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QUESTIM

Final project report

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

CEDR Call 2012: Noise: Integrating strategic noise management into the operation and maintenance of national road networks

QUESTIM: QUietness and Economics STimulate Infrastructure Management

QUESTIM: FINAL PROJECT REPORT

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1 OBJECTIVE OF QUESTIM

1.1 Relevance of mitigating road traffic noise

Road traffic is the dominant source of environmental noise in the European Union (EU) (ref. Fig. 1) and causes the loss of thousands of healthy life years each year in the European population (ref. [4] and [18]).

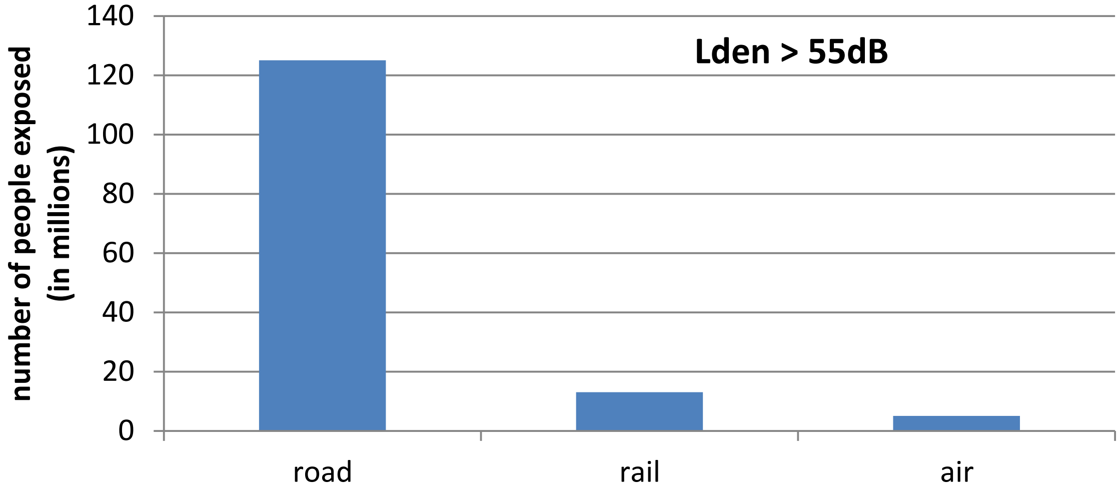


Fig. 1 EU-27 population exposure to environmental noise levels above 55dB Lden in 2012 (estimated based on reported data in 2013) [4]

Traditionally, mitigation measures focus on façade insulation and noise barriers but presently greater emphasis is being placed on measures to control the noise at source. The possibilities for local administrations to reduce the vehicle's power train and tyre sound production are limited as these properties are subjected to EU-wide type approval regulations that do not permit additional tighter limits in member states. Local administrations influence the technical properties of the road infrastructure. It is found that the type of road surface is one of the most important parameters in the establishment of overall road vehicle noise production as illustrated in Fig. 2.

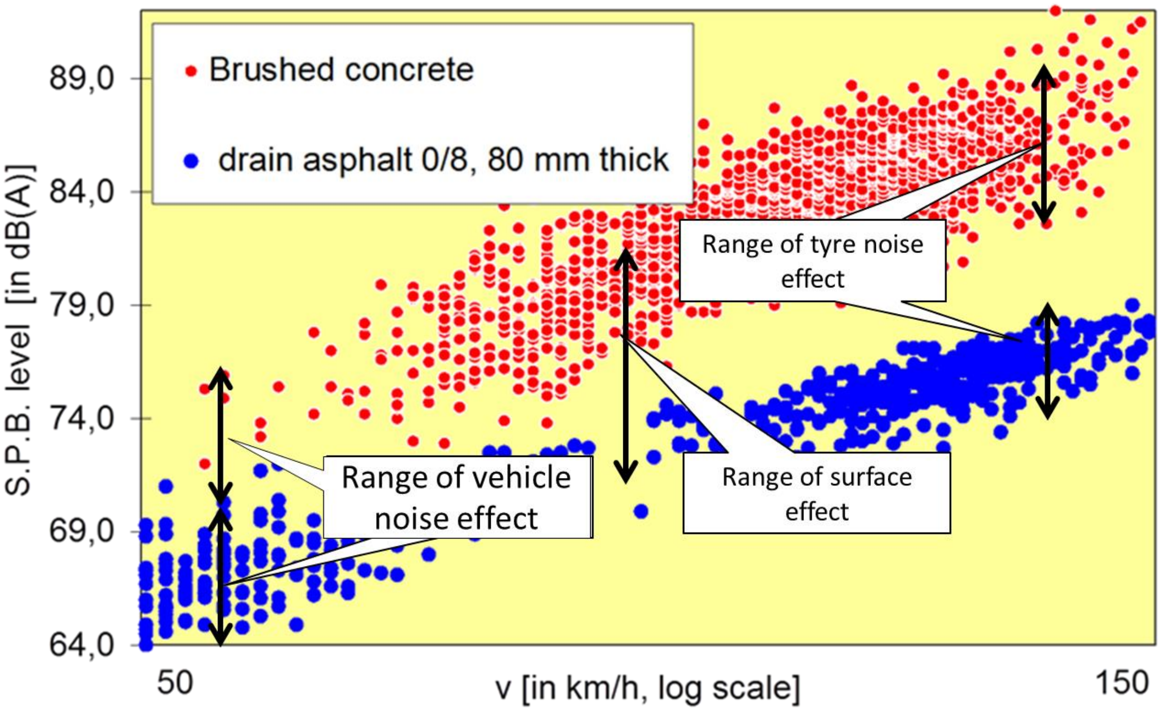


Fig. 2 The relevance of the road surface type to the overall vehicle noise level (red and blue dots present pass-by noise levels of light vehicles on two surface types and arrows present the magnitude of the vehicle, tyre and road surface effect. Noise levels were determined according to ISO 11819-1 (SPB standard), but at a microphone height of 5,0 m (source M+P data).

The statistical pass-by noise (SPB) levels are presented as a function of individual vehicle speed in a traffic stream on two surface types: brushed concrete and a two-layer porous asphalt. Pass-by noise levels on a specific surface vary due to noisy/low noise power trains (low speed) or noisy/low noise tyres (high speed). The arrows on the left and right indicate the total ranges due to these effects. It is evident that the magnitude of the tyre or vehicle effect is significantly smaller than the road surface effect (the centre arrow). For almost the entire speed range, the least noisy cars on the concrete surface are noisier than the loudest cars on a fine graded Porous Asphalt Concrete (PAC) surface.

A further advantage of a low noise surface is that it affects every passing vehicle, while effects of low noise power trains or tyres only become apparent when the majority of the vehicles are equipped with them.

The application of low noise road surfaces has already proven to be a very effective mitigation measure, having the potential to lower road traffic noise levels by 8–10dB compared to standard surfaces. However, several National Road Authorities (NRAs) within the EU still regard low noise surfaces as experimental and only to be applied in situations where standard mitigation measures are not sufficient.

The concerns of NRAs can be explained as follows:

- Uncertainties in the actual performance of low noise surfaces in both their new condition and over their (structural) lifetime.
- Reduced effective lifetime and the more intense maintenance schemes required for these surfaces that do not fit into general pavement management schemes.
- Road builders' lack of knowledge about the processes that cause deterioration of the pavement's acoustic quality and the material technology required to improve its durability.
- Uncertainty surrounding the economic impact of these surfaces; both the cost of building and maintenance, and the effect in terms of savings on other mitigation measures, economic benefits or health improvements.
- Possible negative effects of these types of surfaces on safety and sustainability.
- Uncertainty around the methods to survey the performance of a large network and to implement the effect of these surfaces in the noise mapping procedures.

Previous research projects have examined the acoustic performance and application of low-noise surfaces, such as SILVIA [1] (which also included proposals for the labelling, conformity-of-production assessment and routine monitoring of surfaces). While there have been more recent investigations into the acoustic durability of low-noise surfaces, e.g. the Dutch noise innovation programme (IPG) [10] , the Dutch CROW programme for high speed regional roads [3] , the Danish Road Institute (DRI) study [2] and the Finish Hilja low noise pavement project, these studies have neither been comprehensive, nor attempted to develop robust models for acoustic deterioration. Harsh winter conditions and studded tyre use represent a specific wearing cause for fine textured or porous surface types.

Noise barriers represent the conventional mitigation measure for road traffic noise. Their appearance and material composition vary significantly throughout Europe, ranging from conventional timber fences to more innovative solutions using pre-fabricated components. In some cases, devices on top of the barrier are added to improve its performance. Once installed, many of these barriers will only be replaced due to structural failure or damage, and any possible change in acoustic performance is not considered. A lot is known about the performance of these measures when new, and many NRAs' procurement specification procedures include acoustic performance criteria under new condition. Relatively little is known about the acoustic degradation of barriers in terms of sound transmission or absorption, although some studies have reported indicative results, e.g. work by TRL presented in the QUESTIM WP 4 report [16] .

1.2 Goals of QUESTIM

The objective of the QUietness and Economics STimulate Infrastructure Management (QUESTIM) project is to generate information on the aspects inhibiting wider application of low-noise surfaces and innovative barrier designs, in order to give these technologies a better position in the planning, managing, building and maintaining of roads. The following targets have been identified:

1. To supply NRAs with specific information and pavement management system (PMS) type instruments to integrate low-noise surfaces and barriers in their task to manage their road network quality over longer periods and to manage the noise action plans emanating from the European Noise Directive.
2. To support NRAs with know-how to estimate the effects of future developments in vehicle and tyre technology and to prevent sub-optimal developments with respect to sustainability and safety.
3. To enable NRAs to assess the benefits and the costs of their noise control strategies and to weigh source and propagation related measures with urban planning and sound-scaping initiatives.

1.3 Specific Objectives of QUESTIM

The specific objectives of the project are as follows:

1. To develop a database containing experiences from various areas in Europe with the age related acoustic performance of road surfaces and the related traffic load and traffic type.
2. To identify the mechanisms for the age-related acoustic deterioration of the surface and to relate them to the conditions of road usage.
3. To develop prediction models for acoustic degradation of road surfaces and to supply methods for taking deterioration into account in noise modelling procedures.
4. To develop optimized procedures and technologies to survey the acoustic performance of pavements of large road networks.
5. To identify mechanisms for acoustic degradation and develop indicative procedures for predicting acoustic degradation of noise barriers.
6. To develop survey procedures for barrier performance along large road networks.
7. To develop existing models that will provide a state-of-the-art cost-benefit analysis methodology to assess mitigation measures at a scheme level and to anticipate future tyre and vehicle developments.
8. To develop ways in which noise mitigation measures can be integrated into strategic models, PMS and asset management systems (AMS), to aid long-term planning.

1.4 Benefits of QUESTIM

The benefits of the project can be summarised as follows:

1. Improved knowledge on the lifetime performance of low-noise road surfaces and noise barriers.

2. Improved cost-benefit analysis methodologies at strategic and scheme level, including proposals for integrating noise mitigation measures into PMS and AMS and integration with safety and sustainability aspects.
3. Improved measuring standards to survey pavement and barrier performances of road networks.

Although the QUESTIM project can be understood as a series of separate research topics, a clear relation exists between them as illustrated in Fig. 3.

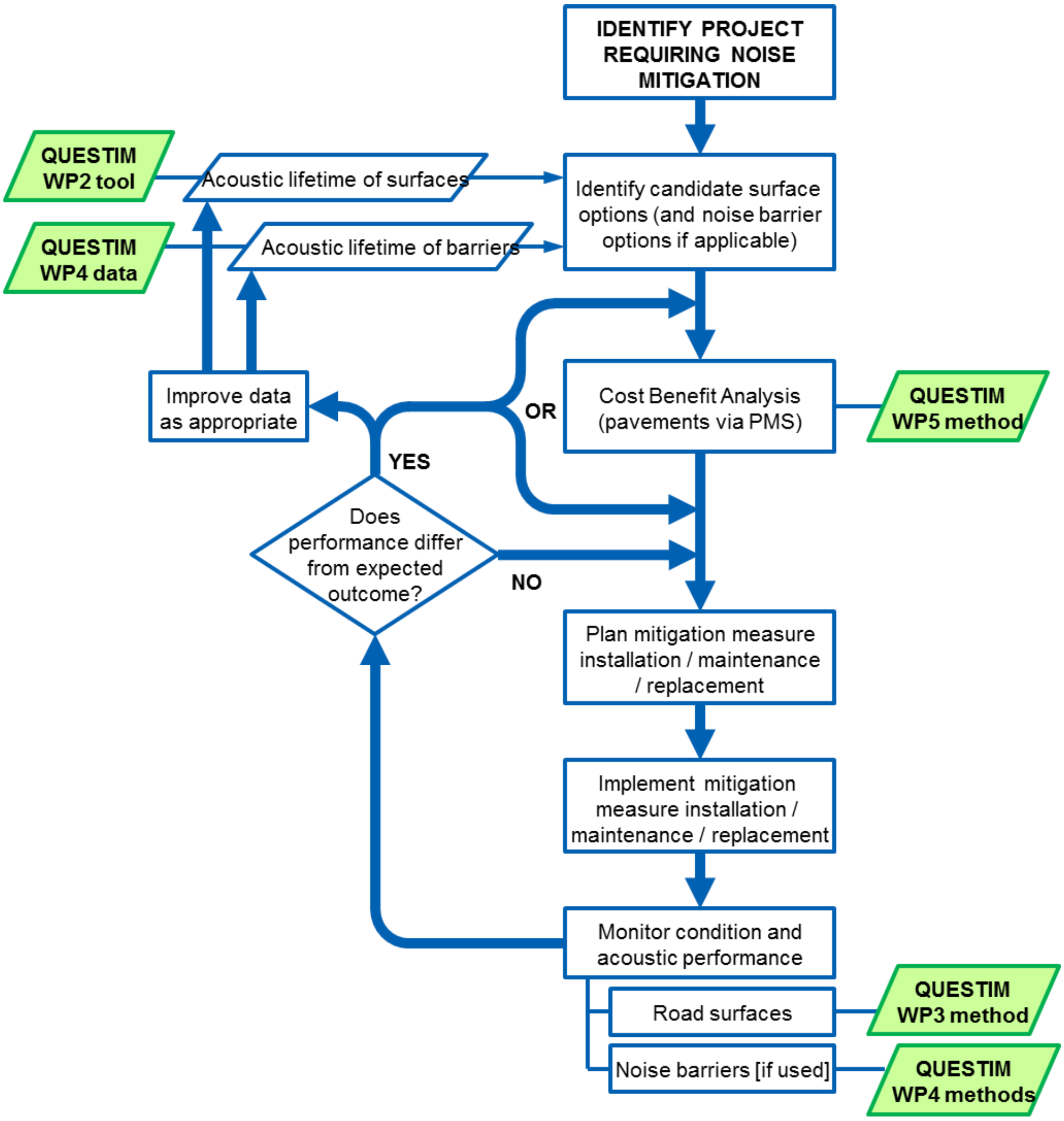


Fig. 3 **How the selection of noise mitigation measures at project level and their installation/ maintenance/replacement align with the activities of the QUESTIM project**

The scheme illustrated in Fig. 3 presents the activities and information requirements of a road authority that has decided to apply a noise reducing road surface in order to reduce environmental noise exposure of the population in the vicinity of the road. It incorporates the following:

1. The planning of the surface, including service life expectancy and resurfacing scheduling. It covers the costs and benefits of alternatives, and enables the balancing of source-related measures against measures in the propagation such as barriers.
2. After laying, a fit-for-purpose monitoring scheme has to be installed in order to follow the development of the surface over time, the calibration against the expected age-related performance and to enable more accurate planning of repair or resurfacing.
3. When barriers are applied in combination with or as an alternative for noise-reducing surfaces, tools are presented that can be used to assess the performance of the barrier during its life time. Possible sources of degradation are described.

The requirement to apply the described procedure may come from legal obligations within the framework of environmental impact studies for new roads or the obligation to meet maximum noise exposure limits permitted in national or local noise acts. It may also originate from policies to improve the environmental noise situation, based in local, national or European noise action plans.

1.5 Organization of QUESTIM

The essential components for the decision and management scheme, illustrated in Fig. 3, are developed in the following four specific Work Packages (WPs):

1. WP 2: *Lifetime performance of low noise road surfaces*. This WP is dedicated to the inventory of available data of age-related acoustic performance of road surfaces and understanding the processes in terms of wear mechanisms. Through analysis of the relationship between surface types, traffic load, environmental conditions and observed aging characteristics, an insight is obtained into the processes and therefore reliable prediction tools for a few surfaces could be developed. The vast amount of data can be used as input for general considerations on application of noise reducing surfaces and its performance over time.
2. WP 3: *Procedures for monitoring acoustic quality of large infrastructures.* The predictions and expectations identified in WP 2 exhibit a limited accuracy. The general trend can be reasonably predicted but for an individual surface, large deviations from the general trends are found. The management of the pavement quality can use the acoustic monitoring to map the deviation and adapt a modified end of service life expectancy. Furthermore, the severity of the actual quality loss can be related to the impact on the living quality of nearby urban areas.
3. WP 4: *Acoustic lifetime performance of noise barriers.* In the planning of noise mitigating measures, both noise reducing road surfaces and barriers have to be taken into

consideration. In this WP, barrier types and their age-related performances are investigated and monitoring procedures are developed.

4. WP 5: *Cost/benefit analysis and life-cycle-costs of barriers and of low noise road surfaces and the development of a PMS that includes noise.* In the planning of mitigation measures, costs and benefits have to be balanced against each other. This WP presents input data and an evaluation procedure. It further introduces the concept of noise mitigation in the infrastructure management systems.

The results of QUESTIM are disseminated through a website, www.questim.org, and by presentations in national and international conferences such as Transport Research Arena 2014 (TRA2014) and EuroNoise2015.

2 QUESTIM WP 2: Understanding and modelling acoustic aging

2.1 Acoustic effect of a road surface

The relevance of the road surface on the noise emission of road vehicles is undisputed. Depending on the surface, the actual traffic noise levels can differ up to 10dB as illustrated in Fig. 2. These graphs present the effect of a few representative surfaces on the average noise level of passing vehicles, determined on the basis of the ISO 11819-1 Statistical Pass-By (SPB) method [5] for both light vehicles (LVs) and heavy vehicles (HVs) as a function of speed. The reduction value is defined as the difference of the pass-by level with the same vehicle class on a reference *SMA8/AC11surf* type. It is important to note that both the reference surface and the surface under tests were in new but broken-in condition (approximately ½–1 year old).

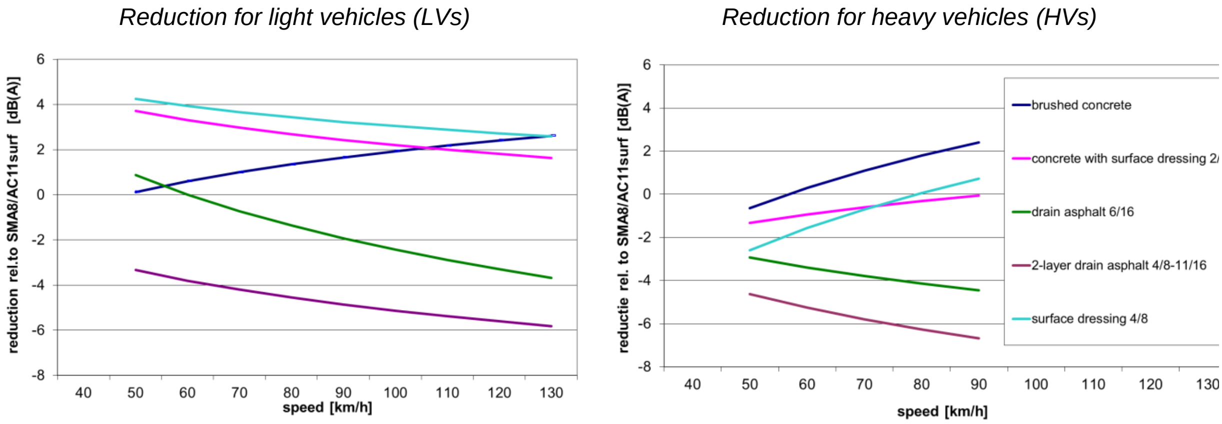


Fig. 4 Pass-by levels of vehicles as a function of speed on a series of surface types relative to an SMA8/AC11surf reference surface. Positive values indicate a higher level compared to

the reference surface, negative values a lower pass-by level. Both the reference surface and the surface under tests were new [8] and [3] . Left: LVs, right: HVs

The noise-reducing effect originates mainly from the suppression of tyre/road noise, since that is the dominant noise source of road traffic but some additional reduction follows from the suppression of power train noise by the absorbing properties of open graded surfaces.

The contribution of tyre/road noise and power train noise to the overall level depends on the traffic composition and the speed. Fig. 5 illustrates the sound level of both sources as a function of speed (for passenger LVs and for HVs).

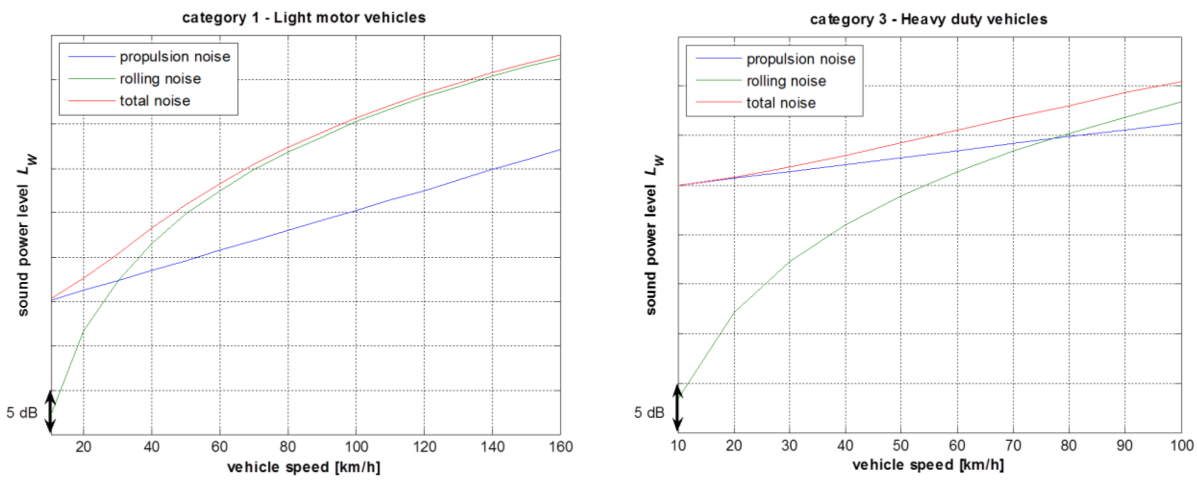


Fig. 5 Relative sound power level of rolling noise, propulsion noise and total vehicle noise as a function of speed. For LVs, the rolling noise already dominates above 30 km/h, and for HVs, the cross-over takes place at approximately 70 km/h (ref. [23])

2.2 Aging of noise reducing effect

Unfortunately, noise reducing road surfaces lose (part of) their performance over time. Practically all road surfaces are found to become noisier over time; "noisier" does not indicate that the surface itself produces more noise but that the noise produced by the same traffic using that surface increases. Extensive research is dedicated to determine age-related performance of surface types under various conditions and in QUESTIM WP 2, an inventory is produced of all available data on age-related acoustic performance of road surfaces in Europe. The graphs in Fig. 4–Fig. 10, illustrate samples from various countries. Specific emphasis was laid on the experiences in the Nordic countries, where harsh winter conditions and usage of studded tyres compose an extra wearing factor. All situations refer to highway use or regional through roads.

Experiences in European excluding Nordic countries

In some cases, the graphs present absolute levels of passing vehicles (mainly determined with the SPB method [5]) or in a few cases, CPX levels [6] . In other cases, the decrease is given relative to a reference value or surface. Absolute levels of SPB data can differ as most data sets in the Netherlands are measured at a microphone height of 5.0m while other countries use 1.2m. Nevertheless, the important content of the graph relates to how levels change with time. A complete overview is provided in the QUESTIM reports [13] [14] .

In the data, we distinguish between the effect on LVs and HVs. Not only the proportions of propulsion noise and rolling noise in HVs differs from LVs but also the structure of the HV tyres and consequently the effect of the road surface on the tyre's vibro-acoustical behaviour are different from LVs.

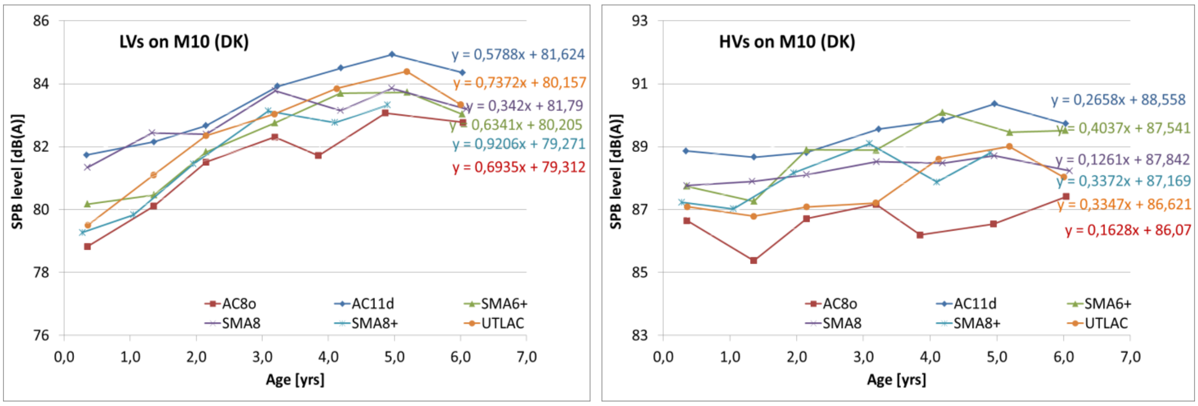


Fig. 6 Experiences on the Danish test location, M10. AC8o: drainasphalt, AC11d: dense asphalt, UTLAC: Ultra Thin Layer Asphalt Concrete, SMA6+ and SMA8+: slightly open

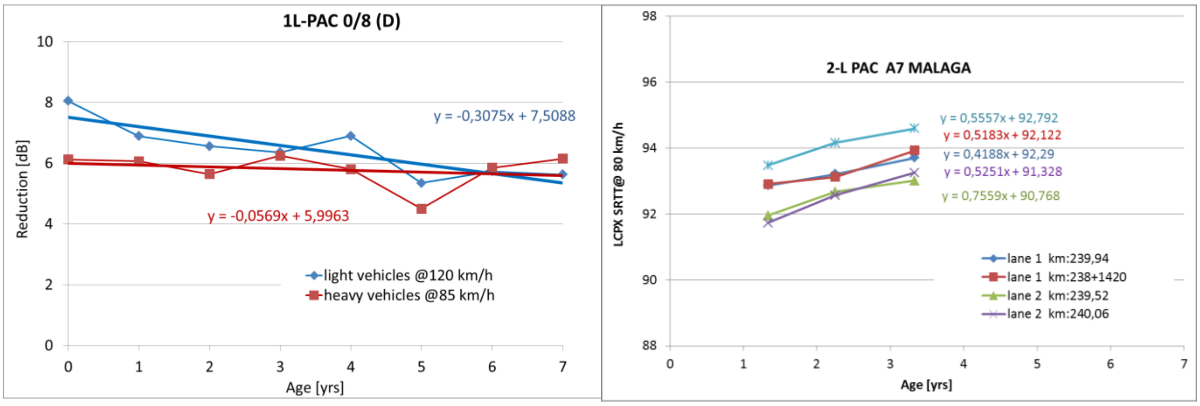


Fig. 7 Left: data from German highways PAC 0/8 for cars and trucks. Note that the reference value is based on German "Gussasphalt" with surface dressing 5/8 (approx. +2dB rel. to AC 11 surf). Right: CPX-Index values on Spanish 2L-PAC on A7 in Malaga

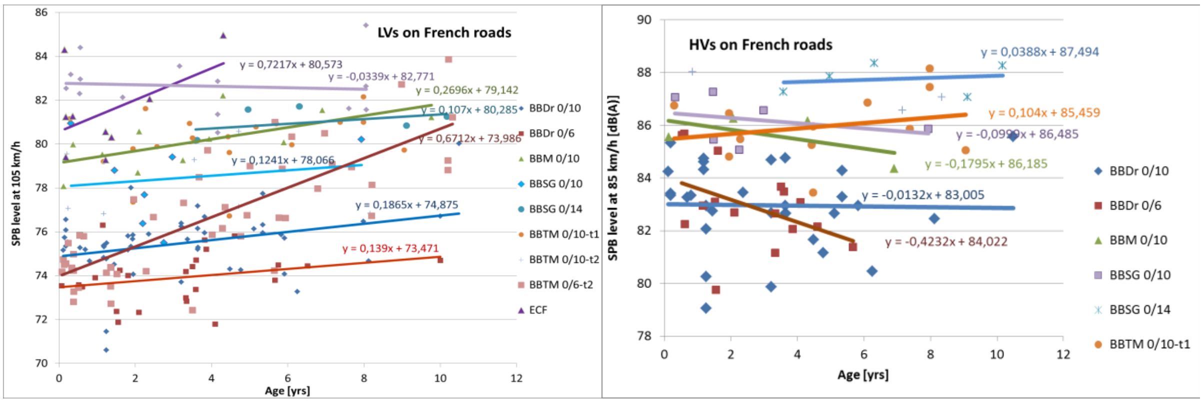


Fig. 8 Compilation of French data on highways and regional roads. Left: SPB for cars, Right: SPB for trucks. Refer to [14] for background information and road surface typing

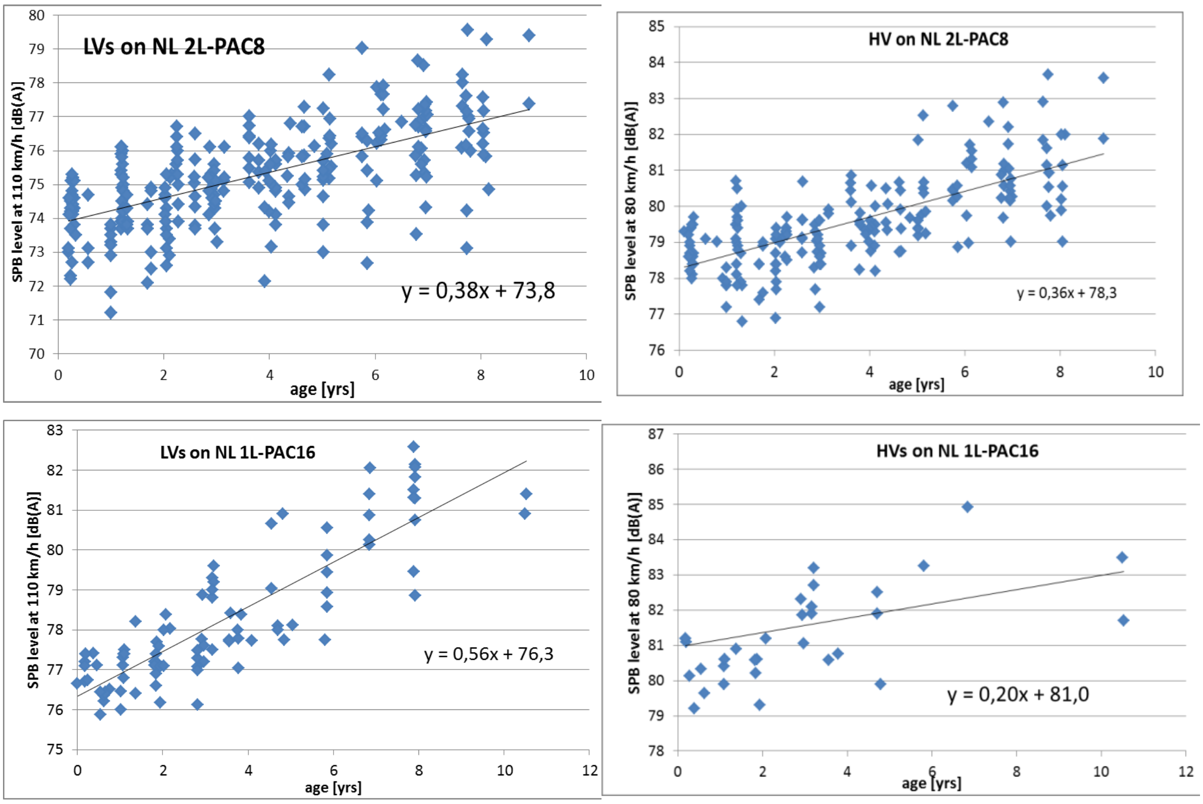


Fig. 9 Data on 2L-PAC and 1L-PAC on NL highways. Diagrams contain several repeated measurements at different locations. In [14] the data for individual locations are presented

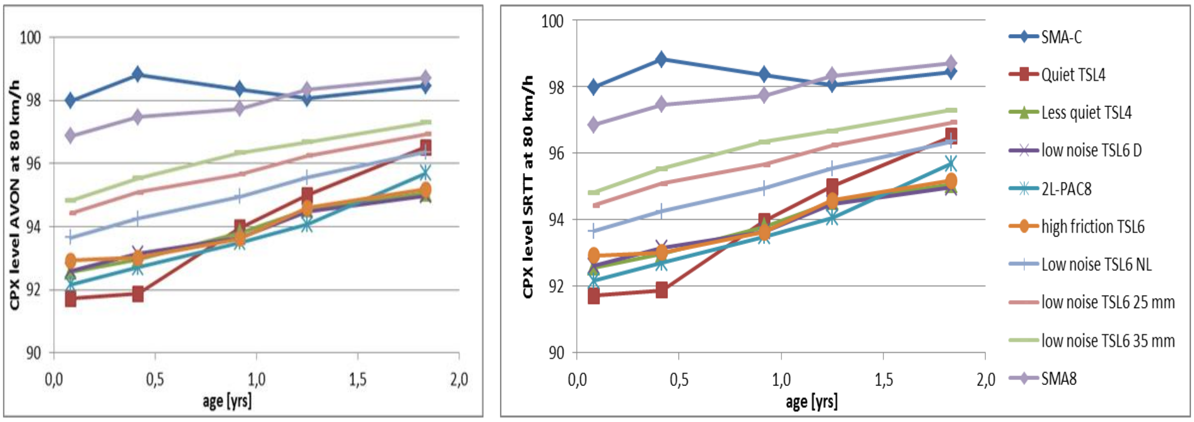


Fig. 10 Experiences in Belgium with acoustic aging. Results of a series of test sections at the Kasterlee test location. Right: CPX-P, left: CPX-H data

Though absolute values and slopes differ considerably, the presented data reveals the systematic increase of noise over age. In a few cases, a decrease is noticed but that is probably caused by the statistical uncertainty in established slopes that are based on a few non-related road surfaces. Absolute values of slopes vary between 0,1 dB/yr. to close to 2 dB/yr.

The best performing low-noise surface we found is a pre-fabricated 2L porous cement concrete system that ages less than 1dB over 7 years for both cars and trucks.

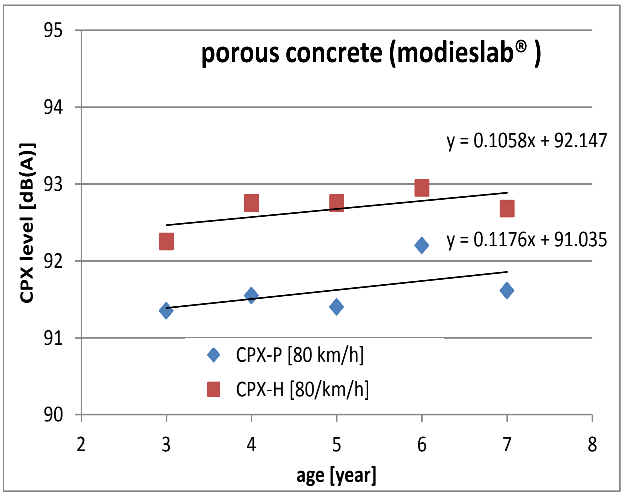


Fig. 11 Performance data of a 2L porous concrete surface on the A-12 in NL. Almost no acoustic degradation is observed over the tested period of 7 years

An interpretation of the data as a function of vehicle category, European country and road surface type is presented in Table I.

Table I Overview of calculated slopes [dB/yr] of different surface types found in various European countries (CPX and SPB are combined)

Surface Type	Source	Slope [dB/yr]	
		LV's	HV's
1L-PAC 0/16	NL	0,62	0,20
	ES	0,30	-
1L-PAC 0/8-0/11	D	0,31	0,06
	F	0,41 / 0,19	0,00
	DK	0,65	0,09
1L-PAC 0/6	F	0,14	[0,00]
2L-PAC 0/8	NL	0,38	0,36
	ES	0,52	-
TSL 0/6 semi open	NL	0,33	0,41
	F	0,60/ 0,67	-
SMA 0/14	UK	0,48	0,33
SMA 0/8 - 0/11	UK	0,58	0,35
	DK	0,35	0,10
	NL	< 0,1	
SMA 0/6	UK	0,60	0,29
	DK	0,48	0,18
HRA 0/20	UK	0,25	0,12
Exposed concrete	UK	0,22	0,09
2L-PC (porous concrete)	NL	0,16	0,12
DAC 0/8-0/11	DK	0,53	0,04
	F	0,12	0,00
DAC 0/16	NL	0,10	0,05
	F	0,11	0,04

Experiences in Nordic countries (N, SE, SF)

The wear of road surfaces in the Nordic countries is non-typical for European conditions. Severe winter conditions, with frequent freezing-thawing cycles, constitute a heavy wear factor that is worsened by the frequent use of studded tyres in winter time.

The strong wear conditions are reflected in the steep increase of traffic noise levels over the years. In several cases, road surfaces have to be renewed after only 3 to 4 years.

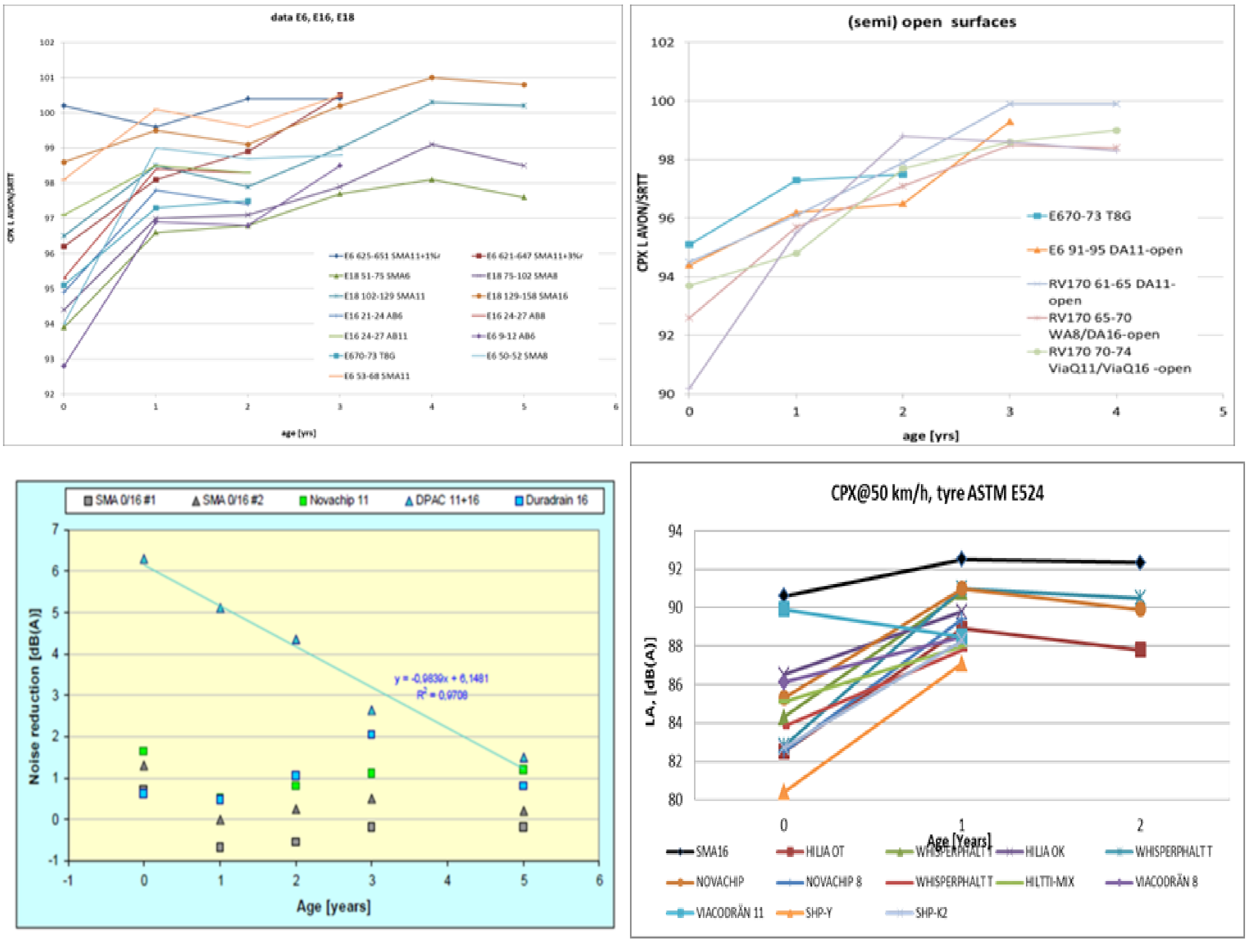


Fig. 12 Experiences in the Nordic countries. Top-left: CPX-I levels on dense ACSURF and SMA surfaces in Norway (80km/h). Top-right: CPX-I levels of (semi) open PAC and TSL surfaces on through roads in Norway (80km/h). Bottom-left: experiences in Sweden. Bottom right: experiences in Finland (mainly urban roads, tested at 50km/h). Detailed information can be found in [13]

2.3 *Understanding aging of road surfaces*

From previous experiences, we have learned that causes of performance loss of low-noise surfaces can be traced to specific deterioration such as clogging of the pores, roughening of the surface by stone loss or filling up of the open porous layer. The understanding of the mechanisms relating to these processes with loss of acoustic performance is found in studying the spectral changes resulting from such variations. The overall effect and spectral changes are illustrated in Fig. 13 for a car and truck tyre for a series of defined changes in the road surface [3] .

The aging effect of a porous, fine textured surface is illustrated in these graphs as a series of consecutive processes. Arrows present the related spectral shifts as follows:

1. Filling-up of the acoustic layer with dirt will cause a reduction of the effective absorption layer and thus shifting the absorption "dip" to higher frequencies and eventually nearly total clogging of the porous layer, leading to loss of acoustic absorption (indicated with arrows 1 and 2).
2. Closing of the top layer by either extensive dirt or compaction of the slightly open top layer amplifies aero-acoustic noise generation and thus increases levels at the mid and high frequency range (indicated with arrow 3).
3. Degradation of the surface texture through stone-loss, increases texture induced vibration of the tyre structure that manifests itself in the lower and mid frequency range (indicated with arrow 4).

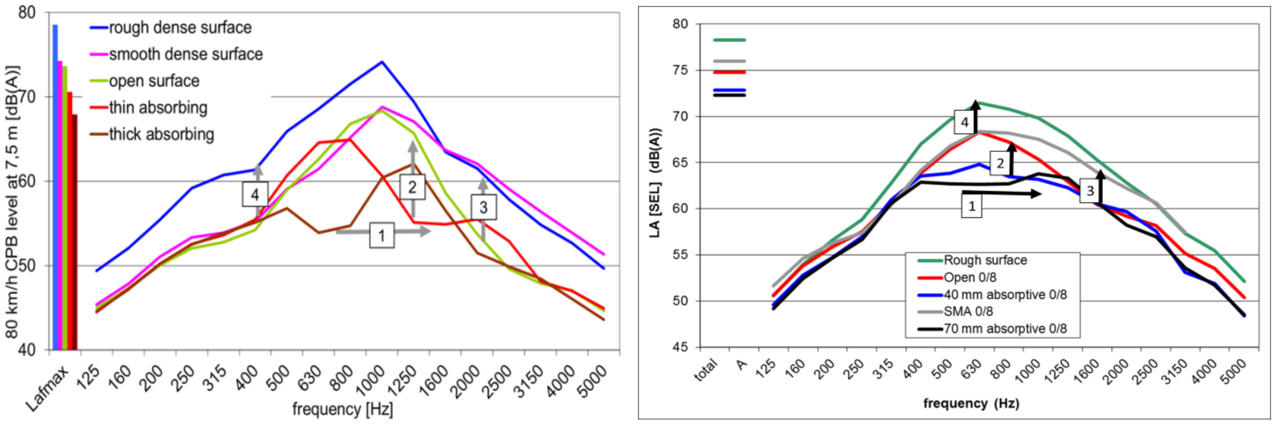


Fig. 13 Spectral composition of rolling noise on various surfaces reflect the effect of specific surface properties. [1] indicate shift in acoustic absorption peak, [2] reduced absorption, [3] increased flow resistance and [4] roughening texture. Left: car tyres at 80km/h (average of 12 types). Right: a mix of steer, drive and trailer tyres, combined into a composite truck. The indicated level is the total Sound Exposure Level during a coast-by event at 70km/h [14]

The acoustic aging of surfaces in case of trucks (refer to the right graph in Fig. 13) is similar to that of cars; although for the traction tyres, sensitivity to certain processes is different. With smoother textures, there is little dependence on texture, so it may be expected that slight texture degradation, caused by stone loss, will not decrease reduction performance. In some instances, even an improvement is found (very smooth surfaces amplify tonal components that, although total levels are lower, may cause specific annoyance). The proportion of power train noise affects the dependence on texture but acoustic absorption is also effective in suppressing this source.

2.4 Spectral changes over time of studied surfaces

The origins of acoustic aging are identified through the spectral shifts over a period, observed at several test locations. The understanding is based on the spectral effects illustrated in Fig. 14. Clear examples of aging through texture degradation, clogging and filling up of porous surfaces are displayed in the graphs.

The 2L-PAC on the A28 presents some texture degradation and filling up, although the top layer remains open as can be derived from the fact that the level at higher frequencies remains low.

The 1L-PAC data in Fig. 14 (top right) reveals almost a complete loss of acoustic absorption, probably due to filling up of the open layer.

The TSL6 data in Fig. 14 (bottom left) reveals a clogging, causing an increase in flow resistivity while the TSL6 data in Fig. 14 (bottom right) indicates texture degradation.

Unfortunately in many cases, combinations of deterioration processes are present or non-expected shifts are found. Some examples are provided in Fig. 15. Top-left: cars on 2L-PAC display combined effects of texture degradation, filling-up and clogging of the top-layer. SMA 6+ data from Denmark displays combined effects that concentrate in the mid-frequency range. The bottom row displays improvements in one spectral range while worsening of another spectral range.

An attempt to understand such combined and sometimes contradictory effects is provided in the following text box.

The Spanish road surface (2L porous asphalt on the A7 near Malaga) is an impressive example of the effect of ageing on various noise generation mechanisms. The low frequent spectral portion of the tyre/road noise decreases while the mid and high frequency portion increases. This means that the texture of the road surface improves significantly with age while the pavement loses its sound absorption over the years. The 2L porous asphalt turns from an effective sound absorbing wearing course into a fine textured dense surface. The clogging of the voids is not only found within the porous structure, it is present up to the top of the porous layer. The closing of the gaps between the coarse aggregate with dirt gives a fine mortar like material between the grains which helps to improve the texture of the porous asphalt in terms of acoustics. The number of contact points the rolling passenger car tyre profile is in contact with is significantly higher than in the case of the open porous surface. The increased number of contact points decreases the contact force per contact point and gives a more regular distribution of the contact forces across the tyre. This results in lower vibration and low frequent noise levels of the tyre. In contrast to this, the surface loses its void content which deteriorates the sound absorption and increases the level of the radiated noise in the mid and high frequency range. Furthermore, the air flow resistance of the tyre/road contact turns from a void induced type into texture induced. In the clogged condition of the porous layer, the air flowing through the tyre/road contact does not escape into the voids of the porous layer but finds its way through the narrow structure of the surface texture being in contact with the tyre surface. This is aeroacoustically more effective than the air flow into the porous layer which causes higher noise levels in the mid an high frequency range.

The majority of the data illustrates combined effects but in several cases, the aging processes can be separated. Refer to [14] for more extensive examples.

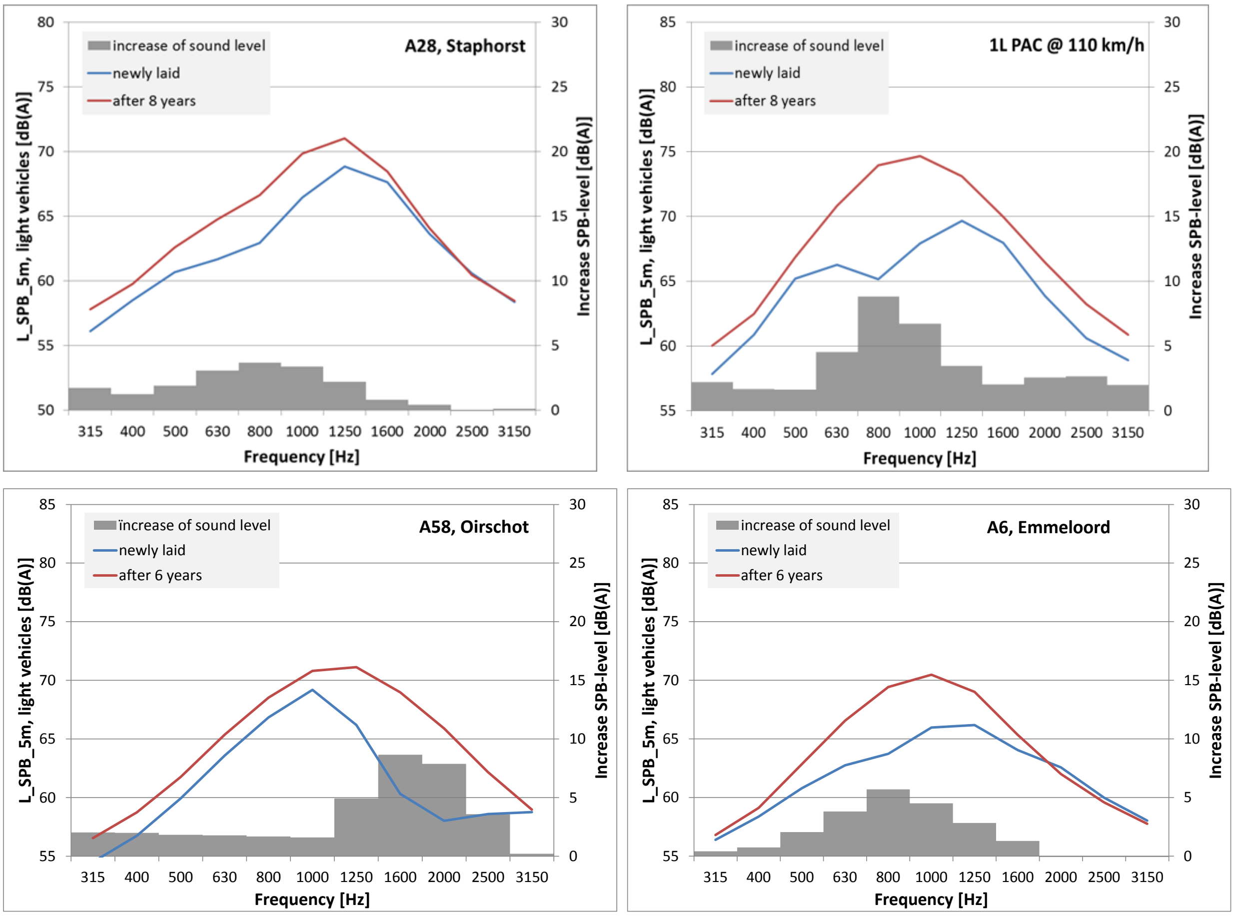


Fig. 14 Graphs of spectral shifts in pass-by noise of LVs @110km/h due to acoustic aging. Top-left: 2L-PAC, top-right: 1L-PAC, bottom-left and right: TSL6

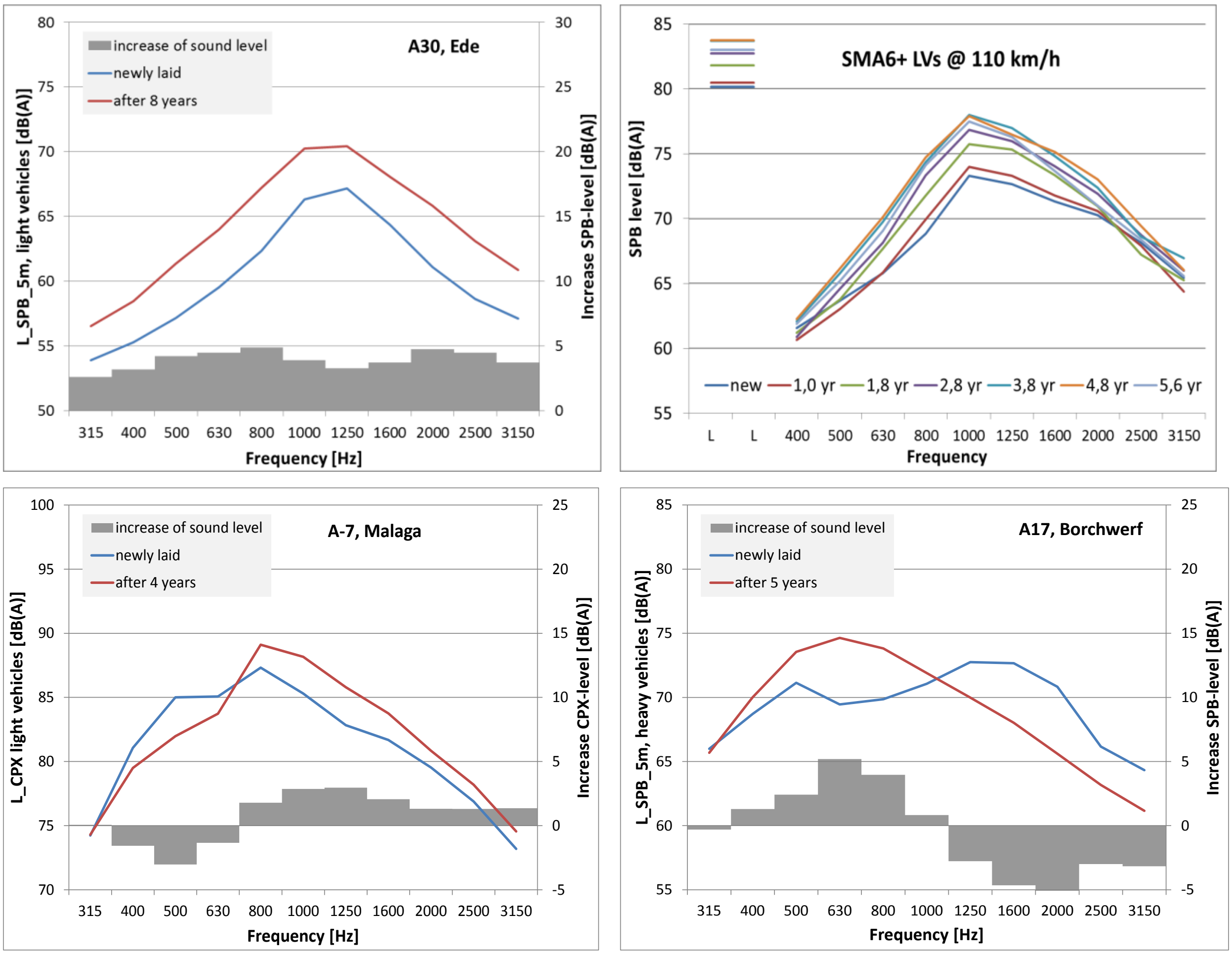


Fig. 15 Results of non-specific deterioration effects. Top-left: SPB on 2L-PAC in NL for LVs, top-right SPB on SMA 6+ in DK for LVs, bottom-left: CPXP on 2L-PAC in Spain, bottom-right: SPB on 1L-PAC in NL for HVs

2.5 Statistical model and its explanatory power

The planning of laying, resurfacing and maintenance and the evaluation of cost-benefit ratios requires a reliable prediction of the noise-reducing performance over the service life. Although the several age-related performance graphs already indicate such behaviour, wide variations are found for similar surfaces. We have tried to explain the variations between surfaces of a single type by adding parameters that describe traffic conditions and quality of the surface.

The relevant parameters are listed in Table II.

Table II List of parameters identified as significant in explaining the age-related acoustic performance of a road surface

1. type of surface	SMA, 1 layer porous asphalt, 2-layer porous asphalt, TSL 6 or 8, brushed concrete, exposed aggregate, dense asphalt concrete
2. type of road	Highway, regional road, urban road, ..
3. age	Years
4. initial value	The reduction value at t=0
5. traffic intensity	Number of vehicle passages (calculated as vehicle intensity times age)
6. HV intensity	Number of HVs (calculated as HV intensity times age)
7. location in Europe	Nordic countries (N, SE, SF), mid Europe (NL, F, UK, EIR, D, DK, PL, ..), Alpine region (CH, parts of AUT), South Europe (I, ES, P, ..)

An ANOVA[1] approach has been applied to select the significant parameters and to calculate coefficients. The predicted level is defined by a linear addition of the selected parameters P_n multiplied with a specific coefficient C_n. Added to this, we include the residual error *R* which is actually a random figure with a standard deviation equal to *R*:

$$L_{\text{predicted}} = C_0 + C_1.P_1 + C_2.P_2 + C_3.P_3 + C_4.P_4 + \cdots + Res \qquad (1)$$

To apply such a procedure, ample data must be available in order to achieve significant results. This restricted the application to NL data as it turned out the be the most complete data set. It can be assumed that such relations will also be valid in mid European countries as the climatic conditions and vehicle usage are similar. Due to the limited amount of data this cannot be corroborated.

For the Nordic countries, the coefficients will be much larger and the relevance of passenger cars is much larger than those of trucks.

[1] *Analysis of Variance*

Table III Results of multiple parameter analysis of acoustic road surface performance. The pass-by level for LVs at 110km/h and for HVs at 80km/h is given by formula (1). The coefficients including the residue are provided here

	C_0 [dB]	C_1 Initial Value [dB]	C_2 Age [yr]	C_3 Total HV Passages (*10^6)	Residue [dB]	R^2
TSL LV	26,7	0,64	0,31	0,05	0,65	0,425*
TSL HV **	81,4	-	0,41	-	0,37	-
1L-PAC LV	75,5	-	0,15	0,46	0,66	0,791
1L-PAC HV	81,0	-	0,20	-	4,1**	-
2L PAC LV	-0,90	1.01	0,43	-0,03	0,58	0,724
2L PAC HV	78,8	-	0,14	0,09	1,34	0,242*

* The low R^2 values indicate that these results lack significance.

** The large value of the residue indicates that the spread between surfaces is dominating over the age relation.

The explanatory power is sufficient for several surfaces, in the order of ±1dB (95% coverage) but 1L-PAC data for HVs show almost no relation with the studied parameters, resulting in a scatter of ±8dB for the 95% coverage. We refer to [14] for a more rigorous treatment of the subject.

2.6 Proposal for road surface effect in CNOSSOS-EU method

Basis of reduction effect

There are several ways the mitigating effect of noise-reducing surfaces can be implemented in calculation procedures but in almost all variants, the effect is defined relative to a reference surface, i.e. the difference between the noise level of a standard traffic flow on the specific surface is compared with the level of the same flow on a reference surface. Frequently, the ISO 11819-1 SPB method is used to define such difference values [20] . Such difference values are age related and a few approaches exist to integrate the acoustic aging of the surface in the determination of the reduction effect:

1. The reduction of a specific surface type is defined relative to a reference. Both specific surface and reference surface are in new condition. This approach assumes an equal aging of both surfaces; however this is generally not found to be the case.

2. The reduction effect of a surface is averaged over its service life. As noise reducing surfaces generally age quicker than the reference, several cycles have to be taken into consideration. This approach implies that approximately half of the time the actual effect is larger than defined and half of the time it is smaller.
3. The reduction effect is defined on the basis of its end-of-service life performance. This approach guarantees that at every moment the actual effect is at least the effect used for the calculations.

All three approaches are found in practice. For the purpose of calculation procedures for environmental noise exposure, the definition based on the average effect is preferred since it presents the best balance between the optimistic and pessimistic approach. Moreover, studies have demonstrated that gradual deterioration is not observed in the environment as a negative effect.

Coefficients in CNOSSOS approach

Within the framework of the European Environmental Noise Directive (2002/49/EC), work has been ongoing towards a harmonized calculation method (**C**ommon **NO**ise a**SS**essment meth**O**d**S** (CNOSSOS), ref. [22]) so results from different nations can be based on a common approach.

The CNOSSOS road traffic model distinguishes between rolling noise and propulsion noise. The sound power of each component is defined in octave bands from 125Hz to 4kHz. The main parameters in the related formula are vehicle type and speed. Added to this is a correction term that includes the effect of the road surface on both propulsion noise and rolling noise. The source strengths formulas are presented in (2) and (3).

$$L_{WR,i,m} = A_{R,i,m} + B_{R,i,m} \cdot lg\left(\frac{v_m}{v_{ref}}\right) + \Delta L_{WR,i,m}\left(v_m\right) \quad (2)$$

$$L_{WP,i,m} = A_{P,i,m} + B_{P,i,m} \cdot \left(\frac{(v_m - v_{ref})}{v_{ref}}\right) + \Delta L_{WP,i,m}(v_m) \quad (3)$$

The correction terms for the road surface effect, $\Delta L_{WR,road,I,m}$ and $\Delta L_{WP,road,I,m}$,are included in (4) for the rolling noise component and in (5) for the propulsion noise component.

$$\Delta L_{WR,i,m}(v_m) = \Delta L_{WR,road,i,m}(v_m) + \Delta L_{studded\ tyres,i,m=1}(v_m) + \Delta L_{WR,acc,i,m} + \Delta L_{W,temp}(\tau) \quad (4)$$

$$\Delta L_{WP,i,m}(v_m) = \Delta L_{WP,road,i,m}(v_m) + \Delta L_{WP,acc,i,m} + \Delta L_{WP,grad,i,m}(v_m) \quad (5)$$

The correction in the rolling noise level for the effect of the road surface is defined as follows:

$$\Delta L_{WR,road,i,m}(v_m) = \alpha_{i,m} + \beta_{i,m} \cdot \lg\left(\frac{v_m}{v_{ref}}\right) \quad (6)$$

The road surface correction for each vehicle type *m* is laid down in a series of six values for $\{\alpha_i\}$ and six for $\{\beta_i\}$. The procedure to establish the values of α and β will be provided in the (not yet published) "Guidelines for the competent use of CNOSSOS-EU", together with some examples of road surface corrections.

The correction for the propulsion noise component is derived from the series $\{\alpha_i\}$, referred to in (6) in the following way:

$$\Delta L_{WP,road,i,m}(v_m) = \min\left\{\alpha_{i,m};0\right\} \qquad (7)$$

The EU-CNOSSOS method prefers the averaging of the road surface effect over its service life, opposed to an initial or final value.

2.7 Effect of future vehicle and tyre technology

Future tyre technology

The tyre development is steered by consumer preferences and for Original Equipment Manufacturers (OEM) also the requirements of the vehicle manufacturers.

Consumer requirements are more frequently based on the tyre characteristics, defined by the European tyre label. This label presents rolling resistance and wet grip on a scale from A to G, and noise in a more general way as a series of "waves". From personal communication with tyre researchers, it is clear that the target labelling is A or B in both rolling resistance and wet grip. Noise levels are considered as less relevant for their product marketing.

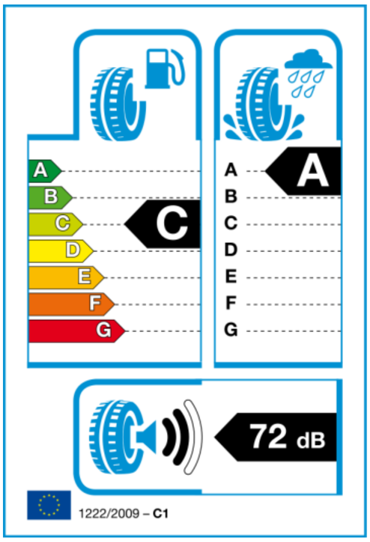


Fig. 16 Example of recently introduced EU tyre label. The number of waves indicate the margin with the current type approval limit value for that tyre type and size. Two waves indicate a margin of 0–2dB. With one wave, the margin is 3 or more dB

The optimization of rolling resistance and wet grip is found in the redesign of the tyre structure and materials. This concludes that maintaining a status quo or improving noise characteristics is achieved by tread profile optimization. In a previous study [24] we investigated the acoustic performances of a large number of tyre/road combinations and found that acoustic achievements of tyres on smooth ISO surfaces were not found on regular coarser textured surfaces as illustrated in Fig. 17.

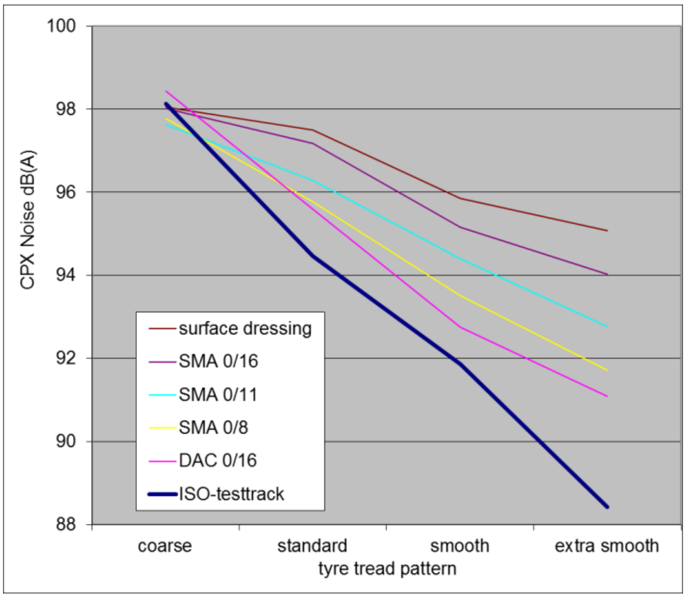


Fig. 17 Rolling noise levels of four types of tyre tread profiles on six different surface types, ranging from a coarse surface dressing to a smooth ISO 10884 test surface

It is to be expected that the focus on rolling resistance and wet grip will lead to acoustic optimization that maintains a status quo when determined on a smooth ISO surface but that acoustic performances on typical roads may not benefit from this. As the trend to larger tyre sizes continues, a deterioration may be expected.

For truck tyres, no major shift in focus is expected since rolling resistance and durability were always the main focus in the developments.

Future vehicle technology

Similar to tyre developments, vehicle developments also focus on fuel efficiency and safety features. Interests in acoustics lie mainly in the interior sound quality and the exterior imago, in the case of powerful sports cars.

A special case is the electric traction system that, in terms of propulsion noise, emits completely different sound signals. Some artificial signals are added for assumed safety issues. However, propulsion noise for cars is only relevant at very low speeds and its contribution is approximately 10% of the total emitted sound energy for cars on through roads.

Sound design is not an issue for HVs and the acoustic quality will be defined by the European type approval regulations. For future years, no effective tightening of limit values is expected other than the shift due to modification of the test procedure.

3 QUESTIM WP 4: Acoustic performance of noise barriers over their working lifetime

Noise barriers are the most widely used form of noise mitigation on European roads, managed by NRAs. Barriers are manufactured/constructed from a wide variety of materials and to different designs but all serve the same basic purpose; namely to reduce noise levels at noise sensitive receivers away from the roadside, e.g. at residential properties, by acting upon the sound propagating away from the road through influencing the propagation path between the source and the receiver.

A key requirement for noise barriers used by NRAs is for them to maintain an appropriate level of acoustic durability over their working life.

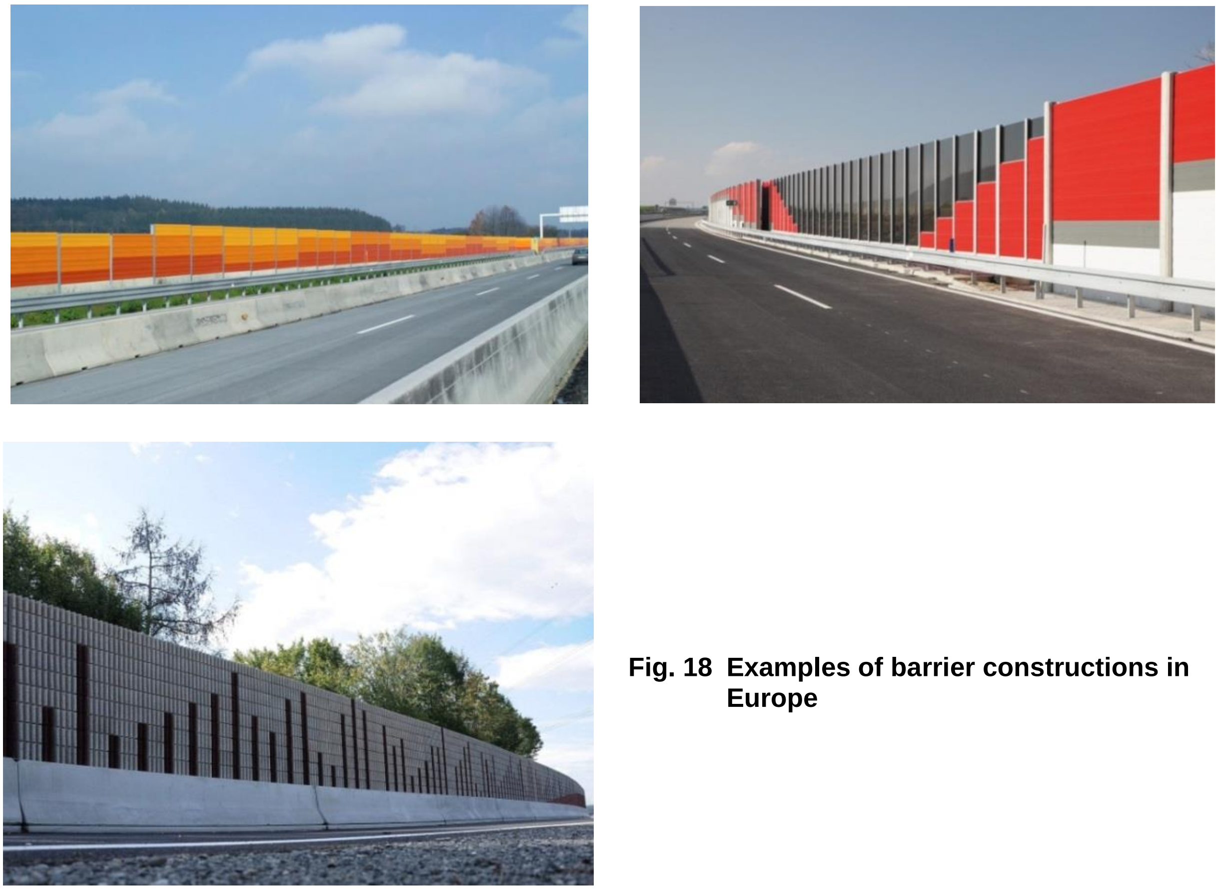


Fig. 18 Examples of barrier constructions in Europe

It is important therefore that the acoustic elements within a barrier are capable, as far as is practicable, of resisting the effects of agents encountered within the roadside environment that may have a negative impact on their acoustic performance. Loss of performance can also result, through damage caused by impact, vandalism, etc.

Degradation will most commonly manifest in terms of changes in the structural integrity of the barrier and its physical condition/aesthetics.

Any change in actual acoustic performance that results from physical degradation or the failure of acoustic elements will, for the most part, be restricted to changes in the intrinsic characteristics of the barrier, i.e. the performance of the individual materials or components of the barrier rather than changes in absolute noise levels at noise sensitive receivers behind the barrier, unless the result is the physical loss of acoustic elements; research studies on the effects of holes and gaps (e.g. [25] [26]) indicate that at distances beyond 20m, the effects of holes and gaps are likely to be relatively small (typically less than 1dB) unless the barriers are high. Degradation of sound absorptive materials may result in some increase in reflected sound; the magnitude depending upon the scale of degradation.

Published literature and consultations with noise barrier manufacturers, carried out as part of the QUESTIM project, suggest that many of the noise barrier products on the market are not considered to degrade acoustically over their working lifetime. Barriers constructed from timber are considered to be the most susceptible to loss of acoustic performance.

3.1 Causes for loss of intrinsic acoustic performance

The following provides a summary of natural factors that can adversely affect intrinsic performance characteristics of various types of noise barrier.

Timber: Timber barriers are susceptible to acoustic degradation (e.g. Morgan, 2010) as the planks/boards making up the barrier will warp or shrink resulting in gaps between planks, are susceptible to knots and, particularly in the case of gravel boards, are susceptible to rotting. To address these issues, manufacturers use good quality timber and pressure treat all elements with appropriate preservatives which are resistant to fungi, boring insects and other wood destroying organisms; this protects against the effects of moisture, thereby helping to reduce the effects of warping/shrinking and may help to protect against damage from de-icing salts and chemicals.

Reducing the potential for gaps is most frequently addressed by either overlapping planks/ boards or use of a tongue and groove construction. It is noted that where the acoustic elements are constructed on site from component planks/boards/timbers, care should be taken to ensure that any cut surfaces are treated with an appropriate preservative.

Sound absorptive materials: The acoustic performance of sound absorptive materials will also be adversely affected if the materials are allowed to delaminate or sink/compress to the bottom of the acoustic element due to the effects of vibration, the presence of moisture or if dirt/dust is allowed to accumulate (although in the case of the latter, sound insulation performance of the barrier may increase). At the time of writing, no data has been identified to quantify these effects. Many commercially absorptive materials such as mineral wools are designed to be moisture repellent; compression can to a large extent be avoided through the use of denser materials (although this may affect the absorption characteristics) and ensuring that the materials are well supported or retained.

In the case of cartridge-type systems such as metal barriers, where the sound absorptive material is mounted behind the perforated facing of the cartridge, evidence of settling or delamination is not readily visible. In such instances, it is necessary to allow a water drainage path through the absorptive material; this can be achieved by supporting the material away from the walls of the cartridge.

For barriers where the absorber is mounted on the front of the barrier structure, as is typically the case with sound absorptive timber barriers, the absorber should be protected by an appropriate protective membrane that must itself be resistant to ultraviolet (UV) degradation and the effects of agents such as de-icing/salt sprays, etc. and similarly supported to prevent settling over time.

Concrete: Factors affecting **concrete barriers** such as freeze/thaw cycles, UV degradation and exposure to de-icing salts and chemicals will primarily affect the structural integrity of a barrier rather than its acoustic performance; however this is potentially an issue for porous concrete or wood cement concrete barriers, since they can result in the physical loss of the porous surface from the structure of the barrier.

As with other sound absorptive materials, porous concrete barriers will also be affected by the accumulation of dirt/dust and other materials in the pores. Conversely, it was noted by one manufacturer/supplier that the absorption properties of concrete barriers may actually increase as the surface of the barrier undergoes abrasion.

3.2 Practical data on acoustic durability

Declaration of long-term acoustic performance by manufacturers in terms of absolute changes in intrinsic performance is not widespread. This is driven by the combination of acoustically robust products, a lack of long-term performance data for those barriers where performance does degrade and no mandatory requirement to specify acoustic performance over the working lifetime of noise reducing devices (declaration of the product performance as 'NPD' (No Performance Declared) is sufficient for the purposes of European Conformity (CE) marking to current standards.

In terms of research studies, where data on noise barrier acoustic performance has been collected, these are mainly restricted to acoustic performance in new condition as, for example, is the case with the public database produced as part of the European 7th Framework project QUIESST [27] [28] .

Where durability data is available, this is only from limited tests on two barrier types. A UK research study into the acoustic durability of timber barriers [12] concluded that any degradation in the acoustic performance of single-leaf reflective occurs during the first 5 years after construction. Depending upon the initial performance, this decrease appeared to be in the range of 4–7dB. The same study was unable to collection sufficient data to be able to draw informed conclusions regarding the performance of double-leaf reflective or sound absorptive timber barriers. A series of in situ measurements on two sound absorptive aluminium barriers [32] suggest that the sound absorption performance of such barriers may degrade by between 0,3-0,8 dB after 11 years. Measurement data supplied by one of the manufacturer respondents to the QUESTIM survey (see Table 4.1 in [16]) suggests that the sound absorption performance of such barriers may only decrease by 1 dBA even after 20 years. No data on other barrier types was identified.

The collation of a robust, comprehensive data set of in situ measurements of barriers of different ages is required to allow the derivation of indicative age/intrinsic acoustic durability relationships for different barrier types, if this is deemed beneficial (since noise levels at noise sensitive receivers behind a barrier may be relatively unaffected by intrinsic changes in performance). It is considered that the collection and collation of such data is outside of the responsibility (and probably the capacity) of any single NRA, although limited individual datasets might be collated. The QUIESST project has already established a public database of useful performance data (although this does not identify nor attribute characteristics to specific products/systems) and it has been suggested that involvement of manufacturers and industry bodies such as the European Noise Barrier Federation might be a means of expanding and maintaining such a database; such a database combined with data from NRA measurement programmes might facilitate the development of intrinsic acoustic durability relationships.

4 QUESTIM WP 5: Planning of noise reducing surfaces

Cost-benefit modelling and whole-life costing are established methods that are used within asset management to assist the road authorities and support the decisions they make. These methods use road network data to analyse the impacts of different investment scenarios in order to build a programme of work that best meets the policies and objectives of an organisation.

There is a growing importance that is being placed on the role of environmental considerations within these systems and this section looks at how noise can be incorporated into a Pavement Management System (PMS) and the principles of whole-life costing.

4.1 Principles of Pavement Management Systems

A PMS is an asset management system specifically for road pavements and is one of the key tools for road asset management used by many highway authorities. A well-managed and well-maintained asset management system can help make best use of the available resources to meet the needs of both the managing organisation and the users. The same is also true of a PMS used by a highway authority.

A PMS is commonly used to store data relating to a road network (e.g. inventory, condition and traffic) and applies rules to that data to identify sections requiring maintenance and prioritise the maintenance sections against any given time or budget constraints. However, the variation in both the characteristics of a pavement network and the surveyed data means that there is not one overall assessment approach or set of algorithms that can be universally applied to a pavement network.

Among other things, data is required to enable engineers to perform the following:

- Identify when and where maintenance is needed
- Make decisions on the type of maintenance intervention that will provide the best return on investment
- Plan the maintenance at times that cause the least inconvenience to road users, allowing the networks to be kept operational more of the time
- Improved understanding of the impacts (positive and negative) of the road pavement networks

Externalities

An externality is a cost or benefit that is encountered by a person or party who is not the originator of the economic action [17] . It is normally considered with respect to effects on the wider society, who are affected by the outcome of a change of decisions in which they may not have direct involvement.

Noise is one of the key transport externalities currently discussed for inclusion within option appraisals but there is still a lack of recognised approaches at either a scheme or a network level, especially where a quantitative (or costed) methodology is desired.

Developing such a methodology would enhance a PMS in terms of understanding the impacts of the road pavement networks, as stated above. Knowing the acoustic state of the pavements and how this will change when they are maintained allows the network administrator to infer the potential impact of changes on environmental traffic noise and these can in turn be monetised for comparison with the costs of maintenance and other externalities

4.2 Modelling noise impacts

Environmental noise is a significant problem and a major concern for public health and annoyance in Europe. According to the recent WHO-JRC report on the burden of disease from environmental noise [18] traffic-related noise may account for over one million healthy life years lost per year in the EU and other Western European countries. Urbanisation and a steep increase in traffic are the main drivers of escalating environmental noise exposure in Europe.

The social costs of traffic, rail and road noise across the EU were recently estimated at € 40 billion per year, equivalent to 0,35% of the EU's gross domestic product (GDP). According to the European Commission's 2011 White Paper on Transport, the traffic noise-related external costs will increase to roughly € 20 billion by 2050, unless further action is taken.

From the perspective of NRAs, it is noise from road traffic that is the source of concern. Noise levels at noise sensitive receivers will be heavily influenced by factors such as traffic volume, composition, speed and proximity.

Many governments/road authorities have their own national guidelines or legislation for controlling road traffic noise. These may include approaches such as:

- Type-approval legislation, governing the permissible noise from new vehicles to be sold in the country
- The mandatory evaluation of the potential noise impacts for new schemes, leading to enforcement of environmental noise limits/thresholds
- Taxation policy
- Noise mitigation policies for new or improved road schemes

Additionally, the introduction of the Environmental Noise Directive [19] has sought to address noise pollution by requiring Member States to determine exposure to environmental noise through strategic noise mapping and action plans to reduce noise pollution. This information also serves to inform the general public about the levels of noise they are exposed to and about actions undertaken to reduce noise pollution to a level not harmful to public health and the environment. The noise maps and action plans are produced on a five year cycle and it is anticipated that future cycles may well use the CNOSSOS-EU noise model [22]

It is the aim of integrating noise into a PMS to address many of the issues still faced by a road authority in assessing noise implications against direct costs. In doing so it would likely be computationally, logistically and time prohibitive to expect the enhanced PMS model to perform detailed noise calculations and therefore, baseline noise data are taken from existing noise maps. This neatly circumvents the need for complex noise propagation calculations and allows the focus of the noise data to rest on determining the nature of potential mitigation options, together with the number of people who are likely to benefit from such mitigation.

4.3 Integrating noise into a PMS

Whilst there are stand-alone tools available that can be used for a preliminary assessment of some environmental elements at the project level, there is a lack of consistent methodologies and robust tools both at the project and at the network level. For example, there are tools for the assessment of the environmental impacts of construction and maintenance of various assets but they have generally been designed to be complementary to a costing process and not as methodologies to be incorporated into wider cost assessments. Pricing noise internally within a network level pavement maintenance model will advance our understanding of how the impacts of these externalities can influence the overall cost and the development of strategies for road maintenance programmes. However, from a practical point of view, few models routinely include monetised estimates of environmental effects.

The noise data for use in a PMS needs to reflect the network and analysis being undertaken. For example, if a scheme level analysis is being undertaken, detailed localised noise data is most appropriate if it is available. However, if a network level, strategic analysis is being undertaken then coarser level noise data will allow adequate modelling of policy scenarios at a network level, especially considering that the detailed localised noise data is unlikely to be available for a whole network.

The development of a methodology discussed making best use of available data. As such, European directive driven noise maps are suggested as a potential source of noise data that is likely to provide the best coverage across networks. However, other sources of noise data can be substituted in place of noise map datasets as long as the format provides a measure of the number of properties in different noise bands along the network.

A methodology for integrating noise into a PMS was developed, in addition to describing how to generate the required datasets, although it is expected that datasets should be localised, where possible. The current noise mapping data has enough information for use in the methodology but it is expected that significant improvements to this data will come on-stream as the noise mapping further develops. One clear area for improvement with these data is in being able to determine a ‘per km’ noise value for individual sections of a road which is not possible with the current data. Such data could come from the noise mapping calculations themselves, it would just require the PMS developer to have access to (and an understanding of) the noise mapping inputs at a detailed level. This could be facilitated through appropriate governing bodies (for example, in England, in an agreement between Defra and Highways England).

An overview of the resultant modelling methodology to quantify and cost the noise changes over a treatment profile is described in the following bullet points. It should be noted that noise costs or benefits could be generated in any year of the treatment profile, not just the year(s) in which maintenance occurred. This is because the noise resulting from a maintenance intervention can vary in all years of a treatment profile, not just the individual years of the interventions. To truly account for the noise costs or benefits, the noise therefore requires calculating for each year of the entire treatment evaluation period.

1. Determine the number of dwellings in each noise band for the maintenance scheme using the noise input data set (e.g. dwellings per km).
2. If the noise reducing property of the pavement is being deteriorated, modify the noise data for each year until the first maintenance intervention.
3. For each intervention in the treatment evaluation period:

   a. Determine the initial noise change, constant noise change[2] and years until constant noise change values, using the old and new pavement surfaces for this intervention.
   b. Determine the number of dwellings that existed in each noise band in the year prior to the maintenance intervention. This is used as the reference dwellings in the calculations for this maintenance intervention.
   c. For each year between the current intervention and the next treatment intervention:
      i. Determine the in-year noise change, based on linearly decreasing the initial noise change to the constant noise change from the year of the intervention to the years it takes to reach the constant noise change. Apply the constant noise change for any years beyond the number of years it takes to reach the constant noise change.
      ii. Calculate the change in the number of dwellings in each noise band affected by the in-year noise change,[3] using the reference dwellings as the base values and assuming that the dwellings are distributed evenly within each noise band.
      iii. Apply the change in the number of dwellings to the reference dwellings in order to calculate the number of dwellings that would be in each noise band at the end of that year change.
      iv. For each noise band, calculate the noise costs or benefits by multiplying the change in the number of dwellings by the value of moving between the respective bands.
      v. Sum the noise costs or benefits across each band to calculate a total in-year cost or benefit.
4. Repeat step 3 for each new maintenance intervention within the treatment evaluation period.
5. Apply discount rates to the noise costs through all years of the analysis to calculate the noise net present value (NPV). The user can specify a noise specific discount rate, although it is recommended, for the UK at least, that the standard Treasury Green Book values are used.
6. Include the discounted noise cost in cost calculations as specified by the user during the run configuration (i.e. whether noise costs should be treated as an agency or user cost).

The developed methodology aimed to take account of the competing factors with the different noise surfaces, such as shorter expected lives associated with low-noise surfaces. This ability

[2] The constant noise change assumes that at a future point in time the noise property of the surface will plateau and no longer deteriorate or change. Between these periods a linear change for the noise deterioration has been assumed in this methodology. If a different type of relationship is required, the methodology can be adapted accordingly. If the surface is not expected to plateau in its noise characteristics, the number of years to the constant change can be set at a high value so that it will never be reached before the next intervention is required.

[3] The in-year noise change is a fixed reduction of noise applied to all identified dwellings associated with the specific maintenance scheme and road chainage.

was incorporated into the methodology and means that a greater range of realistic options can be investigated when this methodology is included within a PMS.

The types of questions that can be investigated using this methodology are:

- What are the implications on a road maintenance programme between the different choices of noise surface available?
- If low-noise surfaces are selected at times of maintenance, what are the implications on developing a maintenance programme?
- What are the longer-term effects (e.g. the timing and number of future interventions) when choosing low-noise surfaces for maintenance?

The noise methodology developed can help a road authority develop a greater understanding of the impacts from these types of questions, especially when compared to a more traditional approach that doesn't include externalities alongside the direct works costs when developing a maintenance programme.

5 QUESTIM WP 3: Monitoring the acoustic performance of road surfaces

5.1 General Description

In this WP a choice is made between several monitoring methods and the CPX method (ISO 11819-2) is found to be most appropriate. A procedure is defined and developed for deriving categorical data from CPX measuring data for the use in a PMS and to provide a procedure to link it to geographic and land-use planning information in order to assess the significance of the acoustic condition of the road surface with regard to noise protection issues.

5.2 Definition of the Problem

Road traffic noise is the major pollution in industrialised countries and currently tyre/road noise is its most significant source. Tyre/road noise is profoundly influenced by structural properties of the road surface. Therefore, the effectiveness of noise control measures strongly depends on the condition of the road. For this reason, the acoustical condition of a road pavement should be made part of the road condition registration and evaluation system and the PMS. It is almost as important as skid resistance, transverse and longitudinal evenness and the structural integrity of a road pavement.

The acoustical condition can be implemented into the PMS in two ways as follows:

- **Indirect** implementation of noise as a new attribute:

The level of the tyre/road noise depends on specific properties of the road surface, mainly surface texture and sound absorption. These properties are directly influenced by pavement engineering properties, age, traffic load, etc. and would therefore fit very well in the system of pavement management. However, taking these properties as attributes for the PMS would cause the need for development of improved or even new measuring techniques and a sophisticated model which helps to rate the measurement results with respect to tyre/road noise.

- **Direct** implementation of noise as a new attribute:

  This approach provides for the direct measurement of road traffic noise, single vehicle noise or tyre/road noise. However, tyre/road noise does only predominate the total vehicle noise of LVs. In case of HVs road traffic noise is influenced by the propulsion noise as well. Therefore, the measuring method has to be chosen carefully.

The need of a road surface improvement measure cannot solely be based on parameters that characterize the acoustical quality, unlike the ones for the structural quality. Measures for the improvement of a road pavement become necessary as soon as structural properties such as grip and evenness exceed a certain limit, which is required to keep the road condition safe.

Such a limit cannot be appointed to the acoustical quality because one characteristic value does not determine if the protective goals are reached. The reason being that noise protection does not depend on the road user's requirements but on the requirements that are related to land-use in the surrounding of the road. In the case of acoustical quality, the attribute characterizing noise and the required limit do not refer to the same parameter. Moreover, the required noise levels are inconsistent along the roadway. They depend on land-use and population density.

The acoustic road surface parameters provide information about the physical property and condition of a surface regarding the potential noise emission. In combination with traffic volume, traffic composition, speed and local road traffic conditions, the noise emission of a road can be derived. The relationship between interdependent attributes and the noise impact is depicted in Fig. 19.

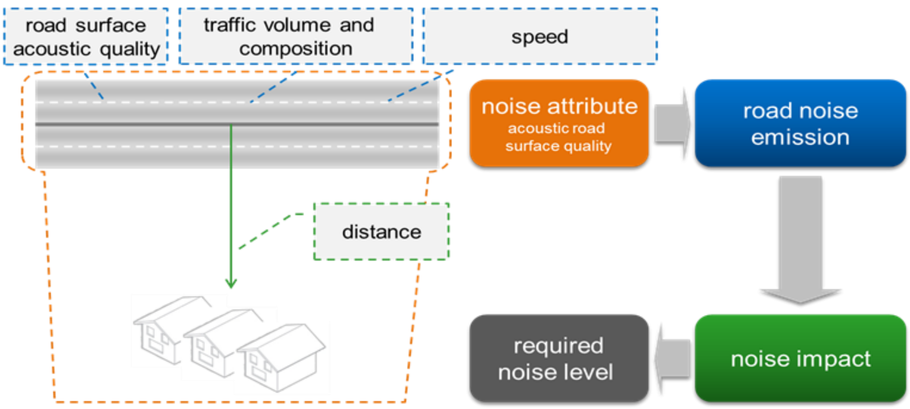
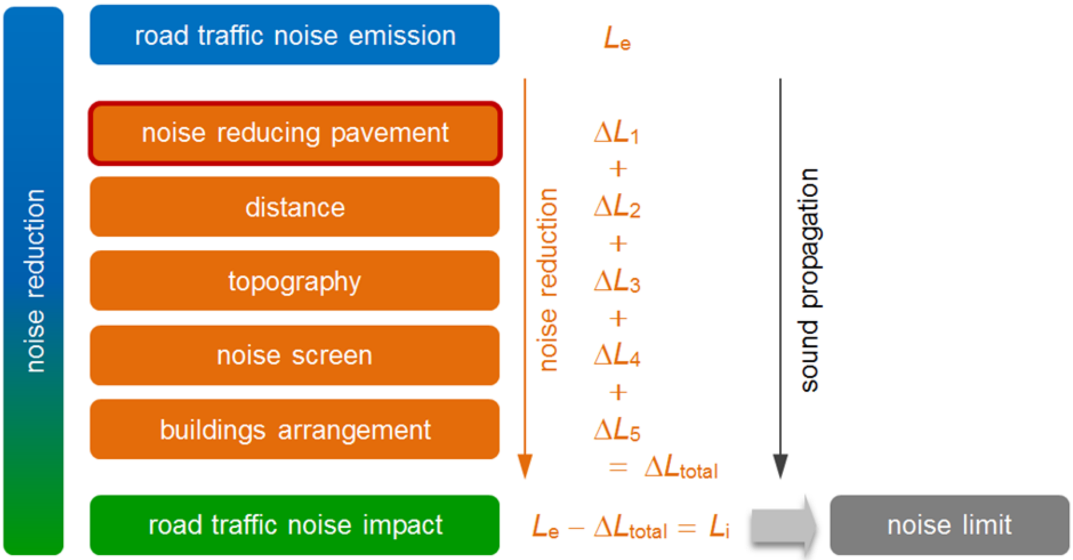


Fig. 19 Schematic depiction of interdependent attributes

The acoustical quality of a road surface is one of several parameters which determine the relationship between noise emission and noise impact caused at a particular place next to the road. A bundle of other parameters completes the scope of possible factors which could help to reduce the road traffic noise on its path to the receiver and to meet noise protection requirements. The stack panel illustrated in **Fout! Verwijzingsbron niet gevonden.** clarifies this issue.



Contributing parameters (orange) concerning the reduction of the road traffic noise (blue) on the path to the receiver (green). L_e = noise emission level of the road traffic, ΔL_i = noise reduction of the specific parameter i, ΔL_{total} = overall noise reduction, L_i = noise impact level

Each of the parameters shown in 0 gives a certain noise reduction value ΔL_i. The overall noise reduction ΔL_{total} is the sum of all single values. In the framework of road network or land use planning processes the parameters and their noise reduction values get concretised.

Distances between road and buildings, specific topography, buildings arrangements, the dimensions of noise screens and finally also the acoustic quality, i.e. the required noise reduction value of the road surface are put into the drawings and statutes of the plan in order to document and ensure the compliance of the plan with legal noise protection requirements. After realisation all conditions remain practically constant over long periods of time regarding their noise reduction effect, except for the acoustic quality of the road pavement. This means that one of the summands in the sum of noise reduction values mentioned above changes with time, gets worse, increases the noise impact and therefore affects the noise mitigation concept of the plan. For this reason, the acoustic quality of the road surface should be monitored and be made part of a pavement management system.

5.3 Definition of the Attribute

The new road condition attribute is called *noise excitation* but it actually refers to *tyre/road noise*. It is based on the ability of the road surface to excite vibrations on a rolling tyre and to influence aerodynamic effects within and the sound radiation from the tyre/road contact, depending on the roads surface's texture and the road surface’s structural properties. Following this definition, the new attribute is considered a derived attribute, not a basic one, in terms of a road condition evaluation system. This is because it needs the interaction with the tyre in order to become effective. In principle, the values for this attribute are related to the usage of the road, rather than to its substance. However, differing from other usage-related characteristics such as unevenness, rut depth, virtual water depth and skid resistance, noise is a functional characteristic of the road that is not or hardly relevant for the road user. It is relevant for people who are living in the vicinity of the road and who are not contributing to the road traffic. For this reason, implementing noise in the PMS yields a new dimension concerning the registration and evaluation of road conditions.

5.4 Measuring Method

An adequate measuring method should meet the following requirements:

- Direct implementation of noise as an attribute of the road surface should be preferred
- A direct implementation leads to direct measurement of noise
- The noise measuring method should be target oriented in such a way that a continuous monitoring of entire road sections is possible with manageable effort
- It should be able to easily trace differences in measured noise levels back to differences in road surface conditions
- Measurement method, boundary conditions and hardware as well as the evaluation of raw data should be definable and have to be based on measurement standards

Suitable methods for the direct measurement of road noise as well as their advantages and disadvantages with respect to an acoustic road condition monitoring are summarized in Table 1 in the WP 3 report. CPX is the method that meets the described requirements best.

5.5 CPX method

In the CPX method, the average A-weighted sound pressure level (SPL) emitted by specified tyres are measured over an arbitrary or a specified road distance, together with the vehicle testing speed, by at least two microphones per wheel track, located close to the tyres. For this purpose, a special test vehicle, which is either self-powered or towed behind another vehicle, is used. Reference tyres are mounted on the test vehicle, either one by one, or at the same time. Two tyre types have been selected as reference testing tyres in order to represent the different tyre characteristics regarding their use for passenger cars (P) or HVs (H).

The tests are performed with the intention of determining a tyre/road SPL, referred to as the CPX level (L_{CPX}), at a reference speed (mostly 50km/h or 80km/h). For each reference tyre, the SPL, together with the corresponding vehicle speed, are continuously recorded. The SPL is determined for 20m segments and normalized to a reference speed and temperature. Averaging is then carried out according to the purpose of the measurement (measuring a particular segment or a number of consecutive segments – a section). The results are two CPX indices: $CPXP_{vref}$ for tyre type P, $CPXH_{vref}$ for H that can be averaged to obtain a $CPXI_{vref}$ as a standard CPX-based index for single-value comparison of the acoustic performance of road surfaces. Measuring equipment and measurements are based on the ISO 11819-2 standard and the reference tyres defined in ISO/TS 11819-3.

Fig. 20 Example of a CPX system with two test tyres and enclosure (source Müller-BBM)

5.6 Uncertainty in CPX results

The evaluation of road surfaces with the CPX method is subjected to a limited accuracy, composed of an uncertainty in the CPX method itself (excluding variation in tyres) and the scatter in properties of the test tyres. In QUESTIM report D3 [15] the individual contributions to the uncertainty are presented. It was concluded that the expanded uncertainty for an 80% coverage is 1,3dB. For a coverage of 95%, an uncertainty of 2,2dB is found. The largest contribution to the uncertainty is the scatter in tyre properties, both at the level of manufacturing spread and due to aging and wear.

It is to be expected that the ISO-TS 11819-3 will contain requirements on the tyre condition that will limit uncertainty to the level of other comparable sources listed in [15] . In order to improve the accuracy of CPX measurements, a strict quality control of the tyres with the following measures is necessary:

- Thorough incoming inspection
- Measurement of the dynamic properties, i.e. point mobility (mechanical impedance)
- Cool (<7°C) and dark storage to slow down hardening of the rubber
- Frequent condition monitoring, especially during measuring season

5.7 CPX Reference Values

To specify the acoustic quality of a road, CPX reference values for the rolling noise for both tyres types and at two different speeds (50km/h and 80km/h) are derived from CPX data gathered for standard road surfaces in Germany, the Netherlands and in Switzerland.

A total of 191 road sections were evaluated. The age of each surface when measured was 1 year ±2 months in Germany and Switzerland, and less than 1 year in the Netherlands.

The graphs in Fig. 21 present the resulting CPX levels for P and H tyre.

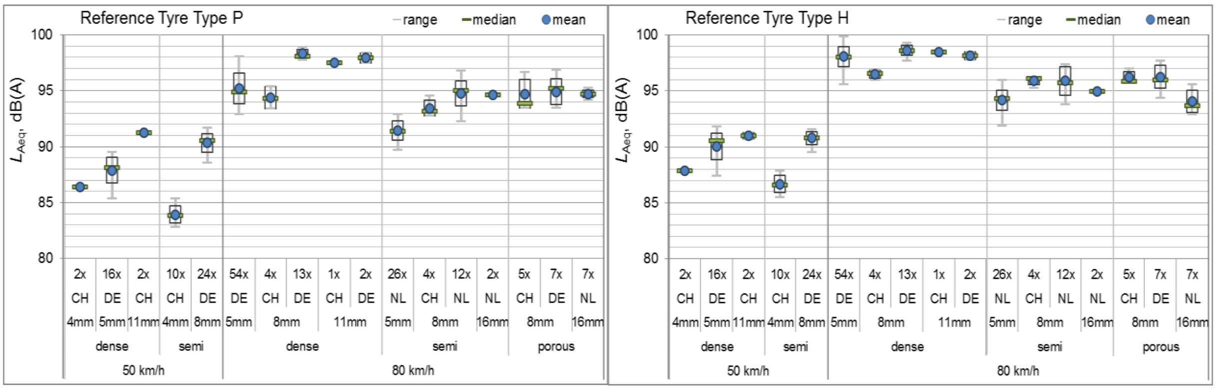


Fig. 21 Average CPX levels, right: tyre type P, left: tyre type H, at 50 and 80km/h. The average standard deviations are represented by the black boxes. The range equals the difference of the extreme values (maximum minus minimum)

Road building practices and road material definitions differ between countries. Aggregation of CPX data is therefore based on the porosity (dense, semi and porous) and maximum aggregate stone size. From these groups, the reference values are derived (refer to Table IV).

Table IV Reference values, grouped by porosity and maximum aggregate stone size, defined by the arithmetic average of CPX-indexes for the nominal speed v. The number of data points (n) and the resulting combined standard uncertainty ΔCPX are also provided

v, km/h	void content	max grain, mm	n	CPX_P, dB(A)	CPX_H, dB(A)	ΔCPX, dB(A)
50	dense	4	2	86,4	87,9	0,8
50	dense	5	16	87,9	90,0	0,3
50	dense	11	2	91,2	91,0	0,8
50	semi	4	10	83,9	86,7	0,3
50	semi	8	**24**	**90,3**	**90,8**	**0,2**
80	dense	5	**54**	**95,2**	**98,1**	**0,1**
80	dense	8	17	97,4	98,1	0,3
80	dense	11	3	97,8	98,2	0,6
80	semi	5	**26**	**91,7**	**94,4**	**0,2**
80	semi	8	16	94,5	96,0	0,3
80	semi	16	2	94,7	95,0	0,8
80	porous	8	12	94,8	96,2	0,3
80	porous	16	7	94,7	94,1	0,4

Although the data originated from only three countries and thus the derived average CPX levels mainly represent the surface types for these countries, the definition of the surface types based on a max. aggregate size and porosity range is generally sufficient to serve as a guidance for other countries. The Nordic countries may serve as an exception since the wear after just one year exceeds that found in more moderate areas in Europe (ref. [13] and [14]).

5.8 Data Aggregation

Smoothing Methods

For pavement management purposes, raw CPX-data is too detailed in two ways as follows:

1. Instead of the exact SPL value, a categorical quantity should represent the acoustic condition of a road segment and its relevance with respect to the local conditions, e. g. existence of receivers, kind of receivers (dwellings, required noise reduction value of the road surface).

2. For easier management, the segment length should be as long as possible. In order to determine a suitable smoothing method for data aggregation, several mathematical operations were investigated and compared using CPX data of a 65km long road section.

In this comparison, the median operation turns out to be the method of choice. The parameters for the smoothing operation, especially the amount of segments to be considered, were determined by a sensitivity analysis using sound propagation calculations. Refer to the WP 3 report [15] for details.

General sections length

In order to determine a minimum section length so that the change of the noise impact is negligible, a sound propagation calculation model with four lanes and several receiver points at various distances was used. An overall good compromise was achieved with a minimum section length of 500m. However a minimum section length of 500m would underrepresent short loud intervals. Therefore, 500m is used as an evaluation length for the aggregation with the median function but the data is not segmented strictly into new intervals of at least 500m length. Therefore, values fluctuating around a particular level are smoothed but changes of the level itself are rendered automatically.

Relevant noise segment length

Instead of the fixed evaluation length of 500m over what CPX-data is aggregated, a length depending on the receivers' distances to the road can be used. With growing distance between the road and the receiver, the effective length of a particular road section involved in the noise impact at the receiver's location grows. With a level decrease of -10dB, the number of contributing 100 m-segments equals: $n = \frac{3d}{50\,m} + 1$

The distance *d* can be derived by using a geographical information system. Buildings as well as road sections are represented in different layers. Using the coordinates of a particular road segment and a particular building, the distance can easily be calculated.

The amount of contributing segments as a function of the distance to the nearest building is used as a parameter for the aggregation along the road for one segment. This distance is referred to as the receiver distance; the shorter it is, the smaller the range. The schematic in Fig. 22 illustrates how the minimum distance or rather the distance to the nearest building a_{min} is sought.

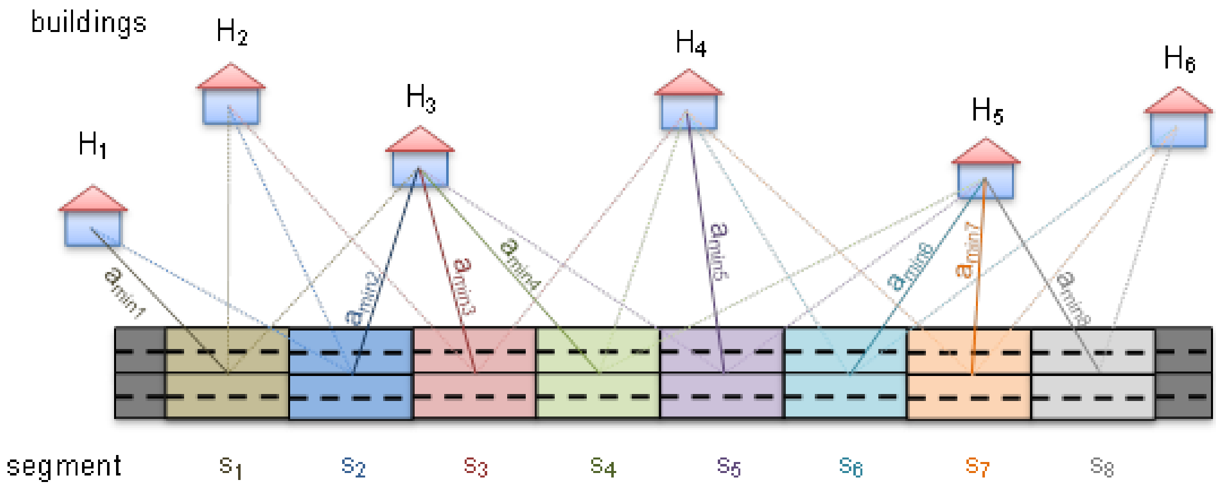


Fig. 22 Schematic of the minimum distance of each 20 m-segment to the nearest building in the surrounding.

Fig. 23 illustratess an example of how the distance a_{min} can be derived automatically; in this case from a geographical and buildings information system. a_{min} can easily be determinend by means of the coordinates of the houses and each segment.

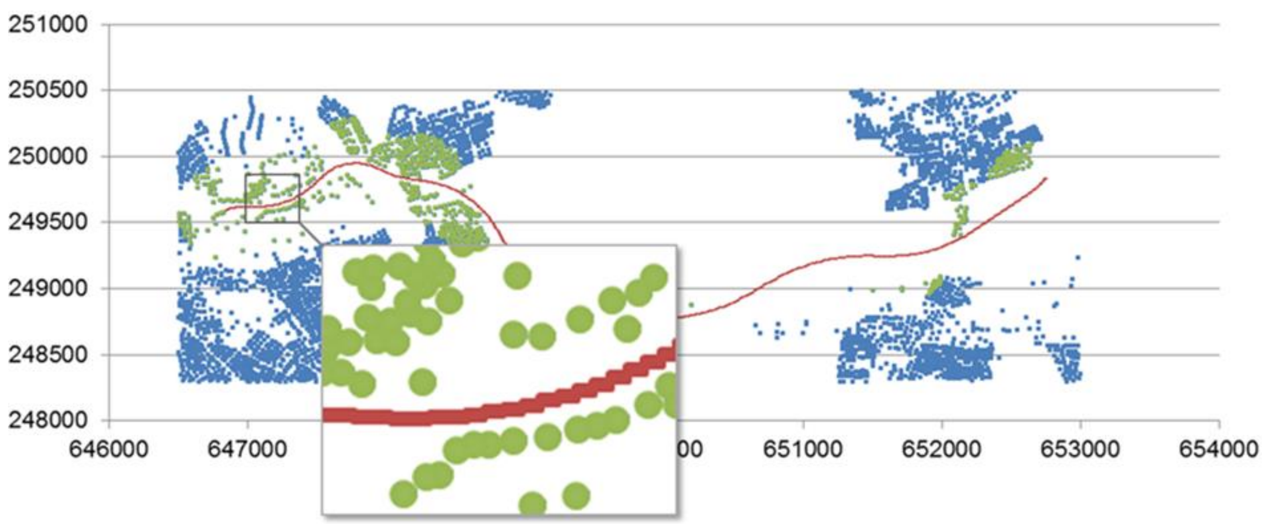


Fig. 23 Example of a real topography of a road with buildings, represented by house-dots, taken from a geographical registry of buildings and roads

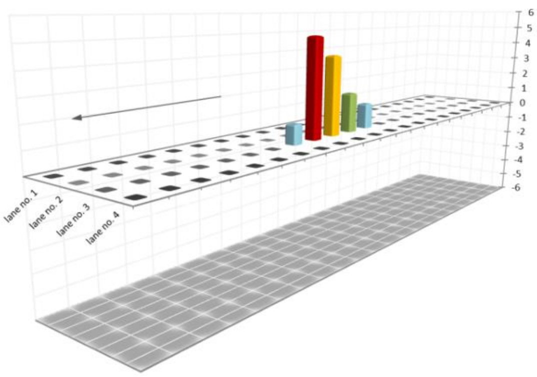
ZRN – Zero Rating Niveau and Comparisons

The acoustic condition of a road section needs to be derived taking additional secondary attributes into account. These attributes are the conceded or legally obligated noise reduction value of the road surface and the population density in the vicinity of the road. The noise reduction value of a road pavement is specified by the road administrator's optional or legally obligated choice of a particular type of road pavement for the new construction or reconstruction of a road. The type of road surface defines the acoustic performance that can be expected from it, either in its initial or future condition. This procedure of defining a reference level for the rating of a usage-related attribute of the road pavement differs from that for other attributes such as unevenness or grip. Noise as a functional attribute is in relationship with environmental noise control requirements and is completely detached from road usage and road user issues. In general, the requirements are stipulated in terms of noise limit values which are valid for different types of land use.

The reference level of a road pavement, referred to as Zero Rating Niveau (ZRN), corresponds to the noise reduction value of the road pavement which is needed to keep the noise impact in the vicinity below a certain level agreed upon or which the road administrator is willing to concede to the residents.

In order to determine the acoustic condition of a relevant noise segment, its resulting (CPX-) level is compared with the ZRN which is due for that particular road section and, when applicable, taking into account its age and remaining service life.

Fig. 24 illustrates the level differences between the relevant noise segment value and the ZRN for five segments on one lane. In the left diagram, the ZRN is 0dB(A), causing level differences of up to 5dB(A). In the diagram on the right, the ZRN is decided to be -2dB(A), causing level differences of up to 7dB(A). The colours indicate acoustic condition categories the level differences could be attached to.



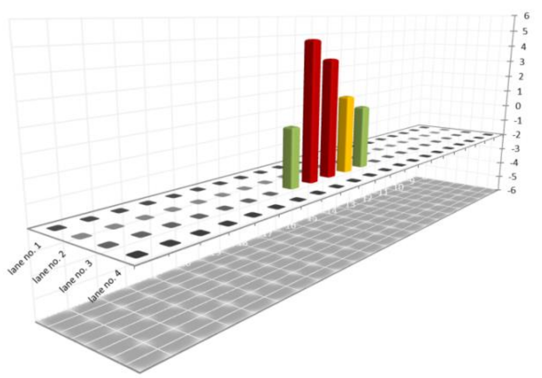


Fig. 24 Effect of the ZRN on the acoustic condition values. Left: ZRN = 0dB(A), right: ZRN = -2dB(A)

5.9 Conclusion

The work in QUESTIM WP 3 addresses two main aspects of the implementation of the new attribute *noise* into a PMS as follows:

1. The aggregation of raw CPX measurement segments up to longer segments which are meaningful with respect to the road maintenance and which homogenize the acoustic parameter without losing the relationship to the noise impact issue.
2. The introduction of a rating procedure which is strongly related to that what is needed in terms of noise protection issues, without implementing the complex calculation procedure to quantify the relation between the noise emission and noise immission levels.

The aggregation of the CPX data can be performed within, excluding the context of noise impact issues. Neglecting the noise impact, the CPX-data can be aggregated as follows:

1. In terms of a PMS, the road lanes should be considered and processed separately.
2. PMSs are based on consecutive 100m road sections.
   Therefore, the CPX-samples should be created this long by averaging consecutive sets of five 20m CPX-segments each.
3. Application of the median function over five consecutive 100m sections for each 100m section.
4. Application of the peak filter.
5. Rounding of the remaining values to 0,5dB.

Taking the noise impact aspect into account, the aggregation procedure could be as follows:

1. In terms of a PMS, the road lanes should be considered and processed separately.
2. PMSs are based on consecutive 100m road sections.
   Therefore, the CPX-samples should be made this long by averaging consecutive sets of five 20m CPX-segments each.
3. Determination of the distances between each 100m road section and the nearest building. If buildings do not exist or are not subject to specific noise protection issues, the distance would be set to infinite.
4. Determination of the length (number of consecutive 100m sections) of Relevant Noise Segments for each 100m road section, based on the distances determined in step 3.
5. Application of the median function over the derived lengths of the Relevant Noise Segments for each 100m section.
6. Application of the peak filter.
7. Rounding of the remaining values to 0.5dB.

Finally, the application of the ZRN assists in introducing a rating scale for the results of the data aggregation in an automated way. The comparison of the aggregated levels with given reference levels makes it easy to decide whether the current acoustical behaviour of a road section is relevant, with respect to noise protection. This supports the road administrators in their decision as to whether a road section has to be prioritized, concerning road maintenance for noise protection reasons. The ZRN can be set for an entire road section of several kilometres. The niveau is applied for each 100m road section in the PMS.

According to road administrations, PMSs are capable of handling separate lanes. The measuring or evaluation data of separate lanes should not be merged within the database. For analysis and review purposes of large road sections, algorithms can be used to derive a global grade for rating. The algorithm could be based on the maximum value to show the worst case. In order to represent noise emissions or the noise impact, the averaging should be energy based and weighted by the traffic volume and composition of each lane.

A bigger concern to road administrations are the measurements on all lanes themselves. Naturally, the costs are a lot higher when measuring all lanes but there are also significant health and safety considerations that need to be addressed if measurements were to be taken at 80km/h in passing lanes. Therefore, the question arises if the acoustic rating of a road section can be carried out in a reasonable way with just the data of the right lanes.

Where the renewal of the road surface wasn't too long ago and was implemented on all lanes at the same time, the differences between the lanes will be negligible. In time, the acoustic deterioration of the right lane is higher than of the others because of HVs. Using just the data from the right lane for the entire road would be a bit pessimistic regarding the noise impact but could still be considered a worst case.

When the surfaces of single lanes are replaced, it becomes a lot more complicated. One way to avoid measuring all lanes would be to incorporate an aging model into the PMS in order to track the acoustic deterioration of each lane. For this, the traffic volume and composition is needed for each lane. The aging effect of low noise road surfaces is investigated, quantified and modelled in WP 2.

6 QUESTIM WP 4: Monitoring the acoustic performance of noise barriers

6.1 For new barrier installations

It is recommended that some form of assessment is undertaken as a form of project sign-off, to check compliance with contract requirements, or conformity-of-installation of the barrier or to ensure that the noise barrier is fit for purpose.

Such checks will serve to primarily provide an indication as to whether the product has been correctly installed in accordance with manufacturer/supplier instructions or is compliant with the intended design. If this is the case, then the intrinsic acoustic performance[4] of the barrier should, in principle, be in line with the values declared as part of the product's CE mark.

[4] The acoustic performance of the materials/components from which the barrier is constructed rather than the noise reduction experienced at noise sensitive receivers screened by the barrier.

Visual inspections are recommended as the minimum requirement, supplemented if necessary by acoustic assessments. The following paragraphs provide further details.

Visual inspections: Wherever possible, visual assessments should be performed using the manufacturer's installation instructions as a guideline for defect detection. Depending upon the type of noise barrier and the expertise of the assessor, this would be expected to identify obvious physical defects in the installed product that may require correction before the installation can be accepted or is deemed fit-for-purpose.

- Timing of inspections: The undertaking of a visual inspection during the installation of the barrier can help to ensure that any potential defects are quickly identified, allowing them to be rectified or prevented from being repeated elsewhere on the barrier. However, if inspections at that time are impractical or are considered unnecessary, then when used for project sign-off/acceptance, the inspection should ideally be taken as soon as possible after completion of the installation, preferably within 1–2 months.
- Quantity of the barrier to be inspected: A visual inspection of the whole length of the installed barrier is preferable, ideally on both sides (the latter point may be particularly necessary if sound absorptive barriers are installed and different materials are visible on each side), e.g. sound absorptive materials on the traffic side protected by a membrane and timber planks on the rear face. If such a comprehensive inspection is impractical or considered unnecessary, then randomly selected sections should be inspected.
- If direct access to the barrier façades is not possible, the level of detail of the inspection will be reduced; in such instances, a drive-by inspection will allow only the most visible flaws/defects (if any) to be identified but only on the visible façade of the barrier.
- What to look for: The following is a summary of key areas that should be addressed by the visual inspection, although this list is not exhaustive. Other areas of focus may arise, depending upon the type of barrier, the method of construction, etc.
    - Physical defects in/damage to the materials that comprise the acoustic elements, including any membranes that are used to protect sound absorptive materials and that are directly exposed to the elements.
    - The quality/correct placement of seals between the acoustic elements or between acoustic elements and posts.
    - The stability and alignment of posts (if used).
    - The quality of fastenings (if any) used to secure acoustic elements.
    - The quality/correct placement of gravel boards and/or ground level seals.
    - The quality, alignment and fitment of doors, access gates, etc.

Acoustic assessments: There are several reasons for performing on-site acoustic assessments as follows:

- To verify compliance with declared performance specifications. This may be particularly important in situations where a barrier is installed using acoustic elements that are constructed on site from 'loose' component materials rather being prefabricated/acoustic elements (such as might be the case for some timber barriers).

- To identify the potential impacts of defects picked up during the visual inspections, relative to declared performance specifications. This would identify whether the defects were acceptable or would need to be rectified.
- To establish the consistency of installation of a barrier on a given scheme.
- To provide baseline data for performance monitoring over the lifetime of the noise barrier.

It is envisaged that the first two of these reasons will be the primary reason that NRAs perform acoustic assessments.

- ***Methodology***: If the objective is to assess performance against declared intrinsic performance characteristics, then acoustic assessments should be performed using the in situ test methods within the EN 1793 suite of standards (e.g. EN 1793-6 for airborne sound transmission [29] . If the objective is to assess the effectiveness of the barrier in reducing noise levels at noise sensitive receivers, then a methodology such as that set out in ISO 10847 [30] should be used.
- ***Timing of assessments***: Measurements can be taken during or as soon as possible after completion of the installation, preferably within 1–2 months. If it is plausible to conduct these measurements prior to the opening of a new road scheme or the removal of any traffic management in place for the barrier installation, this is advantageous as performing assessments once the road section is fully open to traffic may be problematic for logistical reasons.
- ***Quantity of the barrier to be assessed*** (assessment of intrinsic characteristics only): There is no standardised approach for determining the quantity of a roadside barrier to be assessed; the approach adopted may be subject to budget constraints or influenced by the proposed use of the data collected. The ability to perform in situ sound transmission measures will also be strongly influenced by the availability of access to the rear of the barrier.

  In the majority of cases, as it is proposed that acoustic measurements are used to supplement visual inspections, it is expected that measurements at only one or two positions will be required, at random locations along the barrier; if the visual inspections identify obvious defects that might affect performance then additional measurements should be taken at one or two of these positions so that the resulting measurement report would indicate typical performance and a 'lower limit' defined by the faulty sections.

  If a more detailed assessment is considered necessary, it is suggested that these should be performed at regular intervals along the length of the barrier, e.g. every 100m, covering sections of the barrier spanning between 2 or 3 adjacent posts, subject to the availability of access to both sides of the barrier.
- ***Costs:*** The use of the in-situ assessment techniques in the EN 1793 suite of standards is largely confined to research and is therefore not currently commonplace for post-installation checks at the roadside. Indicative cost information is therefore unavailable. However, in principle, two people should be able to perform measurements on multiple panels within a single working day, depending on their position relative to one another and the topography of the site. It should be noted that, depending upon the position of the barrier relative to the road, such measurements may require the use of traffic management, which would increase the overall cost.

6.2 Monitoring condition and performance over working lifetime

Monitoring of the condition and potentially the acoustic performance of noise barriers over their working lifetime will be necessary for NRAs to ensure that the barriers remain robust, intact and fit-for-purpose.

It is expected that the type and frequency of such monitoring will, in reality, be driven by a combination of costs, logistics and barrier maintenance/replacement strategies implemented by individual NRAs, irrespective of any guidance or recommendations proposed within the framework of this project. Manufacturer guidelines (which are a requirement in the durability standards) will provide guidance on both installation and the measures that should be undertaken to maintain their products in order to achieve the maximum possible working life and to maintain performance.

Visual inspections are recommended as a minimum requirement. Unless there is a need to examine the acoustic performance of damaged elements based on the outcomes of visual inspections, acoustic assessments to provide supplementary data may only be required if the acoustic performance of the materials used for the acoustic elements is expected to degrade over the working lifetime. The following paragraphs provide further details.

Visual inspections: These inspections will seek to identify physical defects that were not previously present. If inspections highlight damage to/defects on a noise barrier that are considered likely to have an adverse effect on its ability to effectively screen noise sensitive receivers, then acoustic assessments may be required to supplement the inspections.

- ***Frequency of inspections***: It is recommended that visual inspections of noise barriers should ideally be undertaken on at least an annual basis, irrespective of type/materials.

  However, if this is not considered practical, then inspection frequencies should be informed by the type of barrier and their location. For example, barriers constructed from natural materials such as timber may require more frequent inspection than those constructed from materials such as metal or concrete. Similarly, barriers exposed to harsher climatic conditions or which are more exposed to splash and spray from traffic may require more frequent inspections than those in more sheltered environments.
- ***Quantity of the barrier to be inspected:*** The recommendations here are the same as for newly installed barriers, i.e. visual inspection of the whole length of the installed barrier is preferable, ideally on both sides. If such a comprehensive inspection is impractical or considered unnecessary, then randomly selected sections should be inspected.

  If direct access to the barrier façades are not possible, a drive-by inspection will allow only significant physical defects (such as physical damage missing acoustic elements or where elements are missing) to be identified.
- ***What to look for:*** The following is a summary of the key areas that should be addressed by the visual inspection, although this list is not exhaustive. (additional areas of focus may arise depending upon the barrier type/materials, the method of construction, etc.):

- The physical condition of the materials that comprise the acoustic elements, including any membranes that are used to protect sound absorptive materials and that are directly exposed to the elements.
- The condition of seals between the acoustic elements or between acoustic elements and posts and whether any seals are missing.
- The stability and alignment of posts (if used).
- The condition of fastenings (if any) used to secure acoustic elements and whether any fastenings are missing.
- The condition and placement of gravel boards and/or ground level seals and the presence of gaps/holes at the foot of the barrier.
- The condition, alignment and fitment of doors, access gates, etc.
- Structural damage caused by vandalism or impact.
- Damage caused by vegetation growth on, up against the barrier or through the joints between panels or between panels and posts.

It is important to note that the aesthetics/visual condition of a noise barrier will have an impact on the perceived performance of the barrier by members of the public, especially those at noise sensitive receivers closest to the barrier; a barrier in poor visual condition will be perceived as less effective than a well-maintained barrier, even if the level of acoustic screening provided is identical. Visual inspections are therefore just as important to ensure that physical appearance as structural integrity.

Acoustic assessments: Unless there is a need to examine the acoustic performance of damaged elements based on the outcomes of visual inspections, acoustic assessments to provide supplementary data may only be required if the acoustic performance of the materials used for the acoustic elements is expected to degrade over the working lifetime and there is a desire to monitor this.

- ***Methodology:*** If the objective is to assess performance against intrinsic performance characteristics, then acoustic assessments should be performed using the in situ test methods within the EN 1793 suite of standards, e.g. [29] . If the objective is to assess the effectiveness of the barrier in reducing noise levels at noise sensitive receivers, then a methodology such as that set out in ISO 10847 [30] should be used.
- ***Frequency of assessments (routine monitoring):*** With respect to intrinsic performance, for timber barriers or other barriers where performance might be expected to degrade, acoustic monitoring is recommended 1, 3 and 5 years after installation and subsequently every 5 years; for barrier types where changes in the intrinsic acoustic performance are unlikely, then monitoring after 1 year and then every 5 years after installation is recommended.

  With regard to determining noise levels at noise sensitive receivers, these will be much less sensitive to changes in intrinsic performance and may therefore only be required if there are significant changes in traffic flow or if the barrier sustains significant physical damage, resulting in missing acoustic elements or a significant proportion of holes; in such instances it is expected that it is more likely that the barrier would be repaired to eliminate the gaps/holes.

- ***Quantity of the barrier to be assessed (assessment of intrinsic characteristics only):*** There is no standardised approach for determining the quantity of a roadside barrier to be assessed as part of routine monitoring. The ability to perform in situ sound transmission measures will be strongly influenced by the availability of access to the rear of the barrier in the years after installation.

  In the majority of cases, as it is proposed that acoustic measurements are used to supplement visual inspections, the number of measurements will be similar to those for a barrier in new condition, as described in Section 6.1.
- ***Costs:*** The use of the in-situ assessment techniques in the EN 1793 suite of standards for in service monitoring is not currently commonplace. Indicative cost information is therefore unavailable. However, in principle, two people should be able to perform measurements on multiple panels within a single working day, depending on their position relative to one another and the topography of the site. It should be noted that, depending upon the position of the barrier relative to the road, such measurements may require the use of traffic management, which would increase the overall cost.

6.3 Factors affecting both visual inspections and acoustic assessments

The factors summarised as follows will affect the ability of NRA staff or appointed contractors to safely undertake either visual inspections or acoustic assessments (while solutions can generally be found, there may be cost implications which prohibit the work being undertaken):

- ***Site access*:** Access to the rear of the noise barrier will most likely be required in the case of acoustic assessments of the intrinsic characteristics of the noise barrier. Where access is available, e.g. via gates in the barrier or around the ends of the barrier, then the presence of vegetation or undergrowth either in close proximity to or directly up against the façade of the barrier may hinder or prevent access unless the presence of vegetation/undergrowth is managed.
- ***Traffic management/health and safety*:** Ensuring the health and safety of assessors working on their network is a key requirement for NRAs. Provision of a safe and appropriate working environment is just one factor to be considered. Where noise barriers are located at the edge of the carriageway, the ability to undertake either visual inspections or acoustic assessments (of intrinsic characteristics[5]) may be dictated by whether or not there is a hard shoulder/emergency lane present and any local requirements set by the responsible road authority or site contractor for traffic management, e.g. hard shoulder or lane 1 closures, provision of impact protection vehicles, etc.

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[5] Assessments of the acoustic properties of the materials/components from which the barrier is constructed rather than an assessment of the noise levels experienced at noise sensitive receivers screened by the barrier.

7 Discussion, conclusions and recommendations

7.1 General

Noise reducing surfaces are generally regarded as an effective and efficient way to improve the acoustic climate in the vicinity of roads. Its effect surpasses that of low noise vehicle or low noise tyre technology and, where applied, the response of the public is very positive. High noise barriers may be more effective at short distance but lose effect at larger distance. Moreover, both inhabitants and users of the road, judge them negatively because they obstruct visibility and sight of the land scape.

In spite of the clear advantages, such surfaces are applied on only a minor part of the road network. The lack of enthusiasm is most probably explained by the anticipation of higher costs involved and uncertainty about its service life.

In this QUESTIM project, we have addressed these issues and brought them into relation with planning and monitoring concepts. Since barriers remain a mitigation measure, we have included barriers in our study.

7.2 Acoustic aging of surfaces

The investigation of the aging of the acoustics performance has brought forward a large amount of experimental data on age related acoustic performance of different types of road surfaces in Europe. Already varying aging effects are observed between areas in mid and south Europe.

The Nordic countries must be regarded as a specific region due to the special winter conditions and tyre usage found there. No common effects between the Nordic countries and mid/south Europe can be found. While HVs impose the greatest wearing factor for mainland Europe roads, passenger cars with studded tyres are the destructing factor in the Nordic countries.

Road surface types that show strong negative trends in one country, seem to remain rather stable in other countries. Even within a country, significant variations are observed. Two road surfaces of the same type exposed to similar traffic loads, applied under similar conditions, may exhibit up to a factor of three difference in acoustic performance loss per year.

Positively, in the majority of cases, acoustic loss per year remains below 0.5dB/yr. for a mixed traffic fleet. It was found that the aging effect for HVs is generally lower than for LVs. This can be understood from the higher contribution of propulsion noise and the lower sensitivity of HV tyres for texture degradation.

Dense surfaces (such as SMA, cement concrete and AC surf) show steady acoustic performance over the years. Porous surfaces tend to lose their reduction effect more quickly but, in general, noise reducing performances remain observable over a service life of 10 years.

It was found that although semi dense thin surface layers (TSL) perform impressive when new, they tend to lose their effect within an eight year period.

The cause and nature of the acoustic degradation is investigated by studying the spectral changes in the traffic noise over time. A distinction is made between HVs and LVs.

Two mechanisms are identified as follows:

1. Noise increase due to texture degradation as it manifests itself as a gradual increase in the lower frequency range
2. Noise increase due to filling up and clogging of (semi) open surfaces as can be noticed from the level rise at mid and higher frequencies.

In several situations of HVs on TSL and 1L-PAC, a rise at low frequencies, combined with a decrease at high frequencies, was observed. The cause of this is not yet understood.

An attempt was made to model the deterioration effect based on objective parameters. From the total data, we were able to isolate data sets that comprised enough data points and usage data to perform a multi-regression analysis that could lead to a prediction model for the time related acoustic performance.

The data provided several indications that the intensity of HVs is an important deteriorating factor. Multi parameter statistical analysis revealed that the HV intensity stood out as a significant explaining parameter. Also, comparison of slow and fast lanes, revealed distinct differences; generally, the HV used slow lane performed worse. In the few cases where such an effect could not be noticed, we found that the local traffic situation forces HVs to use the fast lane more often.

Very surprisingly, one of the most significant parameters we found is the initial performance of the road surface. A road surface that performs better than average when new, remains better than average during its service life. The relevance of HV intensity was second to this.

However, half of the variation could not be explained; typical residues are in the order of 0.6dB, and the prediction model for the HV performance of single layer porous asphalt completely failed. This non-explained part can be traced back to variation in material properties, experiences and skills of the road builder and specific effects of the location. Indications for these causes are found, but no numerical value can be attributed to it.

The parameters and their influencing coefficients are presented in Table III. For a more rigorous treatment, refer to [14] .

The interpretation of acoustic aging of surfaces is performed differently in various countries. The EU CNOSSOS calculation method, bases its road surface correction on the average effect, compared to a reference situation. Such averaging can also be used when the service life of the specific surface and the reference surface differ, as illustrated in Fig. 25.

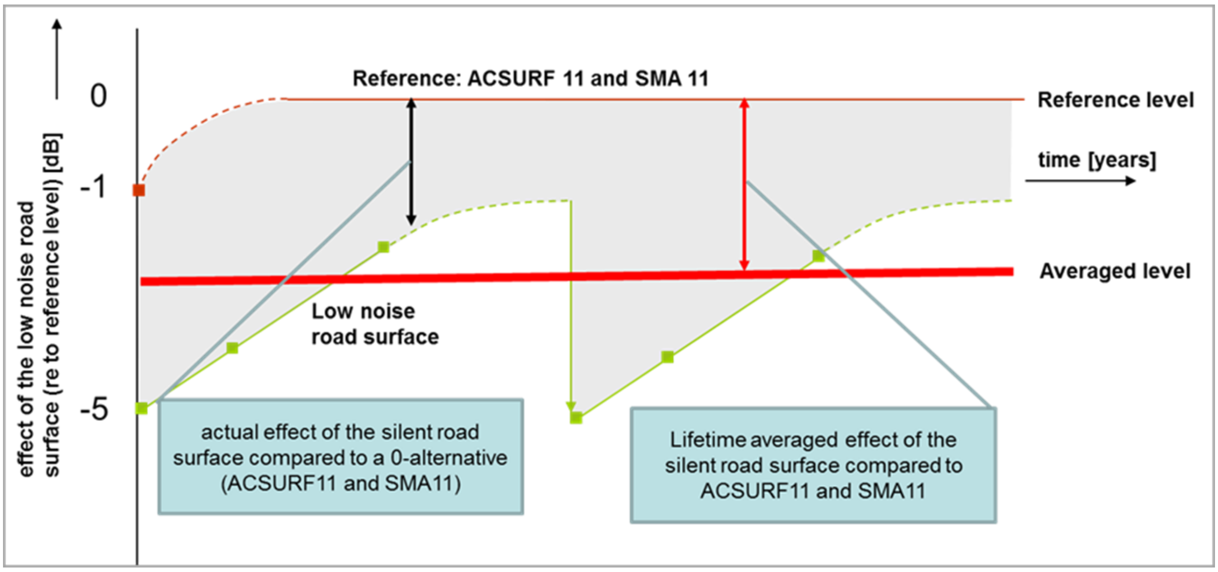

Fig. 25 Graph illustrating the different resurfacing periods for the reference and for the specific surface. In evaluating the surface the development in time of the reference surface and the specific surface must be taken into account. The example shows an initial reduction of 4dB and a time averaged reduction of 3dB

The limitation of predicting the development of low-noise surfaces requires regular monitoring of the actual performance. The CPX system (ISO 11819-2) is found to be most competent for this task. It is found relevant to reduce the number of measured data points to a smaller set that has a clear relation with the relevance of the surface condition for the sound exposure of the nearby housings. A procedure is developed for this (refer to part 7.4).

7.3 Acoustic aging of barriers and its monitoring

Noise barriers can suffer from a reduction in acoustic performance over their working lifetime, but this is for the most part restricted to the intrinsic properties of the materials, with the performance of the barrier in terms of noise levels at noise sensitive receivers being screened by the barrier largely unaffected unless there is significant physical damage to the barrier or acoustic elements are missing/removed.

Any changes in intrinsic acoustic properties are dependent upon the materials used for the construction of the barrier, the quality of the construction and the operating environment. Many existing noise barrier products on the market are not considered to degrade acoustically, although timber barriers are considered to be the most susceptible.

The work within QUESTIM has highlighted that the way in which road authorities, specify, procure and monitor the performance of noise barriers on their networks varies considerably. It has also identified that there is a lack of published data on the long-term acoustic performance of noise barriers.

The QUESTIM project therefore recommends visual inspections as being the minimum requirement for barrier monitoring, both following installation and over the working lifetime, as this will allow the most significant defects to be readily detected. The need for acoustic assessments and the methodology used will depend upon the individual requirements of a road authority but are recommended where:

- There is a need to demonstrate compliance with specified performance criteria.

  This might be in terms of declared intrinsic performance by a manufacturer or modelled/ predicted insertion loss performance (the difference in noise level with and without the barrier) at noise sensitive receivers. For example, it is the experience in the Flemish Road Directorate ref. [31] that barrier insertion loss is generally below theoretical expectations.

- To identify the impacts of defects identified by visual inspections.

  Based upon the expertise of the project team, the QUESTIM project has proposed procedures for in-service assessment of noise barriers and, in the case of visual inspections, identified characteristics/properties for an assessor to specifically look out for. The frequency of such assessments should be informed by the materials used and their location.

It is acknowledged that the test procedures proposed for acoustic assessments are *existing standardised methods* and that new or innovative methods have not been developed within the framework of QUESTIM.

This is because any testing method used must provide results that are directly comparable to/have a well-defined, robust relationship with results from the standardised test methods. To date, research has not yet identified alternative (simpler) procedures that can satisfactorily achieve this, particularly for the intrinsic performance test methods, and that was not the scope for undertaking such investigations within the framework of QUESTIM.

Fig. 26 Barriers are made of different materials and vary in their appearance

The standardised intrinsic performance test methods were designed to be applicable in real-world scenarios and can indeed be applied to testing noise barriers installed at the roadside. However, logistical, safety and cost reasons that are outside the scope of the EN standards mean that the tests cannot always be readily performed over the working lifetime of a barrier other than during the construction phase when the necessary site requirements might already be in place. As such, for those road authorities who wish to have a quantified understanding of how defects affect the acoustic performance of barriers on their networks, there exists a need for valid alternative test methods to be identified.

7.4 Monitoring of acoustic performance of road surfaces

QUESTIM WP 3 developed a procedure for evaluating the acoustic performance of road surfaces. As preferred measuring method the CPX method was chosen that enables continuous monitoring of long distances. Based on experimental data of long distance monitoring and taking into account the implication of road surface inhomogeneity's for the noise exposure in the environment an aggregation and evaluation method was developed. The evaluation length is 100m, a length adopted from general PMSs. In order to aggregate the detailed CPX data two alternatives were developed:

1. The acoustic value attributed to that 100m section is based on median averaging over a fixed length of 500 m around this section (so section *i* is based on the median of section *i-2, i-1, i, i+1* and *i+2*). The length of 500m is an optimum based on evaluation of several long stretches in rural and in urban areas).
2. The acoustic value of the 100 m section is based on the median of a relevant noise section whereby its length is defined by the actual distance to the surrounding houses. Short distances lead to short relevant noise segments, while houses at large distances averaging will take place over a much longer sections.

Afterwards a peak filter and rounding to 0,5dB is applied to both alternatives. The aggregation supresses local fluctuations that are insignificant for the noise impact, but still sensitive enough to detect sudden changes, e. g. of the surface.

The desired acoustic quality is defined as a ZRN and mapping the aggregated levels against this ZRN shows the possible deviation. A ZRN does not necessarily have to be a fixed value. It can be defined depending on the required acoustic quality in the environment or the expected performance of the chosen low noise road surface. The latter can be defined as a function of age to detect any deviation from the expected aging. Such deviation can then be inputted to a PMS and may lead to rescheduling any maintenance or resurfacing of the road.

Generally CPX monitoring takes place in the slow lane where most of the traffic concentrates and where the more noisy HVs run. The contribution from the adjacent lanes however cannot be neglected though and also it cannot be assumed that the condition of the slow lane is similar to that of the other lanes. We observed that the middle and fast lanes do deviate considerably from that of the first lane, usually being in an acoustically better condition. However, safety considerations may prevent testing in the other lanes and in those cases a standard aging prediction including its uncertainty has to be applied.

7.5 Planning and managing of low noise surfaces and barriers

In QUESTIM WP 5 data are presented on the benefits of reducing environmental noise exposure. Benefits originate from savings on health issues related to high noise exposure and on the willingness to pay for an improved noise climate in residential housing (hedonic pricing). The overall social costs, associated with the exposure of the European population to traffic noise, are estimated at € 40 Billion per year and external costs may increase to € 20 Billion in 2015.

A reliable cost-benefit tool is key in planning and managing road network maintenance and while section of most road networks will not be resurfaced on the basis of noise it would be beneficial, especially in cases where noise is a sensitive issue, to understand the cost-benefit impact of various noise reducing options. The integration into existing PMSs of a prediction formula for the time related acoustic performance of road surfaces, such as that developed in WP 2, can allow the noise impact of various road surfaces to be assessed at the planning stage without having to complete a full environmental assessment. In this way the optimal surface type may be selected, that gives the best balance between the profits for the environment and the costs of the road owner.

The QUESTIM project has created a new, proof-of-concept methodology illustrating how this integration might work in practice, and provided a worked example. It highlights all the different ways in which integrated information may be used including being able to look at where to intervene, when to intervene, what forms of mitigation to consider given a fixed intervention point and even just the expected noise impact of intervention which has already been decided.

Uncertainties in the method largely arise from the quality of the input data covering road traffic information, road surface acoustic properties and geospatial information on noise sensitive receivers. However, if the implementation is well handled it should be possible to derive valuable noise estimates for planning from even fairly sparse levels of data. For example, use of a prediction formula for the acoustic properties of the road surface negates the need to take detailed measurements.

The full implementation of the noise functionality into a PMS will naturally depend upon the format of the PMS and noise data being used and would comprise a not insignificant amount of effort in software development for the road authority.

The European Noise Directive intends to evaluate and communicate the extent of noise pollution through the realisation of noise maps and noise action plans, every five years. The effectivity of the executions of the actions defined in the action plans can be improved drastically when noise is added as a parameter to the planning and managing of the road network. Such links can be established through the PMSs already in use by NRAs for their road network.

The noise maps already comprise of extensive road network data and through a direct link with the source receiver relations included in the noise maps, target qualities can be defined for the PMS.

8 Conclusions and recommendations

8.1 Conclusions

- Noise reducing surfaces are an effective and efficient method to mitigate environmental noise even when reduced service life is taken into account.
- For through roads they can be regarded as a reliable instrument to improve the quality of the environment.
- A reliable cost-benefit tool is key in planning and managing road network maintenance and while section of most road networks will not be resurfaced on the basis of noise it would be beneficial, especially in cases where noise is a sensitive issue, to understand the cost-benefit impact of various noise reducing options.
- The management of the surface over its repeated surface life with input from regular monitoring helps to achieve the environmental targets during its repeated service life.
- The acoustic monitoring of road surfaces is important in order to establish a comprehensive knowledge base with respect to the long term acoustic behaviour of road surfaces and types of road surfaces. Without such information the decision-making process in road building and road maintenance in consideration of noise protection issues is uncertain and runs the risk of either jeopardizing noise protection requirements or being inefficient. Acoustic monitoring also helps to learn from the road surface acoustic behaviour with respect to road pavement materials, laying processes and long term stability under the influence of traffic, weather conditions and winter services. This establishes the opportunity to decide for particular material and mixture properties, laying methods and maintenance strategies in order to improve the reliability and efficiency of noise reducing road pavements.
- Introducing tyre/road noise excitation as a new attribute within the PMS requires a somewhat modified perspective on how this attribute should be implemented. In contrary to the existing attributes like skid resistance, evenness, crack formation etc., noise is not a functional property of the road that concerns the road user and his expectations and requirements with regard to safety, human health and goods protection and comfort while driving on the road. The noise attribute focuses on environmental issues outside the well-defined area of the road. Noise protection requirements change permanently along the road depending on the land use and to what extent the acoustic performance of the road surface is expected to contribute to the noise mitigation. Therefore, the categorisation of acoustic measuring results needs to be related to the noise protection requirements the NRA is obliged to.
- Noise barriers, often seen as an alternative to noise reducing surfaces, are generally designed to require minimal maintenance. Acoustic degradation most readily affects the intrinsic properties of a noise barrier but not necessarily its performance at noise sensitive receivers.

  Degradation most commonly manifests in terms of changes in the structural integrity of the barrier and its physical condition/aesthetics. Regular visual surveys are therefore recommended with the need for any acoustic testing generally depending upon the requirements of the road authority.

- Where significant damage or vandalism occurs, resulting in major damage to or removal of acoustic elements, this may affect noise levels at receivers screened by the barrier and it is important that prompt remedial action is taken – this is not currently always the case and barriers can remain with sections being unfit for purpose for considerable periods of time unless the structure is deemed to be structurally unsound. It is noted that a barrier in poor condition may be perceived as being less effective by those residents being protected even if practical assessments prove this not to be the case.
- With the changing nature of how individual road sections are operated, e.g. the introduction of smart motorways in England which will in some instances remove the presence of an emergency lane, it would be advantageous if test methods could be implemented without the need for operators and/or equipment to be static on the carriageway side of the barrier.

8.2 Recommendations

1. Further work in understanding the causes of early acoustic failure of road surfaces is absolutely necessary. The large non-explained fraction in the variation analysis shows that there are a series of causes of early failure that are not yet identified. The consequence is that it is difficult to optimize the surface. Development of improved material technology and laying procedures will increase service life and reduce costs. However expectations cannot be met when the causes of break down are not better understood.
2. It is very unfortunate that spectral data is scarcely available. In most areas in Europe acoustic measurements only result in total levels, although the technology to assess spectral distribution is widely available. With modern computers, the processing of spectra data does not involve more work and most important with about the same effort a lot more relevant information can be produced. The limitation of spectral data hampers the identification of aging mechanisms in other areas in Europe. Only with spectral data one is able to identify acoustic aging processes.
3. The most promising way of implementing the noise aspect into a PMS is to base it on the application of the CPX-method. By means of CPX measurements large infrastructures can be monitored in a complete and consistent manner. In order to make it also the most efficient method the CPX measurements can be restricted to the first lane of a road section and to sections which run along built-up and noise sensitive areas only. Undeveloped areas should not be subjected to acoustic monitoring. Adjacent lanes are as important as the first lane with respect to the noise emission of a road section. In order to account for their contribution to it and to include them into the evaluation of the acoustic condition of the entire road section, the acoustic condition of adjacent lanes can be derived from the acoustic condition measured on the first lane by applying the road surface aging model developed in WP 2.

4. A database system that allows the CPX data to be related to geospatial information and to be synchronized with official roadway points in a systematic and consistent way should be pursued in order to make acoustic data easily available for NRAs.
5. The application of monitoring with the CPX standard (ISO/DIS-11819-2) requires two essential components:
    a. A standardization of the test tyres. The total uncertainty of the system is for about 50% caused by the variation in test tyre properties.
    b. More regular monitoring in different areas in Europe requires a reliable normalization to a reference temperature. The procedure for doing this still lacks in the present procedure.
6. Integration of the acoustic quality of road surfaces into PMS (or generally AMS) in form of categorical data with respect to the necessary noise protection in sensitive areas – essentially a grade for the surface's noise based on its condition and caused noise impact.
7. The acoustic road surface effect is a part of the total road vehicle sound emission. The development towards a common European procedure to establish environmental noise levels thus requires a common procedure to establish this effect based on proven measurement standards. This has to be developed within the framework of the CNOSSOS project. The present situation is that different countries use different procedures leading to very different values for the correction coefficients.
8. The practicalities of applying the standardised intrinsic performance test methods at the roadside to assess noise barriers mean that there is potentially the need for alternative, simpler test methods to be identified or developed, e.g. the application of acoustic cameras, laser scanning, etc. Research would need to be undertaken to determine the relationships between the results from such tests and the standardised tests used by barrier manufacturers to declare performance. Relationships on performance in the far-field should also be investigated.
9. Further practical data are required on the long-term intrinsic acoustic performance of noise barriers, even though many noise barrier products are not currently considered to acoustically degrade over time. The introduction of CE marking under the Construction Products Regulation and the forthcoming revision of acoustic durability standards might perhaps go some way towards achieving this (although declared durability performance may well be based on expert judgement rather than practical testing). Whilst some manufacturers may choose, going forwards, to monitor barriers that they install, it may well fall upon individual road authorities to undertake their own lifetime monitoring programmes for barriers on their networks, using appropriate test methods.

    However, the development of a robust intrinsic acoustic durability relationships will require the collection and collation of suitably comprehensive datasets which may be outside of the capacity of any single NRA. However combined NRA efforts and industry involvement as outlined below might help achieve this.
10. Further practical data are also required on how noise barriers perform according to the new in-situ test methods. Manufacturers will be required to declare such performance once the relevant EN standards are introduced into the European harmonised specifications for noise barriers, but the wider availability of the published data is

considered beneficial in assisting road authorities in understanding and selecting appropriate, acoustically durable noise barriers for use on their networks. It is considered that the collection and collation of such data is most likely outside of the responsibilities of national road administrations, although individual, internal databases may be established by administrations, e.g. as an additional component of PMS. The QUIESST project has already established a public database of useful performance database (although this does not identify nor attribute characteristics to specific products/systems) and it has been suggested that involvement of industry bodies such as the European Noise Barrier Federation might be a means of expanding and maintaining such a database.

11. It is recommended that NRAs should build experience in building upon on the implementation of acoustic target quality and warning/intervention levels in PMSs. It is expected that different NRAs would have differing budgets, PMSs, timescales and requirements for maintenance but that lessons learned in fully considering noise in maintenance planning could be shared.

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