indicative Cost Band: Band '++'. The systems are expected to be considerably more expensive than conventional surfaces, especially in terms of initial installation. Assessment of the cost-effectiveness would have to be based on a road-by-road basis, taking into account the type of surface that would normally be used, the frequency of salting/gritting and the quantities of salt/grit and/or the frequency of clearing with snow ploughs and the costs associated with those operations.

Potential for use by NRAs: The concept still requires further development and proof of effectiveness before it will be ready for routine use by road administrations. It is not considered that the technique will ever be appropriate for widespread use due to the additional infrastructure required.

(c) Heat capture/storage for road surface cooling

In addition to surface heating it is possible to consider the opposite problem of pavements which are too warm and lose durability as a result.

Both the Dutch (WinnerWay, undated) and Japanese (Fukuhara et al, 2002) systems described previously could be applied for this purpose.

Japanese research (Kawakami, 2008) explains that cool pavement techniques include water retention and heat shield pavements. With a heat shield pavement the surface is coated with a special paint that enhances solar reflectance. However, it was acknowledged that improvements are needed in terms of both preventing the removal of the coating from heavy traffic and applying the coating in an efficient and automated manner. Four types of thermal barrier were tested and maximal temperature reductions of between 10 and 20°C were achieved when the control pavement temperature was very high (~60°C).The structure, cooling performance and skid resistance of the test surfaces were tested after 400000 wheel loads of heavy vehicles and results showed that cooling performance was largely maintained and rutting and skid resistance were similar to the control pavement, indicating that there was no detrimental impact to the pavement from the coating. Further work was to be carried out to try and reduce initial costs and improve the associated reductions in air temperature.

Potential Advantages: Use of the systems might increase the lifetime of the pavement by preventing softening of the asphalt and rutting during periods of the year with high temperatures. Durability should be further tested.

Potential Disadvantages: The systems are likely to be costly, complex and time intensive to install and may be difficult to maintain. They may also be affected by any routine surface maintenance or other service works (e.g. cable or water mains replacement) that might be required.

Technical Feasibility: Level 2. The tested systems have been proven under extensive testing in the laboratory but require work on both logistics and cost before they are ready for use on public road networks.

Indicative Cost Band: Band '++'. The systems are expected to be considerably more expensive than conventional surfaces, especially in terms of initial installation.

Potential for use by NRAs: The concept still requires further development and proof of effectiveness before it will be ready for routine use by road administrations. It is not considered that the technique will ever be appropriate for widespread use due to the additional infrastructure required.

3.1.4 Modular pavements

The time, costs and impacts on journey time associated with the installation and subsequent maintenance of road surfaces can be prohibitive. It is therefore considered advantageous to reduce construction time. One such approach would be for the use of prefabricated road surfaces which could be easily and quickly installed, and similarly replaced at the end of the surface's lifetime. They would potentially allow road markings, traffic loops, condition monitoring systems, and other useful technologies to be pre-placed prior to the installation of the surface on site. As noted in Section 3.1.2, they are already identified as being a way in which inductive charging systems for electric vehicles might be most readily implemented.

A number of systems have been identified from the literature review that have been trialled, in some cases on public highways. However, there is little evidence that these solutions have been adopted for routine use by road authorities, most likely because of the high costs.
Two such innovative modular surfaces were tested initially within the framework of the Dutch 'Roads to the Future' programme and subsequently in the Dutch road traffic noise innovation programme, IPG (Morgan, 2008) as follows:

- '**Rollpave**': A rollable, porous thin layer surface that was invented and developed by the consortium Dura Vermeer-Intron. The surface is manufactured off-site under factory conditions as a single-layer porous asphalt surface in 50 m long slabs with a width of 3.5 m and thickness of 30 mm. Each slab is then rolled onto a drum. The drums are transported to site and the asphalt is unrolled. A fine iron gauze which is built into the surface during the manufacturing process is then heated by means of induction (to a temperature in excess of 115 degrees) to melt the bituminous layer around the gauze, thereby allowing the surface to bond to the underlying tack coat. A roller is then used to flatten the asphalt mat and the surface is ready for driving on. In principle, reheating the iron gauze to the same temperature breaks the adhesion

between the asphalt and the carrier so that the asphalt mat can be rolled up and removed.
Trial sections were laid on various roads within the Netherlands, including the A50 and the A35. Initial noise reductions were measured in excess of 4 dB(A) relative to a 16 mm Dense Asphalt Concrete surface, with the expectation being for 6-7 dB(A). The expected lifetime of the surface was 10 years, based on the fact that the surface is effectively a thin porous asphalt. Rollpave was comparable to single-layer porous asphalt in terms of skid resistance performance. However, there was increased splash and spray and the surface was less permeable than single-layer porous asphalt. Although the initial costs were high, the expectation was that Rollpave could be laid approximately 50% faster than single-layer porous asphalt and approximately 100% faster than two-layer porous asphalt. No evidence of further test sections have been identified; moreover, the consortium has in the meantime abandoned the idea and disposed of the equipment.

Figure 3.2: Rollpave system

Photographs from Morgan (2008)

- '**Modieslab**': A modular pavement system (www.modieslab.nl) invented and developed by a Dutch consortium comprising Betonson, Heijmans and Arcadis. The surface consists of piled foundations, concrete support slabs and a two-layer porous cement concrete pavement. It is considered to be a rapid construction method for new roads and road widening projects in areas that are sensitive to settlement.

(a) Installation of foundation piles (b) Installation of pile caps (c) Installation of concrete slab

Figure 3.3Modieslab system

Photographs from Morgan (2008)

Test sections were laid on the A50 and A12 in the Netherlands. Initial noise reductions for the surface were in excess of 6 dB(A) relative to a 16 mm Dense Asphalt Concrete surface. The piled foundations and concrete support slabs are expected to have a lifetime equivalent to that of the road. It is expected that the main porous concrete pavement will have a lifetime of 15-30 years. With respect to safety, Modieslab is comparable to two-layer porous asphalt. Modieslab was found to be particularly cost effective for use in areas on soft soils. The construction time on soft soils was much faster than with conventional construction methods which require long settling times to be taken into account. The modular nature of the system means that replacing slabs is likely to be quicker than the maintenance of conventional asphalt. Low-speed surface concepts have also been developed for use on roads with speeds up to 80 km/h and trialled in Hengelo in the Netherlands. It is unclear whether either the high-speed or low-speed concepts have progressed beyond demonstration/trial sections such as those listed above.

An American concept for a modular surface (http://solarroadways.com) is based upon modular hexagonal solar panels, which directly form the driving surface of the road and are capable of withstanding vehicle loads of up to 130 tonnes. The design of the panels is such that the glass is textured to provide a similar surface texture to conventional asphalt surfaces and includes a range of different additional technologies or benefits including heating elements to keep the surface free of snow/ice, LEDs for providing road markings and a means to readily allow for the inclusion of power and data cables. The inclusion of induction charging capabilities would allow for the potential of inductive charging under both static and dynamic conditions. Initial trials in a car park (as shown in the photograph) have been funded by the U.S. Federal Highway Administration and the manufacturers are seeking funding to trial the system on roads.

Figure 3.4: Solar Roadways system (from http://solarroadways.com)

Potential Advantages: The surfaces potentially offer reduced paving times compared to the time required to pave conventional surfaces, thereby reducing impacts on journey time reliability; The surfaces offer, depending upon the design, the scope to preinstall road markings, telematics, drainage, etc. Major maintenance may potentially be more readily and easily undertaken as only the directly affected sections of the road need to be replaced.

Potential Disadvantages: The systems are very costly and the benefit might be very limited. See also the comments under 3.1.3.

Technical Feasibility: Level 3: Trials of different types of modular surface have been undertaken, but have yet to see the surfaces proceed to commercially available products. Level 2 for solar roads.

Indicative Cost Band: Band '++' due to the initial costs. Considered in terms of whole life costs, the increased cost relative to conventional pavements may be reduced.

Potential for use by NRAs: Trials of different types of modular pavement have been undertaken on NRA roads across Europe, which have shown promise but never to such a degree that has resulted in commercially available products. The concepts are recognised as being potentially beneficial by NRAs, for a range of reasons, but it may be some time before robust products are available for widespread use.

3.1.5 Self-healing road surfaces

Maintenance of road surfaces causes disruption and thereby any means with which to reduce the frequency of maintenance might, cost dependent, be viewed favourably by road authorities. One approach would be to modify the design of the road surface so that it can be 'self-healing' to repair minor damage. Whilst this idea might seem fanciful, one such concept has been demonstrated in the Netherlands.

A porous asphalt surface containing small steel wool fibres has been laid on the A58 near Vlissingen in The Netherlands. A significant problem that arises with porous asphalt is that of ravelling, i.e. the loss of stones from the surface due to microcracking in the binder. The porous asphalt laid on the A58 was developed by Delft University (sponsored by AgentschapNL) and can be heated with induction energy due to the fibres that are present in the surface. This closes the microcracks and thereby extends the service life of the road (TU Delft, undated; Garcia et al, 2011)

Potential Advantages: The working life of the road surface is extended as the surface needs to be physically renewed less frequently, reducing costs for the road authority and causing less disruption to drivers. The surfaces can be repaired before ravelling etc. causes sufficient damage to the road surface to cause damage to vehicles. The reduced frequency of repaving saves money and uses fewer material resources.

Potential Disadvantages: The technique has so far only been shown to work for single-layer porous asphalt.

Technical Feasibility: Level 3. The concept has been trialled on the public highway.

Indicative cost band: Band '=', assumed on the basis that the only modification to the porous asphalt is the inclusion of the steel wool fibres. However, this cost estimate is based on one possible option for 'self-healing surfaces'; indicative costs cannot be estimated for other types of self-healing surface.

Potential for use by NRAs: The concept has been trialled on public roads and, although further investigations are likely to be required, might therefore be implemented in the near future by road administrations on their networks as an alternative to more intensive/disruptive maintenance procedures. However, the primary prohibiting factor restricting its application is that the technique has so far only been shown to work for single-layer porous asphalt, which is not used by some road administrations.

3.1.6 Air pollutant capture

As noted in Section 2.1.3, vehicle emissions are one of the main sources of air pollution. Whilst treating the problem at source (i.e. directly on the vehicles) is clearly the most preferable, this is not an option available to National Road Administrations, so measures which could assist in controlling the dispersal of emissions away from the roadside are likely to be considered positively if they can be proven to be effective.
An alternative solution would be to apply an appropriate catalyst to the road surface, hence in an after-emission treatment of the pollutants as close to the source as possible.

Therefore, photocatalytically active materials can be added to the surface of pavement and building materials (Chen, 2009). Air purification through heterogeneous photocatalysis consists of different steps: under the influence of UV-light, the photoactive TiO2 at the surface of the material is activated. Subsequently, the pollutants are oxidized due to the presence of the photocatalyst and precipitated on the surface of the material. Finally, they can be removed from the surface by the rain or cleaning/washing with water, see Figure 3.5.

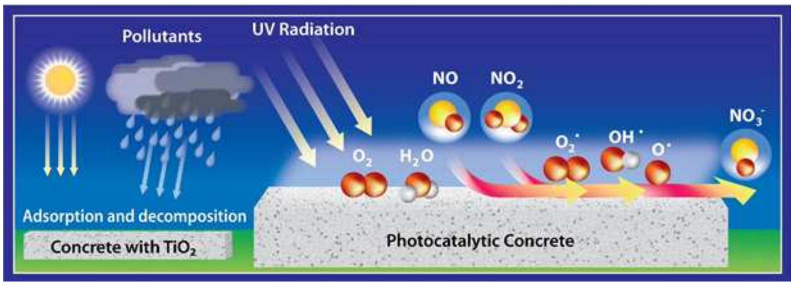

Figure 3.5. Schematic of photocatalytic air purifying pavement.

Heterogeneous photocatalysis with titanium dioxide (TiO2) as catalyst is a rapidly developing field in environmental engineering, as it has a great potential to cope with the increasing pollution (Ohama, 2011). The application of TiO2 as air purifying material originated in Japan in 1996. Since then, a broad spectrum of products appeared on the market. Regarding traffic emissions, it is important that the exhaust gases stay in contact with the active surface during a certain period. The street configuration, the speed of the traffic, the speed and direction of the wind, all influence the final reduction rate of pollutants in situ.

Towards pavements different types may be distinguished: photocatalytic pavement blocks, for instance applied in Antwerp, Belgium (Beeldens, 2008), Bergamo, Italy (Guerrini, 2007), Hengelo, The Netherlands (Balari, 2013) and in Japan. The combination of a hot mix asphalt and a cementitious mortar to which TiO2 is added (Crispino, 2007), is applied in Italy and in France or alternatively concrete overlays or double layered pavements as applied in Paris, France (Gignoux, 2010) or Wijnegem, Belgium (Boonen, 2013).

In the case of concrete pavement blocks, TiO2 is added to the wearing layer of the pavers which is approximately 8 mm thick. In the case of cast-in-place concrete pavements, the TiO2 is added in the top layer (40 mm thick). The fact that the TiO2 is present over the whole thickness of this layer means that even if some surface wear takes place, for example by traffic or weathering, new TiO2 will be present at the surface to maintain the photocatalytic activity. Alternatively, TiO2 dispersion (Dylla, 2010, Brovelli, 2013) may be sprayed on the surface of the pavement to provide a more direct action, and a lower initial cost (e.g., lower TiO2 consumption). In this case however, the longevity of the photocatalytic action could be questioned because of loss of adhesion to the surface in time.

Overall, laboratory results indicate a good efficiency towards the abatement of NOx in in the air by using these innovative materials. Also, the durability of the photocatalytic action was shown to remain intact for the pavement blocks of Antwerp (Boonen, 2013), though regular cleaning (by rain) of the surface is necessary. However, the translation from the laboratory results to the “on-site efficiency” is still a difficult and critical factor, because of the great number of parameters involved.

In addition, durability of the photocatalytic action in time (for products mixed in the mass and/or applied on the surface) can still be problematic for some products with loss of activity in time due to the covering of the TiO2 at the surface by dirt, the detachment of the TiO2 from the surface or the deposition of products from chemical reactions which can take place at the surface. In other cases, even a severe de-activation of the coating was noticed due to high humidity conditions in combination with strong pollution levels and low UV light intensities in a tunnel test site (Gallus, 2015).

Advantages: A reduction of airborne pollutants would improve air quality in the vicinity of the roads, if they could be reduced significantly, thereby offering positive health impacts to pedestrians and residents close to the road.

Disadvantages: Satisfactory levels of pollutant capture are difficult to be demonstrated and one must bear in mind that photocatalytic applications are not effective everywhere; “good” contact between the airborne pollutants and the active surface is crucial and factors such as wind speed and direction, street configuration and pollution sources all play a very important role. Durability of the photocatalytic materials is still a topic that needs to be investigated further

Technical Feasibility: Level 2-3 in terms of whether the solution can be successfully implemented, however, there is less certainty of the overall efficiency on site. This innovative technique should be compared to other measures aimed to improve urban air quality on a cost-benefit analysis basis. Here, also more modern combustion technologies (e.g. EURO standards) or implementations of low emissions zones resulted in a reduction of the urban NO_2 levels by only a few percent at maximum in the past.

Indicative Cost Band: Band '=', based on the judgement of the authors and the limited published data.

Potential for use by NRAs: The concept still requires further development and proof of effectiveness before it will be ready for use as a recognised air pollution measure use. It is not considered that the technique will ever be appropriate for widespread use due to the factors such as local climate/topography; the durability of the photocatalytic materials would be dependent upon the volume of traffic on the road.

3.1.7 Energy generation by vibrations

A recent Dutch trial project (Jansma and Hendriks, 2012) has investigated whether it is possible to harvest energy from vibrations caused by traffic by using piezoelectric materials. It was considered that potential applications for energy collected in this way could include, for example, acting as a sustainable energy source for the batteries of road sensors, LED lighting in cat eyes or LED lighting on a roundabout, although this would depend upon the level of energy collected. The trial was undertaken on the N34 near Hardenberg in the Netherlands.

The research was carried out by an engineering company, Tauw, and the University of Twente. The quantity of harvested energy is dependent upon the traffic volume and traffic speed. In the trial on the N34, the quantity of energy harvested was insufficient to power traffic lights or public lighting, but sufficient for (wireless) movement sensors detecting traffic and alerting traffic lights. As such, the use of piezoelectric sensors in pavements is still in its formative stages and further optimisation is required beyond the work carried out on the N34.

Potential Advantages: This approach would provide a sustainable method of energy generation. The method uses innovative techniques to power small devices without the need for cabling.

Potential Disadvantages: Embedding piezoelectric material into the surface of the asphalt is troublesome and always a supplementary possible weak point in the surface where damage could occur. The energy quantity harvested is very limited, and so the method appears to have limited applications.

Technical feasibility: Level 2-3. The concept has not yet progressed beyond small scale demonstrations on public roads.

Indicative Cost Band: Band '++' based on the judgement of the authors and the limited trial data

Potential for use by NRAs: The concept still requires further development and proof of effectiveness before it will be ready, if ever, as a recognised energy generation measure for use by road administrations. It is not considered that the technique will ever be appropriate for widespread use on NRA road networks and would most likely only be applicable to heavily trafficked roads.

3.2 Bonus (demonstrated) secondary functions

3.2.1 Use of recycled materials.

The use of recycled materials in road surface construction, particularly in terms of the use of reclaimed asphalt materials has become an increasingly common practice and is well reported in the literature; see for example techniques for hot mix recycling, hot in-place recycling (Colas, Undated #2), cold mix recycling, cold in-place recycling (Colas, undated #3) and deep recycling (Colas, undated #1). Recent European projects have also covered asphalt recycling, i.e. PARAMIX (ended 2002, www.cimne.upc.es/paramix) an RE-ROAD (ended 2012, http://re-road.fehrl.org/). As such, the use of such materials will not be discussed within this section of the report.

More innovative use of recycled materials is associated with the development of new types of surface which are designed to offer improved noise reductions over conventional low noise pavements. One such surface type is the poro-elastic road surface. This surface type is a wearing course that has a very high content of interconnecting voids, so as to facilitate the passage of air and water through it, but also possesses some elasticity due to the use of rubber granules or fibres (e.g. scrap tyres, “new” rubber or other elastomeric products) as a main aggregate, sometimes supplemented by sand, stones or other friction-enhancing aggregates. The binder is an elastic resin, such as polyurethane, so it should not be confused with rubberized asphalt (it does not contain bitumen and it is applied at ambient temperature).The surface offers high levels of noise reduction but there have been longstanding issues with the durability of the surface.

PERS surfaces are generally designed with an air void content of at least 20% by volume and with a rubber content of at least 20% by weight. In trials of poro-elastic surfaces reported to date, a polyurethane binder is used to hold the mix together with the binder content ranging from 5-15% by weight. Additional binder is also required to fix the poro-elastic material onto the existing road base course. This may be the same binder as that used to hold the mix together, but epoxy resins have also been used in the past for this purpose.

The surface was originally invented in Sweden in the late 1970ties and later further developed mainly in Sweden and Japan. Trials of the surface type have, for example, been reported by Sandberg and Kalman (2005) and Sandberg et al. (2005) and more recently as part of the Dutch noise innovation project, IPG (Morgan, 2008). Most recently, the surface type has been the subject of investigations within the EC funded “PERSUADE” project (www.persuadeproject.eu); After long investigations in the laboratory (since 2009) and after testing with small scale test areas on little or not trafficked roads, full scale test sections have been constructed on trafficked roads in Denmark , Sweden, Slovenia, Belgium and Poland.

The use of tyre derived materials from waste tyres as a partial aggregate substitute has also been well demonstrated elsewhere.

Potential Advantages: The use of recycled materials reduce the use of material resources which would be required for the construction of asphalt and concrete pavements and can have positive benefits in terms of CO_2 emissions associated with road surface construction. It reduces the quantity of materials sent to landfill.

Potential Disadvantages: In terms of poro-elastic surfaces, their structural durability were so far considerably poorer than conventional asphalt surfaces, but this issue might be solved in the PERSUADE project. There are also potential issues with the recycling of poroelastic pavements. Potential in-use fire risks as a result of fuel spillages would need to be addressed by including suitable fire retardants within the binder.

Technical Feasibility: Level 4 in terms of the use of reclaimed asphalt materials, Level 3 with regard to poro-elastic surfaces.

Indicative cost band: Level '-' to Level '=' for the use of reclaimed asphalt materials. Level '++' for poro-elastic surfaces.

Potential for use by NRAs: The use of reclaimed asphalt materials for pavement construction/maintenance is a proven concept and already in frequent use by road authorities with respect to asphalt pavements. The use of recycled materials such as concrete is largely restricted to the construction of new roads, where it can be used in the capping or sub-base layers.

In terms of other, more innovative uses of recycled materials, such as for poroelastic road surfaces, although on-road trials have shown promise, it is considered that unlikely that the use of such surfaces by NRAs will be for anything other than a limited number of niche, localised applications in the short to medium term.

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4 Summary, conclusions and recommendations

The objective of the DISTANCE project is to provide National Road Administrations (NRAs) with information and guidance on a wide range of topics to assist them in planning and implementing future noise mitigation measures on their road networks. In the current economic climate, budgetary restrictions mean that NRAs must strive to ensure that implemented measures are fit for purpose and durable whilst keeping costs as low as possible. Noise mitigation measures that provide additional benefits beyond simple noise reduction may therefore be an attractive proposition to NRAs if they can be achieved with relatively little additional expenditure or if whole life costs are favourable.

Work Package 3 of the DISTANCE project has sought to investigate how primary NRA assets such as road surfaces and noise barriers might be enhanced to provide additional benefits, referred to here as 'secondary functions'. Options have been identified and assessed in terms of their known or anticipated (whichever is applicable given the technical readiness of the option) advantages, disadvantages, and likely costs (relative to conventional measures); the level of technical readiness, i.e. how ready they are for commercial application, has also been identified.

The previous sections of the report have reported on the different options that have been identified, from both a comprehensive literature review and an open exchange of novel concepts within the project team, as having secondary functions.

Table 4.1 and Table 4.2 on the following pages summarise the different options identified. Within these tables,

- **technical feasibility** defines when the option is considered likely to be ready for routine implementation by NRAs, as follows:
    - *'Now'* indicates that there are considered to be no (major) technical obstructions, and/or that the option is already available, i.e. Technical Feasibility Level 4;
    - *'Near'* indicates that the option is still under development, in an experimental phase, or commercialisation is expected to be imminent, i.e. Technical Feasibility Level 3, and
    - *'Future'* indicates that the option is still only a concept. in the early stages of investigation/development, or that substantial research is required to bring the option to the point of commercially availability, i.e. Technical Feasibility Levels 1 and 2.
- **financial impact** indicates the estimated supplementary cost compared to a conventional noise barrier or road surface (represented elsewhere in the report by the Indicative Cost Band);
- **sustainability impact** is split up into 'triple P' approach (planet/profit/people), so that it can be clearly illustrated where there are believed to be multiple impacts; and

Table 4.1: Main features of noise barriers with secondary functions

Description of enhancement	Technical feasibility	Financial impact	Sustainability impact			Why	Why not	Potential for use by NRA
			Ecological ('planet')	Financial ('profit')	Social ('people')			
PVNB	*Now*	*= to +*	✓	✓		*Renewable energy generation*	*Maintenance and overall cost*	
Safety barriers	*Now*	+			✓	*2 functions in 1*	*Safety issues*	
Added devices	*Now to Near*	*= to +*			✓	*Additional reducing noise*	*Difficult to predict noise benefit*	
Enhanced visual characteristics	*Now*	*= to +*			✓	*Urban aesthetics*	*Cost?*	
Transparency	*Now*	+			✓	*Urban aesthetics*	*Cost, safety*	
Recycled materials	*Now to Future*	*= to +*	✓	✓		*Cost and ecology*	*None*	
Green barriers	*Now*	*= to +*			✓	*Urban aesthetics*	*Maintenance*	
TiO2 capture	*Near*	++	✓		✓	*Health issues*	*Efficiency*	
Electrostatic capture	*Future*	++	✓		✓	*Health issues*	*Efficiency*	
Lighting	*Future*	*Unknown*			✓	*2 functions in 1*	*Cost*	
Adverts/information	*Now-Future*	*Unknown*	✓		✓		*Distraction of drivers*	
Rainwater harvesting	*Future*	*Unknown*	✓				*Negative CBA*	

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Table 4.2: Main features of road surfaces with secondary functions

Description of enhancement	Technical feasibility	Financial impact	Sustainability impact			Why	Why not	Potential for use by NRA
			Ecological ('planet')	Financial ('profit')	Social ('people')			
Dynamic markings (lane delineation)	*Future*	=			✓	*Improve safety*	*Insufficient light energy storage*	
Dynamic markings (lane control)	*Future*	*Unknown*			✓	*Improve traffic movement*	*Cost and technology*	
Inductive charging	*Near-Future*	++	✓			*Increased electric vehicle use?*	*Cost and technology*	
Heat capture/storage	*Near-Future*	**	✓	✓		*Renewable energy generation*	*Cost and technology*	
Modular pavements	*Near*	++			✓	*Less disruption to road users. Faster installation and maintenance*	*Cost*	
Self-healing surfaces	*Near*	=	✓			*Less maintenance*	*Limited surface types*	
Air pollutant capture	*Future*	=	✓		✓	*Health issues*	*Efficiency*	
Energy generation	*Near*							
Recycled materials (asphalt & concrete)	*Now - Near*	- to =	✓	✓		*Ecology*	*Durability concern*	
Recycled materials (tyres, etc.)	*Near*	++	✓			*Ecology*	*Durability concern*	

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- **'why/why not'** highlights what, in the authors' estimation, could be the stimulus in the decision making process of whether to integrate a secondary function into a noise barrier or road surface.

- **potential use for NRA** according to the authors' expert judgment based on the previous categories

    - **Green** means 'readily implemented and suitable for widespread use on an NRA road network'

    - **Yellow** means 'readily implemented and suitable for restricted use on an NRA road network'

    - **Red** means 'Not ready for implementation' or 'suitable for very restricted use on an NRA road network'

With regard to acoustic performance, the noise reduction characteristics of noise barriers with secondary functions are expected to be comparable to barriers of the same shape and height, provided that noise insulation properties and, if applicable, noise absorption properties of the materials are comparable with those used in conventional noise barriers.

Similarly, the acoustic performance of road surfaces with secondary functions would be expected to be at least comparable to conventional surfaces, provided that they can be constructed from the same asphalt or cement concrete mixes as conventional low-noise pavements. In the case where recycled materials are used, depending upon the surface type, these may offer improved noise reductions over conventional surfaces.

The review has identified a range of different noise barrier and road surface technologies that provide secondary functions. Some of the measures identified are in fact already used, whilst some are still concepts which require further demonstration to prove their practicality and financial viability for routine use.

However, recommending specific secondary functions for routine implementation by National Road Administrations is not a straightforward issue.

In simple terms, if a road scheme requires noise mitigation then the decision to install either a low-noise road surface and/or a conventional noise barrier might be clear-cut, with the final choice (including the specific type/design) being dependent primarily on cost, the level of noise reduction required and the size of the area to be protected. However, in terms of secondary functions, then the following need to be considered:

- *Is there a need for a specific secondary function(s) at that location*?

  If yes, then the choice will be based on the best solution within that function type, again coming down to cost, level of benefit, and area to benefit. If no, then

- *Is there a benefit to the barrier and/or surface being installed at that location having a secondary function*?

Where there are multiple secondary functions that could be of benefit, it will be down to the individual NRA to determine what is most appropriate for them. In such circumstances, it is considered that for noise barriers that photovoltaic noise barriers would be the most likely candidate, (this will also be the most visible secondary function from a public perspective); for road surfaces, the choice is unclear as the technologies are still largely concepts and the use of recycled asphalts is fairly commonplace.

For any given secondary function, the decision to implement will need to take into account whether the benefit is experienced by a limited number of people or the wider population. For example, transparent noise barriers will benefit residents in the first row of houses behind the barrier and to a lesser extent (particularly in terms of duration) road users, whereas photovoltaic cells might generate energy for a larger percentage of the local population. The benefits will also need to be compared against the cost to install that measure and any infrastructure needed to manage or retrieve the benefit.

It must be noted that not all of the secondary functions identified will be suitable for widespread use on a given NRA road network. This will be particularly relevant in the use of photovoltaics, as the location of the scheme and/or the orientation of the photovoltaic cells as the energy generated may not justify the cost involved for installation of the barrier and management of the collected energy.

The following designed and bonus secondary functions are considered by the authors as being presently available and which might offer the most useful benefits to NRAs:

For noise barriers:

- Noise barriers incorporating photovoltaic elements.
- Integrated noise and safety barriers.
- Enhanced visual aesthetics (including the use of transparency) to better match the noise barrier to its installation environment.
- Green barriers.

For road surfaces

- Use of recycled materials (recycled asphalts).

It is important to note that often, noise barriers and low noise road surfaces are used in combination to provide more effective noise mitigation solutions than using the measures independently. It is considered that none of the barriers or surfaces with secondary functions reported here are likely to conflict with one another in terms of the effects of secondary functions being cancelled out. Indeed, with careful design and planning, it may even be possible to utilise the benefits from one measure to support another, e.g. using energy generated, although such approaches have not been demonstrated. Such considerations would have to be made on a scheme by scheme basis and would be influenced by a wide range of factors, with cost being a key issue.

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