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Technical Report 2017-01
State of the art in managing road traffic noise: noise-reducing pavements

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This report was drawn up by **CEDR Task Group Road Noise**. The main authors were;

Mr Hans Bendtsen (Danish Road Directorate)

Mr Klaus Gspan (Asfinag Austria)

With contributions from the following countries and people:

Austria	Mr Christof Rehling
Belgium	Ms Barbara Vanhooreweder and Mr Sébastien Marcocci
Cyprus	Ms Elena Sophocleous
Denmark	Mr Jakob Fryd
Estonia	Mr Villu Lükk
Greece	Ms Efterpi Giannopoulou
Ireland	Mr Vincent O'Malley and Mr. Stephen Byrne
Italy	Ms Patrizia Bellucci and Mr Alberto De Leo
Netherlands	Mr Wiebe Alberts, Mr Nico Faber and Mr Michiel Roebben
Norway	Ms Helena Gabriella Axelsson
Poland	Mr Łukasz Łach and Mr Piotr Buczek
Spain	Ms Rosa María Izquierdo López
Sweden	Mr Lars Dahlbom
United Kingdom	Mr Ian Holmes

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1 Executive summary

The main purpose of this Technical Report is to make knowledge on noise-reducing pavements from several CEDR member countries available to all the countries. The report primarily focuses on the collection, dissemination, implementation and use of results from research and development of noise-reducing pavements from recent innovative research projects undertaken within specific CEDR member states. The report can be seen as a handbook presenting the European state of the art in the mid-2010s. The target group for this report is road engineers, planners and decision makers.

In 2013, the CEDR noise group highlighted that the most cost-effective tool for noise abatement in relation to the society economy is reduction of the noise emissions from new vehicles and tyres [1]. This was closely followed by the use of noise-reducing pavements which also proved to be very cost-effective for the societal economy. National road authorities (NRAs) generally have more limited influence on which vehicles and tyres that are using the road network but NRAs make the decisions on which pavements to use on new roads as well as when renewing the existing road network. Therefore noise-reducing pavements can be used by NRAs as a tool of noise abatement.

The tyre road noise is generated by the contact of the tyres to the pavements. At speeds over 35 km/h the tyre road noise is the dominant noise source for passenger cars and for speeds over 60 km/h for heavy vehicles. Therefore, the pavements are important for the noise on both urban roads with speeds around 50-60 km/h as well as on national roads and motorways with higher speeds. The generation of noise when the tyres are rolling on a road surface is mainly determined by tyre characteristics, vehicle speed as well as the surface texture and properties of the pavement. According to the knowledge of the authors no precise models are currently available that can be used to adequately predict tyre-road noise on the basis of detailed measurements of the pavement surface texture and other surface related properties.

For an NRA, it is the pavement surface texture that essentially defines the level of tyre-road noise emission from a trafficked road. This gives a series of possibilities and challenges for the pavement design engineers. Noise is an important issue but there are also other pavement functions and factors that should be taken into consideration when developing and using a new pavement type or an improved version of an existing pavement type. A comprehensive and multidisciplinary approach is needed. Relevant functionalities and factors are:

1. noise reduction, and lifetime of noise reduction;
2. rolling resistance (influence on energy consumption and CO_2 emissions);
3. friction (important for traffic safety);
4. drivers comfort (splash and spray), more silent inside vehicle;
5. traffic safety (aqua planning, wet grip, splash and spray and visibility of road markings);
6. cost of pavement;
7. lifetime of pavement;
8. maintenance operations if needed;
9. winter maintenance;
10. restrictions on practical application on roads.

Throughout Europe, there can be national and regional variation in the accessibility of materials, the tradition for pavement design and experiences in the contracting sector. Therefore, pavements that are called the same might vary both in how they are constructed and how they perform in relation to noise and other functionalities.

2 Table of contents

3 Preface

This report from the CEDR Task Group on Road Noise primarily focuses on the collection, dissemination, implementation and use of results from research and development of noise-reducing pavements from recent innovative research projects undertaken within specific CEDR [2] member states. The main purpose of the report is to make such results available and known to all the CEDR member countries so they can be used for implementation when considered relevant. The report can be seen as a handbook presenting the European state of the art in the mid-2010s. The target group for this report is road engineers, planners and decision makers. It is not a report written for specialists in pavement acoustics and pavement technology.

The report is produced in the framework of the third CEDR Task Group Road Noise, working from 2013 to 2016. A small subgroup have written the report on background material supplied by the members of the third CEDR Task Group Road Noise as well as following discussions on relevance and implementation potential within the noise group. The main authors are:

- Hans Bendtsen, Danish Road Directorate
- Klaus Gspan, Asfinag Austria

The authors would like to thank all the other members in the CEDR Task Group Road Noise for their contributions, which have made it possible to produce this report.

4 Definition of the issue of noise-reducing pavements

4.1 Goals, objectives and working method

In recent years, a wide range of innovative noise research projects addressing different aspects of noise-reducing pavements has been undertaken by some CEDR member states. Results generated may be of great interest to other CEDR member states. In many cases, these results are only implemented in the member state that has undertaken the research.

This report primarily focuses on the collection, dispersion, implementation and use of results on noise-reducing pavements from recent innovative noise research projects undertaken within specific CEDR member states. Results and recommendations from the first and second CEDR Task Group Road Noise will be included where relevant. The report also considers how noise-reducing pavements can be used as a mitigation measure for noise abatement implemented during the planning, construction and maintenance stages for new and existing road infrastructure. The focus is on how to manage road traffic noise in a cost-effective manner and how to improve environmental noise quality along national roads. The main goal of the report is to collect and disseminate information on results of recent innovative noise research within CEDR member states.

A comprehensive review of recent research projects on noise-reducing pavements in the various CEDR member states have been performed by the members of the third CEDR Task Group Road Noise. The results are presented in this report, together with relevant and needed background information. The report can be used as a handbook presenting the latest information on noise-reducing pavements in Europe. The limitation of the report is that it is based on the information that the CEDR Task Group Road Noise was able to collect in the period of 2013 to 2016. There may be other projects and results that the task group has not encountered.

4.2 Background

In June 2002, Directive 2002/49 relating to the assessment and management of environmental noise (called END) was adopted by the European Parliament and the Council (EC, 2002) [10]. The END aims to “define a common approach intended to avoid, prevent or reduce on a prioritised basis the harmful effects, including annoyance, due to the exposure to environmental noise”. One of the underlying principles of the END is to monitor the environmental noise problem, by requiring competent authorities in member states to prepare strategic noise maps for major roads, railways, airports and agglomerations. These maps also give information on the number of people exposed to (road traffic) noise throughout Europe. In 2007, the EU countries made their first END noise maps and in 2012 their second END noise maps.

According to the report ‘Noise in Europe 2014’ from the European Environment Agency [29], noise pollution is a growing environmental concern. The report summarises the general impact of noise: “The adverse effects of noise can be found in the well-being of exposed human populations, in the health and distribution of wildlife on the land and in the sea, in the abilities of our children to learn properly at school and in the high economic price society must pay because of noise pollution” [29]. Some of the key messages of ‘Noise in Europe 2014’ are the following [29]:

- noise pollution is a major environmental health problem in Europe;
- road traffic is the most dominant source of environmental noise;
- environmental noise causes at least 10 000 cases of premature death in Europe each year;
- almost 20 million adults are annoyed and a further 8 million suffer sleep disturbance due to environmental noise;

- over 900 000 cases of hypertension are caused by environmental noise each year;
- noise pollution causes 43 000 hospital admissions in Europe per year;
- effects of noise upon the wider soundscape including wildlife and quiet areas need further assessment.

So, handling road traffic noise is a challenge for the European road administrations.

The END noise maps provided data on noise exposure. For (major) roads, they provided data about noise exposure for 30 European countries in 2012:

- from traffic on roads in agglomerations (see Table 4.1);
- from traffic on major roads outside agglomerations (see Table 4.2).

According to [3] there are in total about 76 million people living inside END agglomerations exposed to road traffic noise levels of 55 dB L_{den} or more (see Table 4.1). So, 43 % of the people living in these agglomerations are exposed to road traffic noise levels of 55 dB L_{den} or more.

Table 4.1: People inside and outside END agglomerations in 30 European countries exposed to (major) road traffic noise levels of 55 dB L_{den} or more in 2012 [3].

	number of people exposed by road traffic noise in 2012 in noise bands L_{den} (in million)						total inhabitants:		
road traffic on:	**55-59**	**60-64**	**65-69**	**70-74**	**≥ 75 dB**	**≥ 55 dB**	**inside agglom.**	**outside agglom.**	**EU-30 countries**
all roads inside EU-30 agglomerations	29	22	16	8	1	76	178		
all roads outside EU-30 agglomerations	28	23	9	3	1	64		337	
all roads in EU-30 countries	57	45	25	10	2	140			515
major roads inside EU-30 agglomerations	12	9	6	3	1	30	178		
major roads outside EU-30 agglomerations	12	8	5	2	1	28		337	
major roads in EU-30 countries	24	17	11	5	1	58			515

About 58 million people are living along major roads inside and outside END agglomerations exposed to traffic noise levels of 55 dB L_{den} or more (see Table 4.1). In total, some 140 million people in Europe are exposed to road traffic noise levels of 55 dB L_{den} or more. So, one out of four people in Europe are exposed to high road traffic noise levels.

It should be noted that evaluations like the one mentioned above, do not consider exceedance of road noise limit values. That is because road noise limits values vary in the different European countries. Evaluations like [2] and [29] focus on road noise exposure levels.

The main part of the European road noise problem is concentrated along motorways, regional and municipal roads in urbanised areas. For example in Denmark around 700 000 dwellings are exposed to noise levels exceeding the national Danish guideline of 58 dB L_{den} and 120 000 of these dwellings are located in close proximity to the state road network. The yearly society economical cost of the Danish road noise problem is estimated to be around EUR 500 million for a country with a population of 5.5 million inhabitants.

Figure 4.1: National motorway passing through densely populated urban area, causing noise exposure to the inhabitants.

The first CEDR Task Group Road Noise, active from 2006 to 2008, performed an investigation on how noise was handled within the National Road Administrations (NRAs) of Europe. The results were reported in the CEDR report 'Noise Management and Abatement' published in 2010 [4]. This report proposed fourteen recommendations for good governance regarding noise management and abatement for NRAs. The following four highlighted different aspects of using noise-reducing pavements:

1. The use of noise-reducing pavements should be considered when selecting noise mitigation measures, because such pavements are purported to provide a cost-effective tool in noise abatement. When upgrading existing roads, the use of noise-reducing pavements is sometimes a low cost measure of noise abatement.
2. Integration of noise as an active component in pavement management systems can increase the optimal use of noise-reducing pavements in the ongoing road pavement renewal process.
3. To enhance the current market for noise-reducing pavements, the development and use of a noise labelling system in member states should be considered. Standards for such a system should be developed.
4. There is a need for further research and development into improved and long-time durable measures of noise abatement like optimized noise-reducing pavements, tyres, vehicles etc. There is also a need for better knowledge about health effects of noise.

The second CEDR Task Group Road Noise, active from 2009 to 2012, performed economical evaluations of different tools of noise abatement. The results were reported in 'The European

Noise Directive and NRAs: Final Summary Report CEDR Road Noise 2009-2013' [4]. The results highlighted that the most cost-effective tool for noise abatement in relation to the society economy is reduction of the noise emissions from new vehicles and tyres. This was closely followed by the use of noise-reducing pavements which also proved to be very cost-effective for society. NRAs can generally not influence which vehicles and tyres are using the road network, but NRAs make decisions on which pavements to use on new roads as well as when renewing the existing road network. Therefore noise-reducing pavements can be used by NRAs as a tool of noise abatement.

4.3 Tyre road noise generation

There are two main sources of noise emitted by vehicles when driving on a road:

1. The engine and transmission system;
2. The interaction between tyres and road pavement.

Noise from aerodynamic effects does not normally play a role for road traffic.

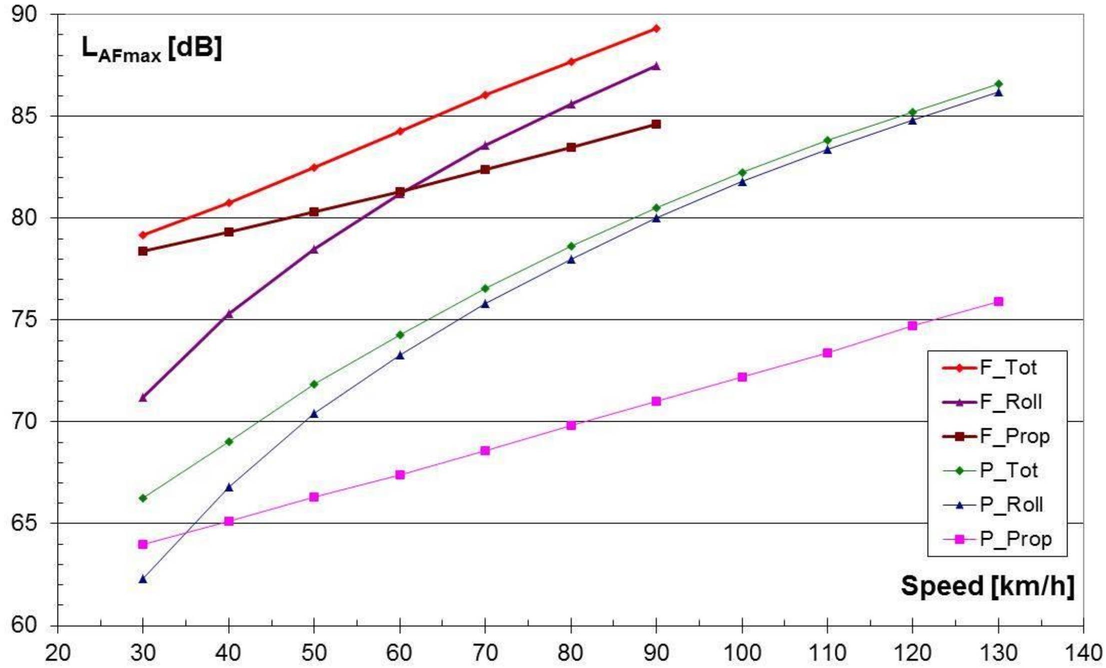

Figure 4.2: Engine noise (Prop), tyre road noise (Roll) and total noise (Tot) at different speeds for passenger cars (P) and heavy vehicles (F) [5]. Based on the Nord2000 road noise prediction method [6].

Figure 4.2 shows the contribution from the tyre road noise and the engine noise as well as the total noise at different speeds. It can be seen that at speeds over 35 km/h the tyre road noise is the dominant noise source for passenger cars and for heavy vehicles the tyre road noise is the dominant source over 60 km/h. Therefore the pavements are important for the noise at both urban roads with speeds around 50-60 km/h as well as on national roads and motorways with higher speeds.

The generation of noise from the tyres rolling on a road surface is mainly determined by the following mechanisms [11]:

- Vibrations in the tyres: The vibrations are generated by the contact between the surface of the pavement and the rubber blocks of the tread pattern of the tyre. Tyre vibrations generate noise in the frequencies from 500 to 1 500 Hz. The noise increases as the road surface gets rougher. Therefore, a decrease in the maximum aggregate size generally leads to a decrease in the noise.
- The air pumping effect: When the rubber blocks on the tread pattern of the tyre hit the road surface, air is pressed out of the cavities between the rubber blocks. When the rubber blocks leave the road surface air is sucked back into the cavities. This air pumping to the surroundings generates noise at high frequencies over 1 000 Hz. If the road surface is open or porous the air will instead be pumped down into the pavement structure and the noise will be reduced.
- The horn effect: The curved tread pattern of the tyres and the road surface acts as an acoustical horn which amplifies the road noise generated around the contact point between the tyre and the road surface. If the road surface is porous (and therefore sound absorbing) the amplification effect will be reduced.
- Absorption during propagation: The engine and tyre-road noise is propagated from the vehicles to the receivers. Under this propagation, the noise might be reflected on the road surface. If the road surface is porous and therefore sound absorbing the noise at some frequency bands will be reduced under the propagation.
- The effect of stiffness: The stiffness of the pavement is important for the determination of the noise generated by the contact between the surface of the pavement and the rubber blocks of the tread pattern of the tyre. If the pavement is elastic, the noise generated will be reduced.

Other mechanisms might also play minor a role in the generation of tyre/road noise [11]. On the background of the current knowledge, it is the general judgment by the authors, that the mechanisms mentioned above are the most important for the determination of the tyre road noise. According to the knowledge of the authors no precise models are available that can be used to predict the tyre-road noise based on detailed measurements of the pavement surface texture and other surface related properties. There is a need for further research into such relations.

As it can be seen from the above, the surface texture of pavements is very important for the generation of tyre road noise. The mechanisms for generation of tyre road noise are not fully understood today.

4.4 Noise optimization of pavements

Table 4.3 shows which properties of a pavement can be optimized in order to reduce the effect of the different noise generating mechanisms.

The noise-reducing effect of both single layer and two layer porous pavements comes primarily from a reduction of the noise generation by the air pumping effect. But the porous pavement structure also reduces the horn effect and reduces noise by absorbing noise under propagation from the vehicle to the receiver along the road. When fine graded porous pavements with a smooth and even surface are used, this also reduces the noise generated by the vibrations of the tyres. In Europe porous pavements with maximum aggregate size of 4, 5, 8 11 and 16 mm have been used.

Table 4.3: Relations between the physical structure of road pavements and the five different noise generation mechanisms.

Noise generation mechanism	Surface texture	Build in air void	Pavement thickness	Elasticity
Vibrations in the tyres	X			X
The air pumping effect		X	X	
The horn effect		X	X	
Absorption under propagation		X	X	
The effect of stiffness				X

Porous pavements are open in the whole thickness of the layer with connected cavities. Porous pavements can be constructed with one or two layers of porous asphalt. Figure 4.3 shows an example of a two-layer porous pavement with small aggregates in the top layer and larger aggregates in the bottom layer. If the built in air void of a porous pavement and/or the layer thickness is increased, this will normally reduce the noise.

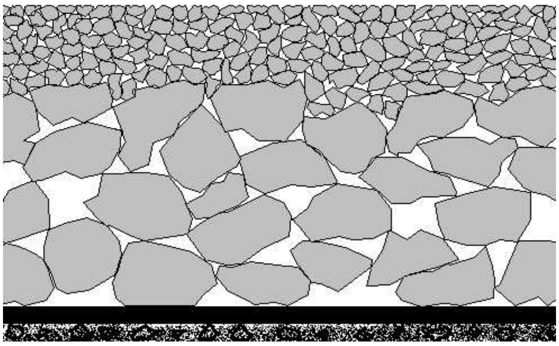

Figure 4.3: Two layer porous pavement [12].

As a contrast to this, open pavements are open only at the upper part of the pavement with cavities having a depth less than the maximum size of the aggregates used for the pavement. The basic concept of using open pavements for noise reduction is to create a pavement structure, with as big cavities at the surface of the pavement as possible in order to reduce to some extend the noise generated from the air pumping effect, and at the same time ensuring a smooth and even surface, so the noise generated by the vibrations of the tyres will not be increased. Such a noise-reducing open pavement can be thin, as the mechanisms determining the noise generation are only dependent on the surface structure of the pavement. Open but not porous noise-reducing pavements can be developed on the background of Open Graded Asphalt Concrete, SMA mixes (Split Mastics Asphalt) and other pavement types.

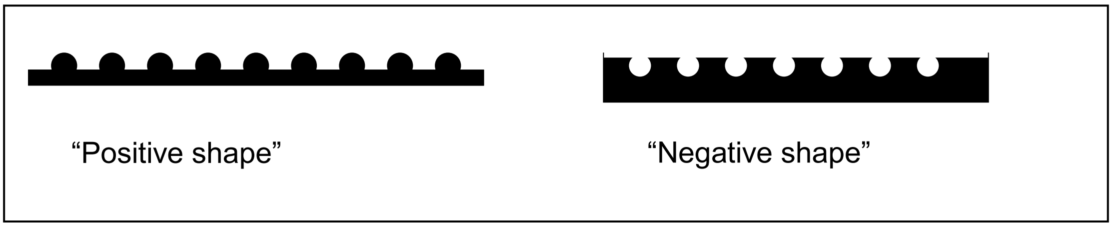

Figure 4.4: Principal sketch of pavements with "positive" and "negative" shape of surface texture [39].

Figure 4.4 illustrates two types of pavements with open surfaces texture. The pavement with a "positive" structure will increase the noise generated from vibrations in the tyre while the pavement with a "negative" structure will reduce the noise generated from vibrations in the tyre. Good compaction and cubic aggregate shape can be used to create a pavement surface with a "negative" texture.

Generally there is not a good correlation between tyre road noise and the Mean Profile Depth (MPD). In [13] an empirical framework for the description of the tyre/road noise has been suggested (see Figure 4.5). A special measure for unevenness (X) has been developed in order to describe the difference in height between the highest points on a road surface profile measured by laser over a length of 1 meter. Another measure (H) was also introduced to describe the average distance between the highest points in the road profile. Both parameters X and H are indicators for the smoothness of a pavement surface. The Mean Profile Depth (MPD) is also included in the description, as an indicator for the openness of a pavement surface.

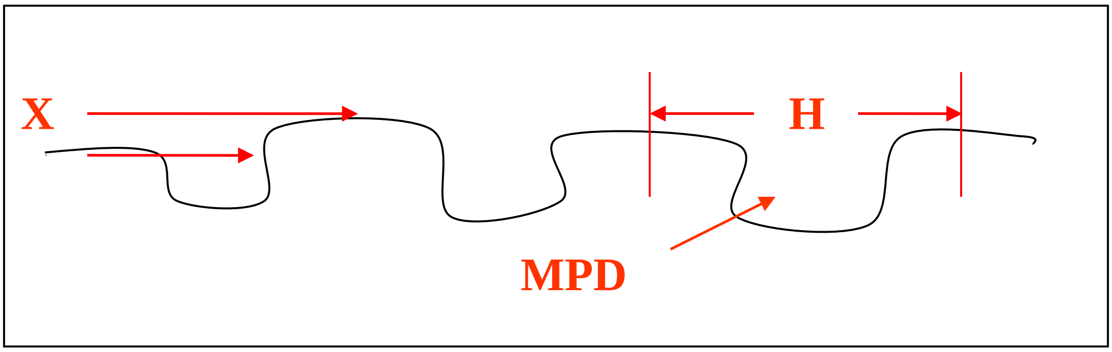

Figure 4.5: Sketch to describe the relation between road surface texture parameters and noise generating mechanisms [13].

The following has to be achieved in order to obtain as little tyre road noise as possible:

1. The highest points of a road surface should have the same height (reduce X) in order to secure a smooth pavement surface and by this reduce the noise generated from vibrations in the tyre. This can be achieved by using cubic aggregates and a good compaction of the newly laid pavement.
2. The distance between these high points should be as small as possible (reduce H) also in order to secure a smooth pavement surface and by this reduce the noise generated from vibrations in the tyre. This can be achieved by using a small maximum aggregate size
3. The cavities between the top points of the pavement surface should be as deep and big as possible (increase MPD) in order to reduce the noise generated by air pumping. This can be achieved by using a high built in air void.

Figure 4.6: Close-up photo of a newly laid SMA pavement with a very smooth and even surface texture that reduces vibration generated noise. Open cavities in the pavement surface can also be observed. These are helping to reduce the noise generated from air pumping.

Generally the noise is reduced when the maximum aggregate size is reduced. A rule of thumb is that a decrease in aggregate size of 1 mm reduces the tyre-road noise by around 0.25 dB for dense asphalt concrete and SMA anything else equal. This highlights that a noise reduction can be achieved by reducing the maximum aggregate size.

If a pavement is elastic this can also reduce the vibration generated noise. In the EU project PERSUADE so called poroelastic pavements (PERS) have developed and tested [14]. This was done by using a porous pavement with a small maximum aggregate size where a large percentage of the stone aggregates are substituted by rubber aggregates from scrapped tyres.

4.5 Tyres and noise

Together with the pavement type the tyres has an important influence on the generation of the tyre road noise. Figure 4.7 shows an example where noise has been measured on six different pavements by the use of seven different tyres. It can be seen that the range of noise for the same pavement is 6 to 8 dB, depending on the tyre. That is quite a big difference between the tyres. But it can also be seen that these different tyres generally range the six pavements in the same way in relation to noise.

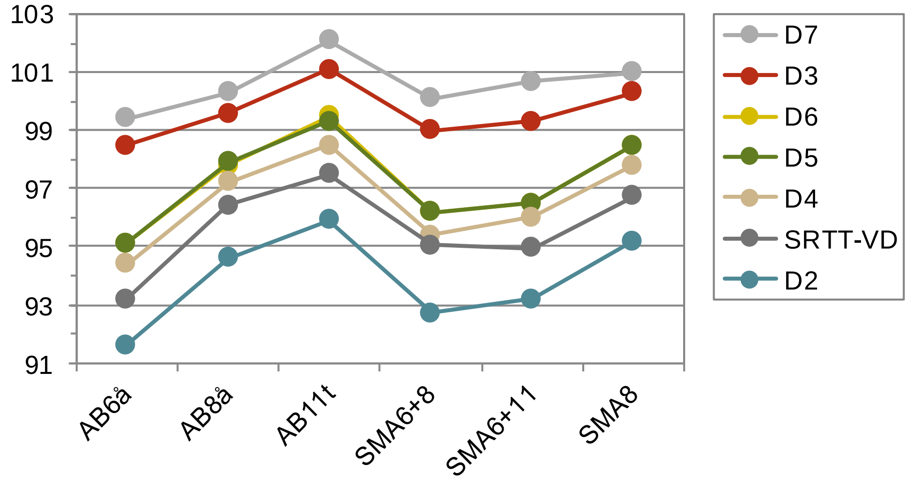

Figure 4.7: Noise measured on six different pavements using seven different tyres. Measurements performed on a Danish demonstration section with noise-reducing thin layers at 80 km/h [8].

4.6 Noise reduction for passenger cars and heavy vehicles

The tyres as well as the engines and the transmission systems are very different for passenger cars and heavy vehicles (trucks and buses). As can be seen from Figure 4.2, the noise emission for a heavy vehicle is generally around 10 dB higher than for passenger cars at the same speed. Due to the very different tyre types and tread pattern textures, noise-reducing pavements might have a different effect on these two vehicle categories. The following are a few examples for illustration.

Table 4.4 show the lifetime noise reduction for two types of single layer porous asphalt in relation to a dense asphalt concrete pavement (AC 11) on a motorway. It can be seen that the lifetime noise reduction for the heavy vehicles is slightly less than for passenger cars.

Table 4.4: Lifetime noise reduction for two types of single layer porous asphalt in relation to a dense asphalt concrete pavement (AC 11) on a motorway with a speed limit of 80 km/h [23].

Pavement	Passenger cars [dB]	Heavy vehicles [dB]
PA 8 type A	3.6	3.4
PA 8 type B	3.9	3.7

Table 4.5 shows an example of the lifetime noise reduction of three types of two layer porous asphalt on an urban road in relation to a dense asphalt concrete pavement (AC 8) [12]. The noise reduction is on average generally 0.6 dB less for the heavy vehicles in this example.

Table 4.5: Lifetime noise reduction for three types of two layer porous asphalt in relation to a dense asphalt concrete pavement (AC 8) on an urban road with a speed limit of 50 km/h [23].

Pavement	**Passenger cars [dB]**	**Two-axle heavy vehicles [dB]**
PA 8-70	2.8	2.3
PA 5-55	2.8	1.3
PA 5-90	2.0	2.0

Finally, Table 4.6 shows the noise reduction over six years of five different types of thin layer pavements on a motorway. It can be seen that for some of the pavements the passenger cars have the highest noise reduction and for others it is the heavy vehicles. In [24] there is no explanation why this could be the case!

Table 4.6: Noise reduction measured over six years for five types of thin layer asphalt in relation to a dense asphalt concrete pavement (AC 11) on a motorway with a speed limit of 110 km/h [24].

Pavement	**Passenger cars [dB]**	**Multi-axle heavy vehicles [dB]**
AC 8 open	2.0	2.7
SMA6+	1.2	0.4
SMA8	0.6	1.0
SMA8+	1.7	1.2
Special 8	0.9	1.6

From the above it can be seen that noise-reducing pavements have a positive effect on the noise for both passenger cars and heavy vehicles. There is a slight tendency that the noise reduction is less for heavy vehicles than for passenger cars.

4.7 Effect on noise of pavement aging

The tyre road noise generally increases as the pavements gets older. Figure 4.8 shows an example of the development of noise for five pavements over a ten year period based on yearly performed road side SPB noise measurements for passenger cars (see Section 4.8). It is obvious that there is an ongoing increase of noise as the pavements gets older.

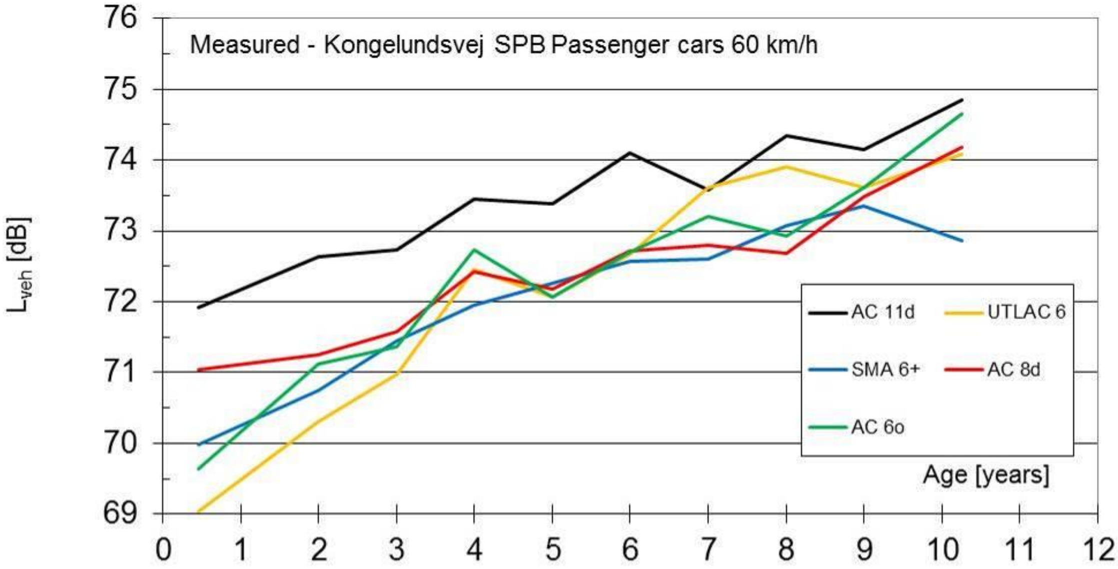

Figure 4.8: Results of road side SPB noise measurements for passenger cars over ten years on five pavements on an urban road in Copenhagen [24].

It can be discussed if the noise increase follows a linear regression or an exponential or logarithmic curve. A Danish investigation from 2014 [9] showed that the three different regressions gives approximately the same good description of the noise increase for measurement series over up to ten years with a slight tendency that an inverse exponential function gave the best description of the noise development. However, there is a lack of end of lifetime measurement series of the lifetime development of noise for different pavement types.

SUPSIL was a joint Dutch Danish project, where one of the objectives was to analyse the development of noise over time [15]. Long-time measurement series from five countries in Europe were collected and analysed. There was generally a large spread in the results. The analysis indicated that the pavement age is a good descriptor for the development of noise. The results show that the noise increase per year is higher for pavements with smaller aggregate size than for same type of pavement with larger aggregate size.

Table 4.7 presents the general average trends of noise increase that was the result of the project for mixed traffic (passenger cars and heavy vehicles) for different pavement types. The increase for dense asphalt concrete is less than for the other noise-reducing types. The QUESTIM project also investigated the development of noise over time for pavements in Europe [30].

Table 4.7 Average yearly noise increase for different pavement types based on results for mixed traffic (light and heavy vehicles) from five countries in Europe [15]. The thin layer pavement type includes pavements based on open graded asphalt concrete.

Pavement type	**Max. Aggregate size [mm]**	**Noise increase [dB/year]**	
		High speed (≥ 80 km/h)	**Low speed (50 – 60 km/h)**
Dense asphalt concrete	16	0.1	-
	≤ 11	0.3 – 0.4	0.3 – 0.4
Thin layer	10	0.2	-
	≤ 8	0.4 – 0.6	0.4
One layer porous	16	0.3	-
	≤ 8	0.3	-
Two layer porous	≤ 8	-	1.0

4.8 Reference noise level for pavements

When new road infrastructure projects are planned, impacts associated with road traffic noise are normally one of the environmental factors that are analysed and evaluated. A noise prediction method is used for noise calculations and noise mapping. Noise measurements are normally not used in most countries in the process of planning new roads [22].

Various noise prediction methods are used in the different European countries [3, 22]. For example the Nord2000 method is used in some of the Scandinavian countries [6]. Noise prediction methods have an emission part that is normally developed on the background of a large amount of noise measurements on real roads. For example in the Danish version of Nord2000 method, it has been decided to use a dense asphalt concrete with 11 mm maximum aggregate size (AC 11) with an average age of eight years as the noise reference level, because the AC 11 pavement was commonly used around year 2000 when the method was developed. This reflects the noise in the middle of the typical lifetime of an AC11 pavement. In this way, the results of the prediction method reflects the average noise over the lifetime of a pavement. For planning and administrative purposes, this is considered a fair way of predicting noise [6] and it reflects the average level of noise exposure on the neighbours to the roads.

As can be seen in Figure 4.8, and according to Table 4.7, the noise levels will be around 2 to 3 dB less in a situation with a new AC11 pavement and a few dB higher than the predicted level at the end of lifetime of the pavement. This means that by replacing an old pavement with a new pavement of the same type a noise reduction of up to 3 - 4 dB may be achieved. However, this cannot be regarded as a tool of noise abatement, as the noise from the new pavement will continue to increase with time.

In Nord2000 [6], as well as in other European prediction methods, it is possible to correct the predicted noise levels according to which of some predefined pavement types that are used. Figure 4.9 shows an example of the pavements included in the Danish version of Nord2000. The red dots shows the noise levels in year 8 that are included in the prediction method and the lines show the expected development over time of the actual noise levels [19]. It can be seen that the noise increase over time for the noise-reducing thin layer pavement (SRS) is higher than for the AC11 reference pavement and the split mastics asphalt pavements (SMA).

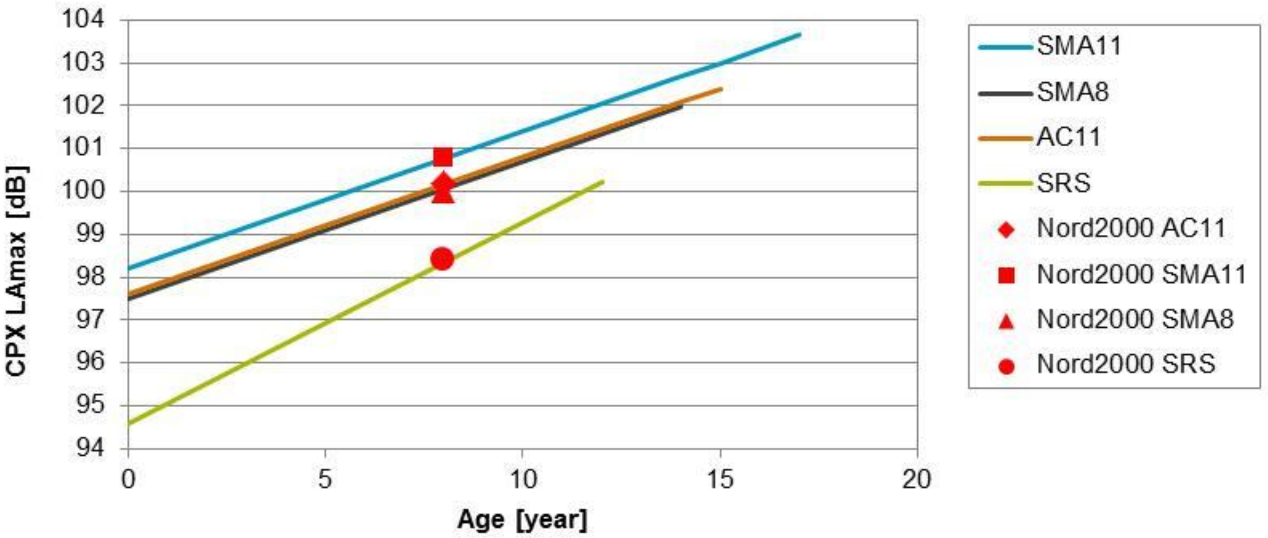

Figure 4.9: Noise emission levels in the Danish version of Nord2000 prediction method [19], at a speed of 80 km/h measured by the CPX method (see Section 4.9). The red dots show the noise levels in year 8 that are included in the prediction method.

When talking about the noise reduction of a pavement, it is very important to be precise in defining what reference pavement type (and which age) the noise reduction is defined in relation to. The reference pavement used can have a big influence on the level of the actual noise reduction that is stated. Therefore it is always important to ask which reference pavement with what age that is used as well as what is the age of the noise reducing pavement!

Due to differences in climate, traffic and traditions etc. there is a variation in what pavement type that can be considered the standard pavement in different European countries. In Sweden a SMA 16 pavement with 16 mm maximum aggregate size is normally used as a reference pavement, where as in Denmark today a SMA 11 pavement with 11 mm maximum aggregate is commonly used at the motorway network. Examples of AC 11 and SMA 16 reference pavements are shown in Figure 4.10. It can be seen that the SMA 16 has a rougher surface texture than the AC 11. When new, the SMA 16 will normally have a noise level around 2 dB higher than the AC 11 pavement.

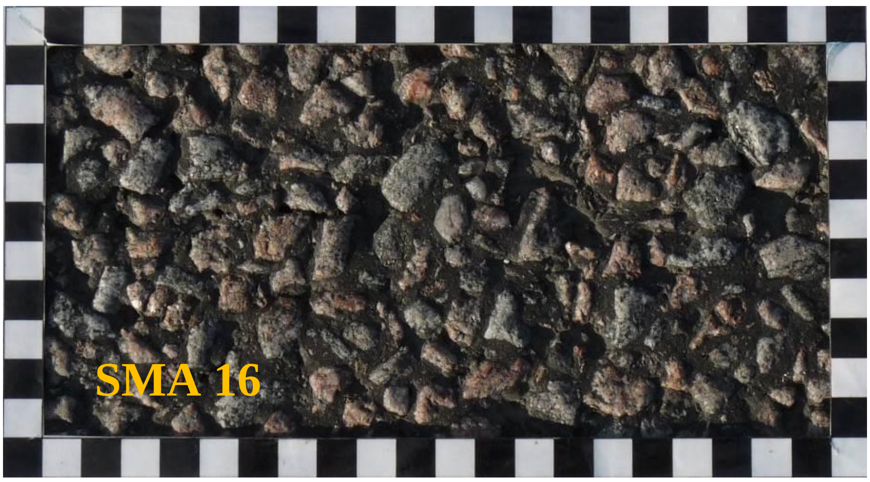

Figure 4.10: Close up photo of a SMA16 pavement normally used as a reference in Sweden (top) and a dense asphalt concrete with 11 mm aggregates (AC 11) used as a reference in Nord2000 in Denmark (bottom). The size of the black and white squares is 10 x 10 mm.

The noise reduction of the same specific pavement can vary in different European countries, depending on how the reference pavement is defined in each country.

Measurements of the noise from noise-reducing pavements are often performed when the pavements are new. It must be recommended to wait one to two months after the construction of the pavement before measurements are performed. Doing so, the bitumen film on the newly laid pavements will be removed by the traffic passing the pavement.

In order to evaluate the noise reduction, it is recommended to compare the measured noise levels with the noise from a typical reference pavement used in the relevant country with the same age as the noise-reducing pavement. In this way the noise reduction will more or less reflect the average noise reduction over the years. Even though it must be remarked that the increase of noise over time for noise-reducing pavements is normally higher than the increase for “normal” reference pavements (see Table 4.7 and Figure 4.9). In an ideal world this should also be taken into consideration. But in order to do this precisely, it is necessary to perform yearly noise measurements over the whole lifetime of pavements before being able to establish the exact noise reduction.

Based on comprehensive noise measurements on standard SMA 11 pavements and noise-reducing thin layer pavements of the SMA 6 type, Figure 4.11 shows an example of the development of noise over time for such two pavements. In this case with an expected lifetime of 17 years for the SMA 11 and an expected lifetime of 12 years for the noise-reducing SMA 6. The example covers a period of 51 years, equal to 3 lifecycles of the SMA 11. In this example, the average noise reduction for the noise-reducing thin layer SMA 6 is 2.2 dB in relation to the SMA 11.

The figure illustrates that for planning purposes it makes good sense to use the average noise levels over time as well as the average noise reduction over time for a specific pavement. Such average noise emission levels for pavements are often built in to the emission part of the national noise prediction methods.

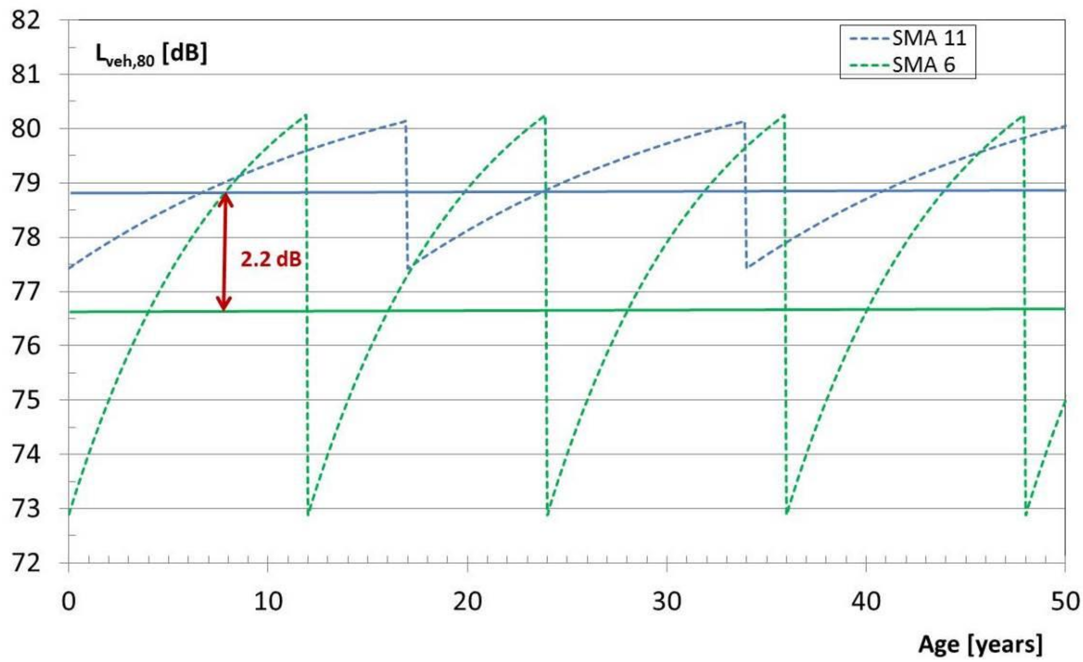

Figure 4.11: Constructed example of the development of noise over time for a SMA 11 standard pavement and a noise-reducing thin layer SMA 6 over a period of 51 years, expressed as noise levels measured by the road side SPB method (see Section 4.9). The average noise levels over the lifetime of both pavements are shown by straight lines [31].

4.9 Measurement of tyre road noise

Noise measurements are a fine tool to quantify the noise levels of different pavement types. It is important to use precise measurement methods. There are two good, standardized and reliable measurement methods that can be applied. These are the so called close proximity method (CPX) [20] where a special measurement trailer is used and the statistical pass by method (SPB) [21] measuring at the road side. There is an ISO standard (or draft standard) for both these methods that have to be correctly followed in order to secure high quality measurement results. Performance of such noise measurements requires highly qualified and experienced personal, as well as high quality and calibrated equipment.

Figure 4.12 show two types of CPX noise trailers that are used in Europe. Measurements performed with open and closed trailers give comparable results if performed correctly.

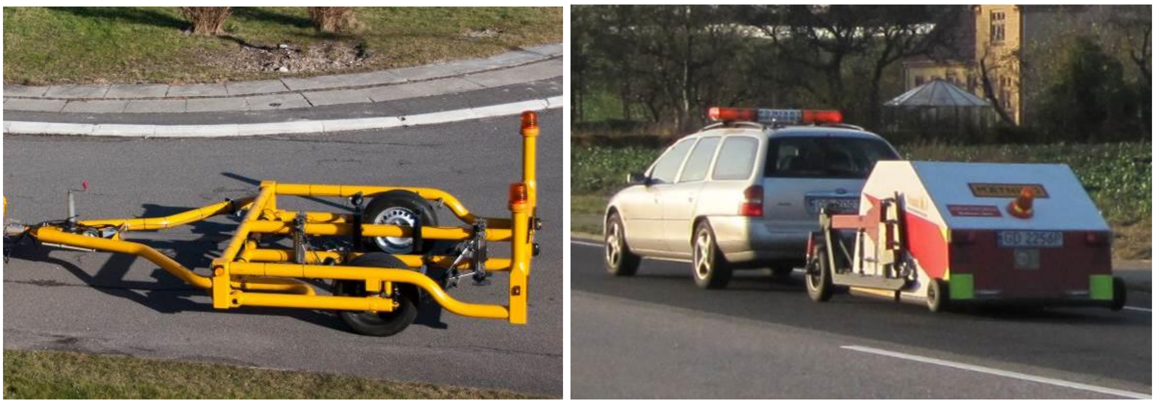

Figure 4.12: Open Dutch produced Danish CPX trailer (left) and a closed Polish CPX noise measurement trailer (right).

When performing CPX measurements a standardised test tyre is normally used. This is the so-called Standard Reference Test Tyre (SRTT). The SRTT is a special passenger car tyre. It is important that the rubber hardness of the test tyre, as well at wear and tear, age, et cetera is within the correct ranges specified in the standard. In some cases other tyres can also be used. Two microphones are placed very close to the test tyre (see Figure 4.13). Therefore the noise levels from the CPX method are normally quite high, typically in the range from 90 to 105 dB.

CPX measurements are normally performed at a speed of 50, 80 or 110 km/h. It can be recommended to perform measurements at the same speed as the speed limit of the relevant road section.

It is recommended to perform CPX noise trailer measurements in the wheel tracks of the road surface, as this is where the tyre road noise from normal road traffic is generated. The CPX method can normally be used on all types of roads, if it is possible to drive at a constant speed. When the CPX method is applied the noise emission from whole sections of a road can be measured meter by meter. It is also possible to perform measurements on all lanes on a motorway, if that is needed.

With this measuring method the noise properties of the road surface can over long distances at reasonable cost to be assessed and this method is also very good for acceptance tests after completion of the new road pavement.

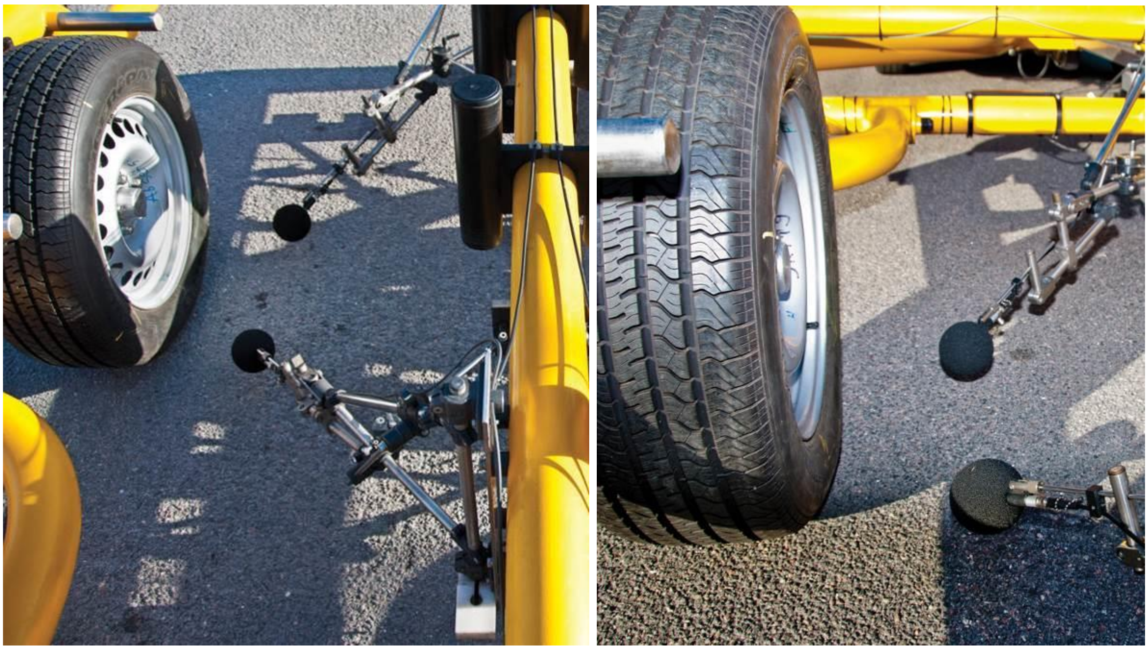

Figure 4.13: Microphone position of the CPX trailer method. Here shown on an open trailer with SRTT test tyre.

In the Statistical Pass-By method (SPB) [21] a microphone is placed 7.5 m from the centre line of the lane where noise is to be measured. The height of the microphone is normally 1.2 m above the road. When a vehicle, undisturbed by other vehicles, passes the microphone with constant speed the maximum noise level is recorded together with the speed of the vehicle. The speed is normally measured by laser or radar (see Figure 4.14). According to the SPB standard [21] the following numbers of vehicles have to be included in a measurement:

- at least 100 passenger cars;
- at least 30 two-axle heavy vehicles;
- at least 30 multi-axle heavy vehicles;
- a total of at least 80 heavy vehicles.

In practice, it is sometimes too time consuming to measure the required number of heavy vehicles. A regression analysis on noise versus speed is performed and, based on the analysis, the noise is predicted at the reference speed used at the location. The result will normally be a noise level for each of the three vehicle categories defined above. SPB results for passenger cars are typically in the range from 65 to 80 dB.

There are some restrictions on where the SPB method can be applied. There must not be reflecting objects like buildings, guard rails or barriers close to the measurement position and the microphone. In addition, there must not be too much soft ground (grass, vegetation etc.) between driving lane and microphone.

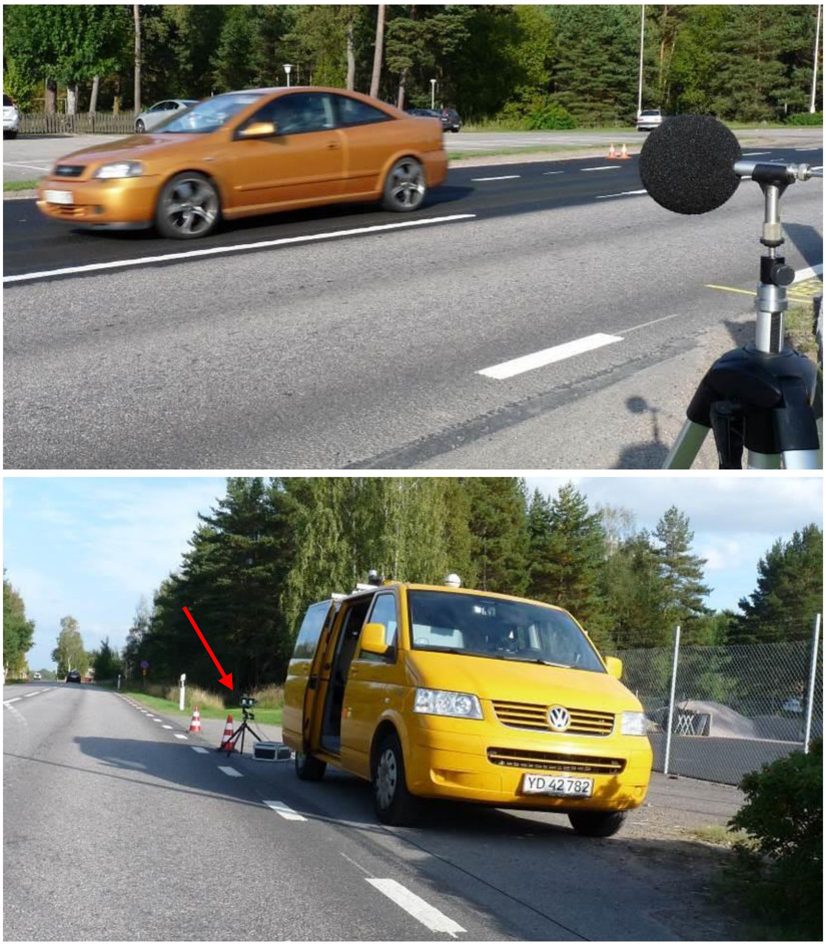

Figure 4.14: SPB noise measurements performed at the roadside on a test section in Sweden. Measurement car with equipment and speed laser (red arrow, bottom) and microphone at road side (top).

SPB measurement results are often normalised to a speed equivalent to the speed limit of the relevant road section. SPB is normally considered a very precise method. The result reflects the noise emission a short section of the lane selected for the measurements.

This method gives very accurate results for the actual noise characteristics of the pavement especially for the entire vehicle fleet. However, a particular limitation with the SPB method is that measurements only provide the results for the road section where the microphone was located. A special version of the SPB method is the so called Control Pass By method (CPB). Using this method, only one or a few selected cars are used for the noise measurements.

The tyre road noise changes with the ambient air temperature. As the temperature decrease, the noise emissions increase. In accordance with the standards for the SPB and CPX methods the results shall be normalised to an air temperature of 20 ºC.

Based on a large series of SPB and CPX measurements on the same pavements a correlation between CPX and SPB results have been developed in Denmark [38] for new dense pavements and thin noise-reducing pavements:

$$SPB = 0.921*CPX - 13.68 \qquad (1)$$

This correlation is not valid for porous pavements.

For measurement results from both the SPB and the CPX methods, it is important that the results are documented in measurement reports drafted according to the relevant standards for these two methods.

4.10 Pavements used today

The third CEDR Task Group Road Noise have performed a small survey on what types of pavements are used on the national road networks in the countries represented in CEDR Road Noise. It must be reiterated that what is considered a reference pavement and a noise-reducing pavement can vary from country to country. The roughly estimated result is presented in Table 4.8. It can be seen that on most roads “traditional” and not specially noise-reducing pavements are used. However, there are some countries using noise-reducing pavements like porous asphalt and thin layers to some extent. Figure 4.15 shows a motorway with a noise-reducing thin layer pavement around Nantes in France. The Netherlands is notable as it is a national policy to use porous asphalt on the state motorways as a measure to reduce noise. This strategy is already implemented on the main part of the motorway network. On the motorway network in Austria, the noise optimized version of the SMA and the noise optimized version of cement concrete pavement are use.

Table 4.8 Very rough percentage estimate of the main pavement types used on the national road network in fourteen European countries. Standard pavement types in yellow and noise-reducing types in green.

MAIN PAVEMENTS:	AT	BE-F	DE	DK	EE	ES	FR	GR	IE	IT	LV	NL	NO	SE	UK
Dense Asphalt Concrete	10		20	40	66	76	most	70	74	97	60	12	65		
Stone Mastic Asphalt	57	65	40	50	6				22		40		20	99	40
Cement Concrete	30	35	30			2									5
Porous Asphalt	3		10			12	some	30		3		69			
Thin Layers				10		10						1			55
Two Layer Porous Asphalt												18		1	

Figure 4.15: Motorway with a noise-reducing thin layer pavement around Nantes in France.

5 Possible ways forward: noise-reducing pavement solutions

5.1 Introduction

As it can be seen from Chapter 4, it is basically the pavement surface texture that defines the level of tyre road noise emission from a road pavement. This gives a series of possibilities and challenges for the pavement design engineers. Noise is an important issue, but there are also other pavement functionalities and factors that have to be taken into consideration when developing and using a new and improved pavement type or an improved version of an existing pavement type. A comprehensive and multidisciplinary approach is needed.

Relevant functionalities and factors are:

1. noise reduction, by passenger cars and heavy vehicles;
2. rolling resistance, the influence on vehicle energy consumption and CO_2 emissions;
3. friction, important for traffic safety;
4. drivers comfort, less splash and spray and more silent inside vehicle;
5. traffic safety, aqua planning, wet grip, splash and spray and visibility of road markings;
6. cost of pavement;
7. lifetime of pavement;
8. maintenance operations;
9. winter maintenance;
10. restrictions on practical application on roads.

These ten functionalities and factors will be considered in the following presentation of different noise-reducing pavement types when relevant and when information is available. The noise reductions indicated are intended to express the average noise reduction over the lifetime of the pavements and it is intended to cover the situation of motorway application where the speed is generally over 70 km/h. Information on noise reduction is best documented for passenger cars. For heavy vehicles, there is generally a little less information on noise reduction than for passenger cars (see Section 4.6).

It must be remarked that not everything is known today in the middle of the 2010s about noise-reducing pavements. There can also be national differences in the countries around Europe. Therefore, the information in the tables will be indicative and of an overall general nature not covering all specific solutions available and applied around Europe. Some of the background knowledge comes from the EU project SILVIA, that developed a guidance manual for the Implementation of low-noise road surfaces [33], as well as from the Tyre/Road Noise Reference Book from 2002 [11].

In order to cover different national reference pavements, the expected average noise reduction over the lifetime of pavements will be evaluated in relation to two different reference pavements. A SMA 16 pavement with 16 mm maximum aggregate size and a dense asphalt concrete with 11 mm aggregates (AC 11) (see Section 4.8). The SMA 16 will as mentioned in Section 4.8 normally have a noise level around 2 dB higher than the AC 11 pavement, when the pavements are new. But as it can be seen from Table 4.7, pavements with large aggregates has a lower yearly increase in noise than other pavements. So, lifetime difference between SMA 16 and DA 11 might be around 1.5 dB.

5.2 Background for technical solutions

In Chapter 4 the mechanisms for generation of tyre-road noise were presented. Based on that information, there are different ways forward to construct noise-reducing pavements. The vibration generated noise can be reduced by securing a smoother surface texture. This can be achieved by using a small maximum aggregate size, cubic aggregates and a good compaction. Reducing the maximum aggregate size and keeping everything else the same, will normally reduce the noise by around 0.25 dB per mm reduced maximum aggregate size. Figure 5.1 shows an example with two dense asphalt concrete pavements; one with 11 mm and the other with 8 mm maximum aggregate size. Over a ten year period exposed to the same volume of traffic the pavement with 8 mm aggregates as an average has a 1 dB lower noise level.

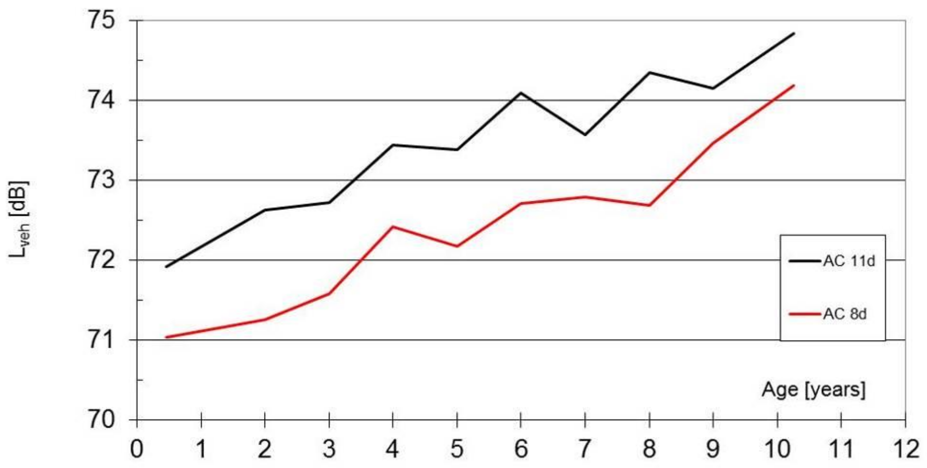

Figure 5.1: Development of noise over time for passenger cars at a speed of 60 km/h for dense asphalt concrete with 11 and 8 mm maximum aggregate size [9].

In the Dutch Danish research cooperation, as part of the Dutch IPG noise research program, it was investigated how reduced aggregate size will influence friction of the pavements [25]. A series of friction measurement results were analysed. The general conclusion was that there is a tendency to get higher and improved friction by reducing the maximum aggregate size.

The noise generated by air pumping can be reduced by creating a more open pavement surface texture. At the same time the amplification of the noise by the horn effect will be reduced and the absorption of noise will be increased. The pavement surface texture will be more open if the built in air voids of a pavement is increased. This can be done by modifying the aggregate distribution curves of the material used for a pavement. Figure 5.2 shows some examples. The AC 11 is dense asphalt concrete with a more or less flat aggregate distribution curve. If the aggregate distribution curve is steeper, the built in air-void will be increased and this will result in a decrease of the tyre road noise. This is the case for the AC 6 open but not porous asphalt concrete and PA 8 porous pavement.

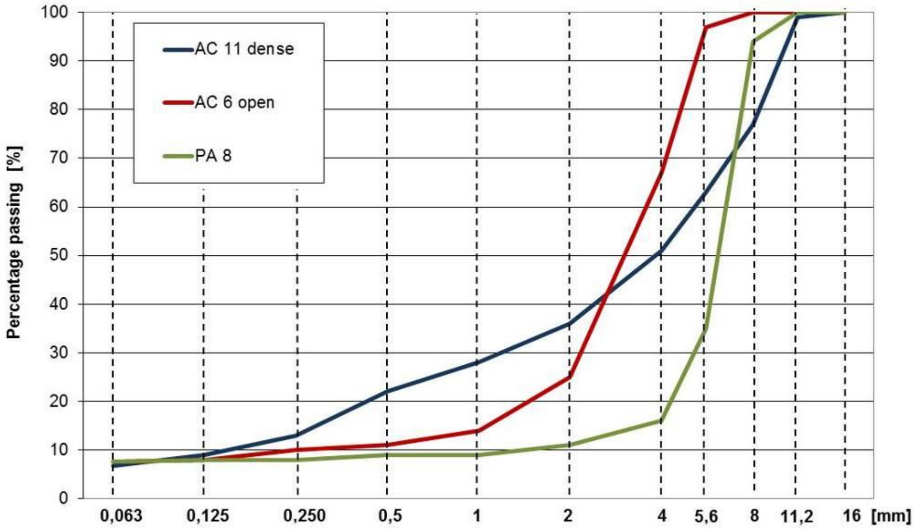

Figure 5.2: Examples of aggregate distribution curves of three pavement materials. AC 11 is dense asphalt concrete, AC 6 is open asphalt concrete and PA 8 is a porous pavement.

The built in air void is one of the parameters that defines the type of a pavement. The following are some typical intervals:

- dense pavements: air void 3-5 %;
- pavements with an open but not porous surface: air void 6 – 12 %, often called noise-reducing thin pavements or thin open pavements;
- porous pavements with communicating pores in the whole thickness of the pavement layer: air void 18 % or higher.

Pavements with a built in air void of 13 to 17 % are normally avoided because the openness and pore structure is undefined and therefore the performance of such pavements is unclear.

The pavement surface texture can be measured by the use of high resolution laser equipment like the instrument shown on Figure 5.3.

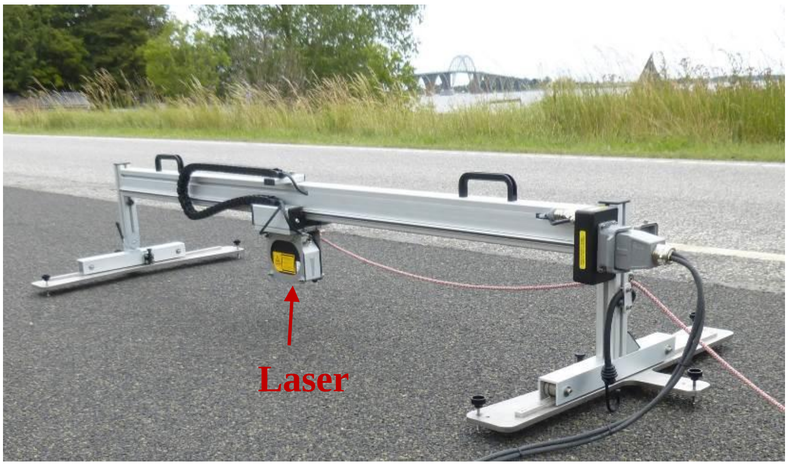

Figure 5.3: Laser equipment for measurement of pavement surface texture (left). The red laser beam can be seen on the pavement (right).

The Mean Profile Depth (MPD) is an expression of how open the pavement surface structure is. In order to illustrate the different surface textures, Figure 5.4 shows the surface texture of three different pavements measured by laser equipment. MPD is indicated for the three pavements A dense asphalt concrete with a dense surface structure and a low MPD of 0.33 mm, a noise-reducing thin layer with an open surface structure and an MPD of 0.71 mm, as well as a porous asphalt with an open surface texture with deep pores and a MPD of 1.17 mm. The three pavements all have a “negative” surface structure, that reduces the vibration generated noise (see Section 4.4).

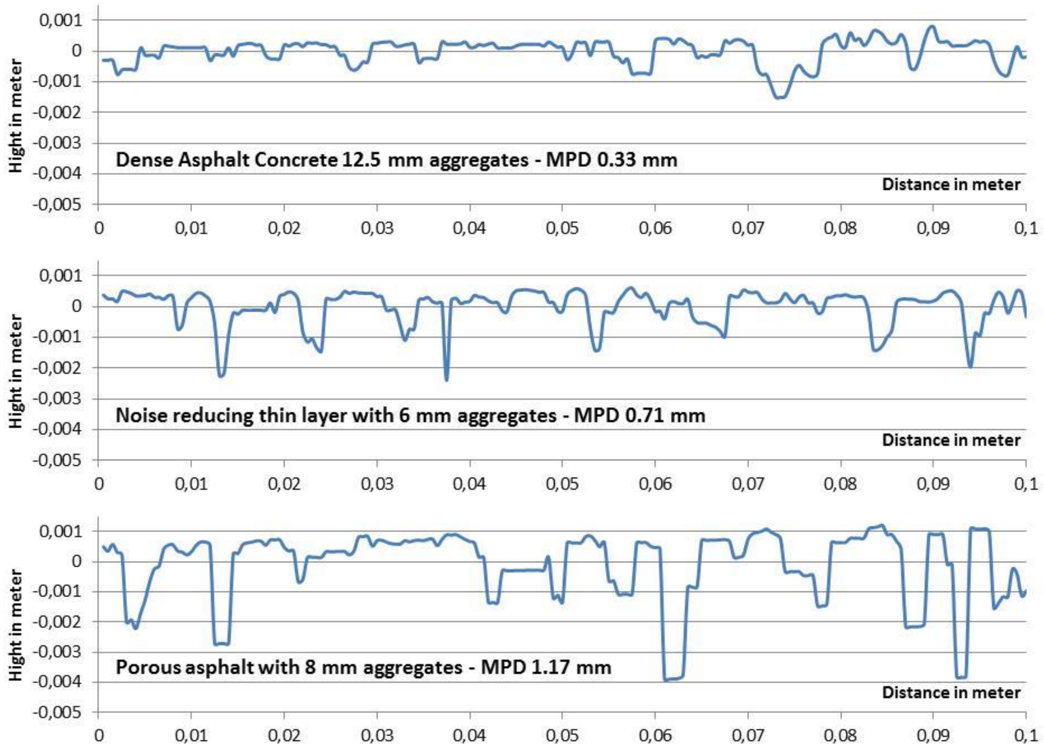

Figure 5.4: Surface texture of three pavements measured by laser. The sections have a length of 10 cm [26].

Throughout Europe there can be national and regional variation regarding the accessibility of materials, the tradition for pavement design and experiences in the contracting sector. Therefore pavements that are called the same, might vary both in how they are constructed and how they perform in relation to noise and other functionalities et cetera.

Generally it is complicated to construct decent noise-reducing pavements with long durability. High-quality materials, good craftsmanship and equipment are needed together with a high level of precision and quality control form the mixing plant over transportation to the construction site and the paying and compaction of the pavement.

Pavements are produced by contracting companies all around Europe. Some companies have developed specific company products that are marketed as noise-reducing. They are often based on the noise-reducing pavement types presented in the following paragraphs.

5.3 Thin layers

One of the commonly used types of noise-reducing pavements is the so-called thin layer pavement. The noise reducing effect of thin layer surfaces is caused by smaller aggregate sizes, sometimes with optimised mixes to make the surface semi-dense or have an open-graded surface; for more information see Section 4.4 [7, 16, 24, 40]. They are marketed under many different names.

In 2011, the Danish Road Directorate performed a scanning tour to Switzerland, France, the Netherlands and Germany, in order to study pros and cons and experiences using thin layer pavements for noise reduction [18]. The purpose was to obtain new knowledge and experience on both physical durability and acoustical effect from thin noise-reducing surface layers. The main results are presented the following.

Throughout Europe reduced durability of thin noise-reducing surface layers has been encountered. In some cases the damages have initiated during the winter season. The reasons for this are often a combination of several mechanisms/conditions. The following are the most important:

1. The thin surface layer has been paved on an uneven substrate of poor quality.
2. Insufficient capability to ensure that water could not penetrate to the binder layer. The partly open structure and the small thickness can lead to water penetration through the surface layer and into the binder layer, where damages can be induced in the winter season due to frost action.
3. The traffic exerts forces of turning and shearing actions on the surface layer.
4. The thin surface layer has been paved rather late in the year (after 15th September).

Several research and development activities are continuously developing better noise-reducing surface layers with optimized noise reduction and good physical durability. The main objectives are to improve the long-term noise reduction and durability. Acoustical optimization of the noise reduction can among others be achieved through using:

1. Small nominal maximum aggregate size (NMAS), typically 6 or 8 mm. Good noise reduction can also be achieved by a NMAS of 4 mm.
2. A large built-in void volume which for thin surface layers is between 8 – 12 % with half open pores. Voids over 18-20 % are also utilized, especially with pavements with 4 mm aggregates.

Figure 5.5: CPX trailer noise measurements (yellow van) on thin layer noise-reducing asphalt applied on rural main road in Denmark.

Based on the collected European information of material and pavement technology the following summary can be drawn up. Optimization of durability of thin noise-reducing surface layers can be achieved by the following guidelines:

1. Layer thickness shall not be less than 30 mm.
2. Typical mix design void volume between 8 and 12 % as half open pores with an open surface texture.
3. The surface layer can be developed with a thickness far greater than 3-4 times the nominal maximum aggregates size without risking permanent deformation.
4. The surface layer shall be placed on a newly paved substrate (typically binder layer) or on an old surface layer in good conditions.
5. Milling of an old surface layer is especially critical and shall be avoided. If used, fine tooth milling shall be performed, and the unevenness from the milling pattern shall be 3 mm at maximum.
6. The substrate shall have the correct profile. Thin noise-reducing surface layers cannot be utilized as levelling course.
7. Rather high binder content shall be used.
8. Polymer modified bitumen shall be ready-made and not produced in-situ during mixing.
9. Reclaimed asphalt is not used in thin noise-reducing surface layers.
10. Surface layers are paved between 15th April and 15th September.
11. Fog seal with bitumen emulsion are sometimes used, without any proof of the effect on durability. However, in The Netherlands the authorities reckon with an improvement in durability of 1 to 3 years.
12. Good tack coating to the substrate is essential, as well as an even substrate.

13. Ensure that water cannot penetrate to the binder layer through these open structured surface layers.
14. If funds for surface layers are available after 15th September, they ought to be used for new binder layers which can be paved with a new thin noise-reducing pavement the following summer. This strategy is recommended as being better than paving thin noise-reducing pavements late in the year.
15. Avoid manual handling of the materials during paving.
16. Skilled and experienced paving crews are necessary to obtain optimal quality of thin noise-reducing pavements.
17. Thin noise-reducing surface layers shall be avoided where turning, accelerating and braking traffic appears, e.g. in and close to roundabouts, lanes with expected stops (toll booths, bus stops, et cetera) and approaching traffic lights.

Table 5.1 gives a general overview and evaluation of the current knowledge about noise-reducing thin layer pavements. The table also includes references to literature where supplementary and more detailed information can be found.

Table 5.1: Summary of information about noise-reducing thin layer pavements.

Functionalities and factors	**Comments**
1. Estimated lifetime average noise reduction for passenger cars	1 – 3 dB relative to AC 11 2.5 – 4.5 dB relative to SMA 16 [16, 24]
2. Rolling resistance (influence on energy consumption and CO_2 emissions)	There is a tendency to obtain reduced rolling resistance using smaller aggregates [40]
3. Friction (important for traffic safety)	Using smaller aggregates improves friction [25]
4. Drivers comfort (splash and spray, more silent inside vehicle)	Drivers comfort is the same as a standard pavement or slightly improved, caused by reduced splash and spray and reduced noise inside vehicle
5. Traffic safety (aqua planning, wet grip, splash and spray and visibility of road markings)	The same as a standard pavement or maybe a slight improvement, caused by improved friction and reduced splash and spray
6. Cost of pavement	Basic cost is often the same as a standard pavement. However, if the sub layer is in a poor condition, it may be necessary to mill of the old veering course and apply a new bearing layer before applying a thin layer. This increases cost [18]
7. Lifetime of pavement	Generally a few years shorter than standard pavements [18]
8. Maintenance operations if needed	Generally no special maintenance operations are needed. Bitumen rejuvenation may increase lifetime [18]
9. Winter maintenance	Nothing significant to note
10. Restrictions on practical application on roads	Not suitable to use at road sections and intersections with turning forces caused by tyres [18]

5.4 Noise-reducing split mastics asphalt (SMA-LA)

The following is a presentation of one version of a noise-reducing thin layer asphalt used commonly in Austria. It is a split mastics asphalt called SMA-LA.

The conventional asphalt pavement of stone mastic asphalt without special noise-reducing properties was developed more than forty years ago and have been used for roads of all load classes. The conventional SMA has a high deformation resistance and the simple, inexpensive replacement. The lifetime of these conventional SMA pavements is approximately 15 years.

Since 2005, there is a low noise version of the stone mastic asphalt: SMA-LA (see Figure 5.6). This relatively recent construction differs from the conventional construction by an altered grading curve with a lower proportion of fine aggregates and thereby a higher void content: in Austria 9-11 percent by volume. The noise reduction is approximately 2.5 dB, compared to an AC and a conventional SMA and depends on the traffic composition and speed [32]. The better noise-reducing results can be achieved with a smaller maximum aggregate size. The thickness is of the SMA-LA layer is 20 to 40 mm depending on the maximum aggregate size.

Figure 5.6: Close-up picture of the Austrian SMA-LA pavement used for noise reduction.

The noise-reducing SMA-LA can be constructed economically using conventional building materials and laying techniques. In relation to porous asphalt, the ongoing operating costs and rehabilitation costs are lower. In relation to porous asphalt, much less salt for winter maintenance is required and the service lifetime is longer.

Problems may occur when such a SMA-LA is used in tight curves and, more generally, where high shear forces caused by the tyres occur. Likewise, the use of this pavement type is currently being discussed on bridges, since the dewatering behaviour has not yet been entirely understood. Table 5.2 gives a general overview and evaluation of the Austrian SMA-LA pavement.

Table 5.2: Summary of information about noise-reducing Austrian SMA-LA pavement.

Functionalities and factors	Comments
1. Estimated lifetime average noise reduction for passenger cars	2.5 dB in relation to a conventional AC or SMA
2. Rolling resistance (influence on energy consumption and CO_2 emissions)	Nothing significant to note
3. Friction (important for traffic safety)	Nothing significant to note
4. Drivers comfort (splash and spray, more silent inside vehicle)	Nothing significant to note
5. Traffic safety (aqua planning, wet grip, splash and spray and visibility of road markings)	Nothing significant to note
6. Cost of pavement	Economical solution
7. Lifetime of pavement	Longer than porous asphalts, shorter than with conventional AC and SMA pavement and pavement in concrete
8. Maintenance operations if needed	-
9. Winter maintenance	No major problems and no above-average salt consumption
10. Restrictions on practical application on roads	Not suitable to use in tight curves and more generally where high shear forces caused by the tyres occur

5.5 Porous asphalt

A porous asphalt is a very open graded asphalt mix with communicating porous in the whole layer thickness (see Figure 5.7). Porous asphalt can be applied in one layer or in two layers [12, 23]. By applying two layers, the total thickness of the porous layer increases and this improves noise reduction. The noise reduction mechanisms for porous asphalt are described in section 4.4.

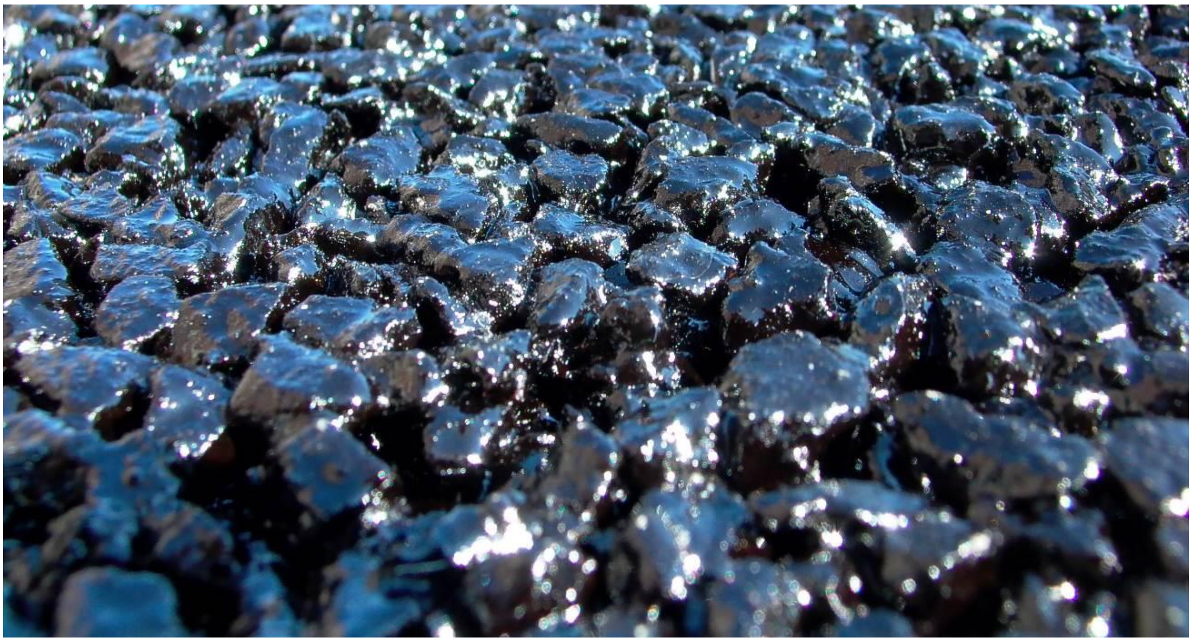

Figure 5.7: Close up photo of newly laid porous asphalt. The open porous structure between the aggregates can be seen. Bitumen film can be seen as well on the aggregates.

Figure 5.8: Two layer porous asphalt on a Dutch motorway seen from the roadside. The top layer has a smaller aggregates size of 6 or 8 mm, the bottom layer has 16 mm aggregates.

The Danish Road Directorate performed a scanning tour to Bavaria in Germany, Switzerland, France and the Netherlands in 2011, in order to study pros and cons and experiences using porous pavements for noise reduction. The primary areas of interest were knowledge and experience on winter service of porous asphalt. The main results are presented in the following [17]. Also, information from Austria and a Swedish example has been included.

On the Bavarian motorway network 28 km porous asphalt has been constructed to abate noise. Problems with shorter lifetime depending on traffic load are observed (see Figure 5.9). This increases the cost of using of porous asphalt. Some problems with clogging are also observed. The introduction of a new ‘double’ salting machine combining wet and dry salting have improved price and quality of winter service. Sometimes speed reduction is used.

Figure 5.9: Older porous asphalt with significant ravelling in Bavaria, Germany.

In Switzerland, there are 250 km of porous asphalt on the motorways. However, the national road administration is not in favour of porous asphalt because of durability problems and too short lifetime. These problems increase the cost. Porous asphalt is only used on motorway sections where the noise regulation requires noise reduction that cannot be achieved with noise barriers. In such locations, extra salt is used.

In France, the national road administration has stopped using porous asphalt. The primary reason to stop the use of porous asphalt was the high cost of winter service. The pavement type is still used on 200 km by one private motorway company, presumably because of the reduction of splash and spray thus increasing driver comfort. No information on winter service retrieved.

In the Netherlands, the state policy requires porous asphalt on the whole state motorway network to reduce noise and, at present, 70 % of the Dutch motorway network has one layer porous asphalt (and 20 % has two layer porous asphalt) (see figure 5.9). The lifetime for single layer porous asphalt in the Netherlands is seventeen years, one year shorter than the lifetime for dense pavements. For two layer porous asphalt the Dutch lifetime is 13 years. At the end of the lifetime the loss of aggregates (ravelling) is the dominant failure mechanism. The contracting sector has considerable experience on porous asphalt. Frost damages have been observed on old porous asphalt in severe winters. Problems with snow in pores and black ice have been observed. Intensive monitoring in winter periods by road staff and sensors and frequent salting are applied. Between 30 to 40 % additional salt is used. Sometimes lanes are closed and sometimes speed reduction is used. The road administration has significant and valuable experience in performing winter service of porous asphalt.

Figure 5.10: Motorway with porous asphalt in the Netherlands.

No statistics and analyses concerning traffic safety comparing porous pavements and dense pavements has been found in the four countries [17], with the exception of a Dutch study from the 1990s concluding that the traffic safety level on average was the same on porous and dense pavements. Indications in Bavaria and Switzerland show that similar results have been achieved in unpublished internal surveys.

In the past, a lot of porous asphalt has been used in Austria. The biggest problems were in the winter service by the higher salt consumption and the required shorter turnaround time for winter maintenance. It also turned out to be a significant problem that the end of lifetime occurred suddenly. After alternative noise-reducing road pavements (like SMA-LA) were developed, porous asphalt is currently no longer used on the motorway network.

One of the advantages of porous asphalt is its effect to drain away rainwater. Therefore, the road users have no splash and spray and thus improved visibility. However, this entails in turn an increased risk that the road users may drive a little bit faster in rain and underestimate the braking distance because the road is wet, despite no splash and spray.

On the background of the information collected during the scanning tour, the following tentative conclusions have been drawn [17]:

1. Porous pavements are used to reduce road traffic noise and they are normally considered to have a better noise-reducing potential than thin layers optimized for low noise.
2. Porous pavements can be produced with good durability ensuring a lifetime just some years less than ordinary dense pavements. However, in some countries there are problems with durability.

3. Well produced and well maintained porous pavements can withstand winter and frost damages, even though there is a tendency that porous pavements are more sensitive to damages than dense pavements. However, in some countries there are problems with winter and frost damages.
4. Good professional skill and experience is needed in the contracting sector to ensure good durability of porous pavements.
5. With appropriate monitoring and management of salting and snow removal, it is possible to service porous pavements in the winter periods. No countries had new statistical information on special traffic safety problems in the winter periods.
6. A more frequent salting process (60 to 90 minutes) and 30 to 50 % more salt per year is needed for porous pavements than dense pavements.
7. Situations with snow pressed down in the pores occur and this can result in an icy surface and it can be more complicated to remove.
8. Situations with black ice, a thin coating of glaze or clear ice on roads, can occur on porous pavements and it can be more complicated to remove than on dense pavements.
9. It can be necessary to close lanes or reduce speed on sections with porous pavements in winter periods.
10. A large scale use of porous pavements develops and improves good skills and technologies both for constructing and servicing porous pavements especially in winter periods.

In order to get a sufficient noise reduction, it might be necessary to combine different tools of noise abatement. An example from Sweden is where national motorway E4 passes the city of Husqvarna (see Figure 5.11). In order to fulfil the noise requirements of the environmental authorities, a combination of noise-reducing two layer porous asphalt, noise barriers and speed reduction from 110 to 90 km/h have been used [44].

Figure 5.11: At motorway E4 in Husqvarna in Sweden a combination of noise-reducing pavement, noise barriers and speed reductions have been applied to fulfil noise guidelines.

Table 5.3 gives a general overview and evaluation of the current knowledge about noise-reducing porous pavements. The table also includes references to literature where supplementary and more detailed information can be found.

Table 5.3: Summary of information about noise-reducing porous pavements.

Functionalities and factors	Comments
1. Estimated lifetime average noise reduction for passenger cars	One layer porous asphalt [23]: 2 – 4 dB relative to AC 11 3.5 – 5.5 dB relative to SMA 16 Two layer porous asphalt has a noise reduction of 1 to 2 dB relative to one layer porous asphalt
2. Rolling resistance (influence on energy consumption and CO_2 emissions)	There is a tendency to obtain reduced rolling resistance using smaller aggregates
3. Friction (important for traffic safety)	Using smaller aggregates generally improves friction [25]
4. Drivers comfort (splash and spray, more silent inside vehicle)	Drivers comfort is generally improved caused by reduced splash and spray and reduced noise inside vehicle
5. Traffic safety (aqua planning, wet grip, splash and spray and visibility of road markings)	A slight improvement caused by improved friction and reduced splash and spray. A slight reduction caused by worsened conditions in winter time [17]. Solid statistics are not available
6. Cost of pavement	Generally a higher cost than standard pavements [23]. The reduced lifetime increases cost
7. Lifetime of pavement	Porous pavements can be produced with good durability ensuring a lifetime of just a few years less than ordinary dense pavements. However, there are problems with durability in some countries [17, 23]
8. Maintenance operations if needed	If porous pavements are applied on emergency lanes it may be necessary to clean these lanes. Bitumen rejuvenation may increase lifetime [18, 23]
9. Winter maintenance	Complicated and challenging [23]. With appropriate monitoring, managing, salting and snow removal it is possible to service porous pavements in the winter periods [17]
10. Restrictions on practical application on roads	Not suitable to use at road sections and intersections with turning forces caused by tyres [17]

5.6 Optimized cement concrete pavement

The main focus of this report is on noise-reducing asphalt pavements. However, this section will provide some information from Austria on how cement concrete pavements can be optimized for reduced noise emission.

In primary road network come in some countries both asphalt construction and concrete construction methods used. The advantage of the concrete construction lies in the long lifetime and the resulting low maintenance costs, even in sections with high percentage of heavy vehicles. The current generation concrete roads can deal with high load capacity, has a high resistance to deformation, longer repair intervals and lesser conservation expenses. Properly built concrete pavements has renewal intervals of 40 years.

Especially from an economic point, Austria uses these concrete pavements on the high-level motorway and expressway network. In many areas, however, the use of a concrete pavement is limited. For example, on bridges and in some noise sensitive areas. For noise reduction, the two layer concrete pavement has been designed in Austria. In the USA and Germany the two layer concrete pavement is also a standard construction method.

The noise emission of a noise-reducing concrete pavement is about the same as for an AC or a conventional SMA and depends on the traffic composition and the speed [32]. During lifetime the noise increases only slightly. Even after more than ten years under traffic, it hardly loses its noise-reducing properties. The difference between a conventional concrete pavement and a noise-reducing concrete pavement is about 1.3 dB [32].

A method has been developed to completely recycling old pavements in the construction of new pavements. This is an important aspect in times of sustainability and resource conservation.

Currently, research projects aim at further improvement of the noise reducing properties of concrete roadways. For example, research on open-poured concrete pavements. Another very promising research currently deals with the mechanical surface treatment by grinding, to optimize the noise reduction, the grip and the flatness. With grinding (see Figure 5.12) they aim at a noise reduction in the order of a SMA- LA pavement.

Figure 5.12: Examples of different surface treatments of concrete roads. To the right, longitudinal grinding.

Concrete pavements are often constructed with joints between concrete slabs. If the pavement can be constructed without joints or with a reduced number of joints the noise can be reduced.

Table 5.4: Summary of information about noise-reducing cement concrete pavements.

Functionalities and factors	Comments
1. Estimated potential lifetime average noise reduction for passenger cars	0 – 1.5 dB relative to AC 11 [32] 1.5 – 3.0 dB relative to SMA 16
2. Rolling resistance (influence on energy consumption and CO_2 emissions)	Nothing significant to note
3. Friction (important for traffic safety)	Nothing significant to note
4. Drivers comfort (splash and spray, more silent inside vehicle)	Nothing significant to note
5. Traffic safety (aqua planning, wet grip, splash and spray and visibility of road markings)	Nothing significant to note
6. Cost of pavement	Construction costs higher than with asphalt construction, through the long lifetime lower lifecycle costs
7. Lifetime of pavement	Lifetimes of up to 40 years are possible
8. Maintenance operations if needed	With today's technologies, renovations can be carried out relative easily
9. Winter maintenance	No major problems and no above average salt consumption.
10. Restrictions on practical application on roads	Not suitable to use at insufficiently dimensioned existing bridges and higher costs for use at new bridges

5.7 Poroelastic pavements

A poroelastic pavement (PERS) is a futuristic noise-reducing pavement still under development. The basic idea is to make a porous pavement elastic and in this way further reduce the vibration generated noise. This is done by substituting a large percentage of the stone aggregates by rubber granulate from scrapped tyres (see Figure 5.13 and 5.14). Such pavement types have been developed and tested in the laboratory and on eight full scale test sections in Belgium (see Figure 5.15), Denmark, Poland, Slovenia and Sweden in the EU project PERSUADE between the period 2009 to 2015 [14]. The noise-reducing potential of such pavements is as high as 8 to 12 dB, but the big challenge is developing a pavement type with sufficient durability [27]. At the end of the PERSUADE project the durability remains a mayor challenge and therefore further research and development is needed. The evaluation by the authors is that PERS pavements will have a shorter lifetime than ordinary asphalt concrete pavements. This is a pavement type that might in the future be used in noise hotspots, where many dwellings are exposed to high noise levels. In such situations, it might be a cost-effective solution to use poroelastic pavements.

Figure 5.13: The components used in poroelastic pavements are stone aggregates here 2/5 mm maximum aggregate size, granulated rubber from scrapped tyres and polyurethane.

Figure 5.14: Close-up photo of ten month old poroelastic pavement on test section at Kalvehave in Denmark. The size of the black and white squares is 10 x 10 mm. The dark aggregates are rubber and the lights are stone aggregates [14, 27].

Figure 5.15: A 40 m long and two month old test section with poroelastic pavement in one lane at Herzele in Belgium [14, 27].

The Dutch road administration, Rijkswaterstaat, is working on the development of an ultra-quiet road surface that will last at least seven years [28, 34]. The noise reduction goal is 10 dB, compared to dense asphalt concrete and is intended as a cost-effective alternative to the roads where two layer porous asphalt with an additional noise barrier is insufficient to meet the noise limits. To date, no results are available.

Table 5.5 gives a general overview and evaluation of the current knowledge about noise-reducing poroelastic pavements project based on the results of the PERSUADE project. The table also includes references to literature where supplementary and more detailed information can be found.

Table 5.5: Summary of information about noise-reducing poroelastic pavements based on the results of the PERSUADE project [27].

Functionalities and factors	Comments
1. Estimated lifetime average noise reduction for passenger cars	In the first year [27]: 8 – 10 dB relative to AC 11 10 - 12 dB relative to SMA 16 but no long-time measurement series are available
2. Rolling resistance (influence on energy consumption and CO_2 emissions)	Generally higher than for ordinary pavements [27]
3. Friction (important for traffic safety)	Friction over or close to national guidelines. Friction lower than for ordinary asphalt pavements [27]. Long-time development of friction not known
4. Drivers comfort (splash and spray, more silent inside vehicle)	Reduces splash and spray as ordinary porous pavements
5. Traffic safety (aqua planning, wet grip, splash and spray and visibility of road markings)	Has not been investigated in detail
6. Cost of pavement	Significantly higher than cost for porous pavements
7. Lifetime of pavement	Shorter than ordinary porous pavements. It is a technical challenge to improve the lifetime of PERS pavements
8. Maintenance operations if needed	No knowledge available
9. Winter maintenance	Same as for porous pavements. PERS can be sensitive to steel snowploughs and steel brooms used for snow removal
10. Restrictions on practical application on roads	Not to be use at road sections with turning forces caused by tyres

5.8 Perspective in relation to pavement solutions

This report presents an overview of the existing comprehensive knowledge about noise reducing pavements. But the process producing the report has shown that there is a lack of knowledge in some areas related to noise-reducing pavements:

1. There is a need to improve the structural lifetime of both thin layer pavements, as well as porous pavements and other noise-reducing pavements.
2. There is a need to improve the lifetime noise reduction of both thin layer pavements, as well as porous pavements and other noise-reducing pavements.
3. More knowledge is needed on how to perform winter maintenance of porous pavements in different climate zones.
4. There is a lack of end of lifetime measurement series of the lifetime development of noise for different pavement types.
5. With regard to the standards and guidelines on noise properties of road pavements, it should be noted that these have often been established based on SPB measurements. To be able to work with the CPX measurements also, it would be important to investigate the correlation between the two measurement methods better and be able to provide relevant factors for all types of road pavements.
6. No precise models are available that can be used to predict precisely the tyre road noise by detailed measurements of the pavement surface texture and other surface related properties. There is a need for further research into such relations, as well as a need to develop such models that can be a valuable tool for both road administrators and contractors.
7. There is a need for improving the durability and lifetime of poroelastic pavements with high noise reduction.
8. According to the current results for noise reduction of cement concrete, there is still a very high optimization potential with regard to the pavement surface texture.

It is the judgement of the subgroup that even though a series of research and development needs have been highlighted, the current knowledge has such a level and quality that it can be used as a technical background for implementing noise-reducing pavements when constructing new road infrastructure and when renewing and maintaining the existing road network. As it can be seen from Table 4.8 a series of European countries are already using different types of noise-reducing pavements.

6 Implementation and comparison of the possible ways forward

6.1 Noise-reducing pavements in all stages of road planning

The use of noise-reducing pavements can be implemented in both the planning and construction stages of new motorways, as well as in the ongoing process of maintaining the existing road network.

In the CEDR project ON-AIR a guidance gook on the integration of noise in road planning was drafted in 2015 [35]. The objective of this guidance book was to present tools and guidelines which can facilitate the integration of noise abatement into the three most common planning and management situations of national road administrations, as follows:

1. planning of new roads and motorways;
2. planning of reconstruction and enlargement of existing roads and motorways; and
3. maintenance and management of existing roads and motorways.

A holistic approach was applied by using the strategy of integrating noise considerations in the whole chain from strategic planning, environmental impact assessment and detailed project development to management, as well as maintenance of road infrastructure. The earlier potential noise problems are identified, addressed and mitigated in the road management planning process, the more successful the noise abatement solution. In addition, cost-effectiveness will be improved.

Noise abatement at the source is generally more successful and cost-effective than reducing noise by barriers or building insulation. Noise-reducing pavements is a measure to reduce noise at source and it is, at the same time, a measure that the road administrations themselves can decide to implement. Therefore, the integration of noise-reducing pavements at all levels of road planning is an important issue within the ON-AIR guidance book.

The road engineers decide what type of pavement to apply when renewing worn down old pavements. This decision has a significant influence on the noise from traffic on a road or motorway. It is therefore important to have noise on the agenda along with other relevant factors such as durability, lifetime, price, rolling resistance, traffic safety, winter maintenance, et cetera, when deciding which pavement type to use [35]. The Danish Road Directorate has developed a method for how noise can be taken into consideration as an active parameter in Pavement Management Systems (PMS) [19]. The CEDR noise project QUESTIM [36] has also described procedures for doing this.

6.2 Noise integration in the tendering process

Generally, the road administrations tender out pavement work to the market and the contracting companies bid for such tenders. Based on the bids, the road administration selects the best offer, considering the various criteria. Pavement performance criteria, such as evenness and friction, can be part of the tendering requirements. Noise is a relatively new performance criterion for pavement works. It is a challenge for road administrations to decide how to incorporate noise into the tendering process, in combination with the requirements of service life and expenses for maintenance.

In the planning process, a required level of noise reduction is often decided or conditioned. Often the required level of noise reduction is necessary in order to fulfil noise guidelines that has been defined or set for a given road project by the authorities or the environmental regulation. Such noise guidelines often refer to lifetime average noise levels (see Section 4.8), but when a completely new pavement is applied, it is only possible to measure the noise in the initial stage and not over the whole lifetime of the pavement.

Different approaches can be applied and have actually been applied in certain European countries that actively use noise-reducing pavements [38, 41, 42, 43]. The level of actually controlling the noise by measurements varies from no control, over initial control after laying a pavement to long time measurements over many years. Possible solutions are as follows:

1. specify a pavement type such as a thin layer or a porous pavement, without control measurement of noise after application;
2. national system of noise labelling of pavements produced by different contractors, without control measurement of noise after application;
3. noise reduction criteria in tendering for the initial noise, but no requirements for specific pavement types, with control measurement of noise after application;
4. noise reduction criteria in tendering for the initial noise, as well as the development of noise over time but no requirements for specific pavement types, with control measurement of noise every year.

This ends up with four different approaches; two without and two with control measurement of noise after application. In Section 6.3 each solution will be described further and pros and cons discussed.

The testing of the noise performance, conformity of production, of a new pavement after construction can be based on different types of measurements. It will generally include direct noise measurements performed either by the roadside SPB or the trailer CPX method (see Section 4.9) or the use of both measurements methods. The SPB method provides a precise result, but in just one cross section of a road, whereas the CPX method provides results for the entire road section. These noise measurements can be supplemented or combined with measurements of other properties that have an influence on the noise level such as:

- laser measurements of the surface texture (see Section 5.2),
- measurement of porosity,
- measurement of acoustical absorption.

In the EU project SILVIA [33], conformity of production test methods for noise were developed, including a broader range of measurement methods. The selection of measurement methods to apply in conformity of production test could fulfil the following criteria:

- be relatively easy to perform and not too costly;
- have a reasonable high level of precision;
- secure a transparent measurement procedure that is understood and accepted by both road administration and contractor;
- not being too complicated.

If the SPB or the CPX methods are used for performing conformity of production testing of noise-reducing pavements, it is crucial that the methods are applied in a way that secures high precision and that it is possible to check the results by performing additional measurements by a second independent measurement company. It could be suggested to establish a calibration and certification procedure for the companies who want to be able to provide noise measurements for conformity of production testing of noise-reducing pavements [38, 41]. If other measurement methods are also included in the conformity of production testing, a calibration and certification procedure could also be considered for those methods.

In the current Danish system [38, 41] for labelling and classification of noise-reducing pavements, such a certification procedure has been established for CPX measurements. Each company who wants to offer a CPX measurement service are required, every year, to undertake a series of CPX measurements on approximately ten different pavements on a motorway and an urban road. Each company undertakes the measurements on the same ten pavements. Based on the results every company receives a CPX-DK correlation constant that has to be used in the next 12 months when performing conformity of production testing measurements. This system is designed to ensure that all the participating companies are able to measure comparable noise levels. Such a procedure could also be established for SPB measurements if relevant.

In the end the measurements included in conformity of production testing of the noise performance of a newly applied pavement might be used by the road administration either to accept or reject the work performed by the contractor. If the work is rejected it immediately raises the question about what consequences this rejection shall have. There are a wide range of possibilities, consequences and costs:

- The actual pavement job can be considered a learning process for the contractor, the road administration as well as the whole contraction sector in the actual country. The consequence could be that nothing is done in relation to the actual pavement job, but that the experiences are collected and used in coming noise-reducing pavement works.
- A fine system can be applied where for example for every 0.5 dB the measured noise level is too high the price of the job will be reduced with a certain percentage for example 10 %.
- The road administration can require that the pavement is removed and a new and better one applied on the account of the contracting company.

If fines or a possibility to redo the pavement work is built into the tenders of noise-reducing pavements, it might have at least three consequences:

1. The contractors will improve their efforts to do their best every time in relation to the noise reduction of their pavements.
2. The contractors might invest in development and testing of improved products in order to be able to fulfil the noise requirements and thereby have a better position in the competition between contractors.
3. The contractors will increase the bidding sum for projects with noise-reducing pavements in order cover the risk that they will get a reduced pay or have to redo a pavement. This will increase the cost of noise-reducing pavements, but presumably also in a longer perspective secure that the required noise levels are actually met in most pavement tenders.

Currently, there are no joint European procedures and regulations in this field of integrating noise in the tendering process and there is no common reference pavement or reference noise level. The procedures used today often vary from country to country. In the ongoing EU project ROSANNE [37], one of the objectives is to work on such methods and procedures.

6.3 Four different approaches for tendering noise-reducing pavements

The four different approaches for integrating noise in the pavement tendering procedures are generally outlined and evaluated in the following. As already described in Chapter 5, noise-reducing pavements are normally more expensive to use than normal standard pavements. But the different options for tendering procedures might have an influence on the price the contractors will charge for constructing a noise-reducing pavement. A brief evaluation of this has been carried out in the following for the four tendering options. The results are summarized in Table 6.1 below where the economic aspects only relates to differences caused by the tendering procedures.

1 - Specify pavement type and no control measurement

The road administration specifies in the tendering material a pavement type like a thin layer or a porous pavement. This can also include maximum aggregate size, built in air voids etc. These specifications can be defined based on the road administrations knowledge on the noise reduction of pavement types. As there are no specific noise level requirements, it will not be relevant in relation to the work performed by the contractor to perform control of noise after application. However, for the development of internal knowledge in the road administration, as well as by the contractors, such measurements can be very beneficial.

This method of specifying a pavement type has often been used in the first phases of developing and introducing noise-reducing pavements. Using this method, there will be some uncertainty on the noise reduction that will actually be achieved. The noise reduction achieved might vary between contractors as well as from pavement job to pavement job. The contractor will normally not have to increase bidding price, as there are no specific economic risks for the contractor in relation to noise.

2 - National system of noise labelling of pavements and no control measurement

A national system for the noise labelling of pavements can be established. Based on noise measurements, the contractors can get a noise label for a specific product if it fulfils certain noise requirements. In the tendering documents a road administration can request a pavement that fulfils a certain noise label and all the contractors that has such a label can bid for the tender. Conformity of production testing of noise can be performed after the pavement has been constructed, but this is voluntary and no fine system is applied if the required noise levels are not fulfilled.

The current Danish system for tendering noise-reducing pavements is an example of this [38, 41]. The tendering system requests the noise level after four weeks of traffic to be 4 dB lower than the defined Danish reference. If the noise level is 7 dB below the reference, the pavement may be declared ‘special noise-reducing’. Noise levels are measured using a CPX trailer. The road administration can in the tendering request a noise-reducing pavement. Prior to being awarded a contract, a tenderer must declare the expected noise performance of the road surface that he proposes to lay, supported by data obtained from an already constructed test section using a calibrated CPX trailer. The current Danish system has no conformity of production testing of noise.

3 - Noise criteria in tendering and control measurement

Noise reduction criteria are included in tendering documents for the initial noise, but no requirements for specific pavement types. Conformity of production testing of noise shall be performed after the pavement has been constructed, in order to validate if the contractor has fulfilled the noise criteria set up in the tendering documents. Such a system can be combined with a noise labelling system as described above.

A fine system will here be built into the contract, if the pavement fails to meet the required noise levels. When that is the case, it can be expected that the contractors will increase the bidding price in order to cover this risk of failing in relation to noise. But another effect is that in a market where fines for not fulfilling noise criteria is adapted, over time the contractors can be expected to further develop and improve their noise-reducing products in order not to be forced to pay fines. This can also improve the competitiveness of the contracting companies.

Such a system has been used in one special occasion by the Danish Road Directorate [31]. In a call for tenders it was specified that the contractor, after having built the pavement, should document that he has in fact delivered the requested noise reduction. If not, a financial penalty would be issued or he may have to repave.

4 - Noise criteria in tendering for the initial as well as long-time noise measurement

Noise reduction criteria are included in tendering documents for the initial noise as well as for the noise every year (every second year or the like) over the lifetime of the pavement. Conformity of production testing of noise shall be performed after the pavement has been constructed in order to validate if the contractor has fulfilled the noise criteria set up in the tendering documents. And the noise measurements will be repeated every year to monitor if the noise criteria are still fulfilled. If the noise criteria are not met the contractor will have to remove the noise-reducing pavement and apply a new and better pavement, not only in the initial situation but at any time when the noise level becomes too high.

In this case it can be expected that the contractors will increase the bidding price significantly in order to cover this risk of maybe having to apply a new pavement because of failing in relation to noise. Another effect is that in a market with such high consequences of failing to meet noise criteria, could be that the contractors can be expected to use significant resources to develop and improve their noise-reducing products and the long time performance. Such a product development can also improve the competitiveness of the contracting companies.

An example of applying such a system can be seen in one special case in Sweden (see Section 5.5). The environmental court had defined some noise levels that were not to be exceeded at any time for a section of the national motorway E4 passing residential areas the city of Husqvarna. A tender for noise-reducing pavements with a specific maximum noise level requirement, measured by the CPX method, was sent out. Noise measurements would be carried out every year. The winning contractor had to secure that the requested noise level was not exceeded at any year. If the noise level was exceeded, the contractor had to apply a new and better noise-reducing pavement.

Table 6.1 gives a short overview of the pros and cons of the four different approaches for integrating noise in the pavement tendering procedures. The pros and cons are presented in respect of the three pillars of sustainability, namely the social, economic and environmental aspects.

Table 6.1: Overview of the pros and cons of the four approaches for integrating noise in the pavement tendering procedures, presented in respect of the three pillars of sustainability, namely the social, economic and environmental aspects.

Approach	Social aspects	Economic aspects	Environmental aspects
1 - Specify pavement type and no control measurement	Uncertain if required noise levels in planning and legislation will be fulfilled	Normally no extra costs	The level of noise reduction is uncertain
2 - National system of noise labelling of pavements and no control measurement	Medium certainty that required noise levels in planning and legislation will be fulfilled	Normally no extra costs	Medium certainty that the required initial noise reduction is reached
3 - Noise criteria in tendering and control measurement	High certainty that required noise levels in planning and legislation will be fulfilled	When a fine system is applied, contractors will increase the bidding price in order to cover this risk of failing in relation to noise	High certainty that the required initial noise reduction is reached. Contractors can be expected to develop and improve their noise-reducing products
4 - Noise criteria in tendering for the initial as well as long-time noise measurement	100 % certainty that required noise levels in planning and legislation will be fulfilled, because a new pavement will be constructed if not	When a fine system is applied, including yearly control measurements and the risk of applying a new pavement, contractors will increase bidding price significantly in order to cover this risk of failing in relation to noise	100 % certainty that the required lifetime noise reduction is reached. Contractors can be expected to use significant resources to develop and improve their noise-reducing products

7 Summary

Tyre road noise is generated by the contact of the tyres to the pavements. At speeds over 35 km/h the tyre road noise is the dominant noise source for passenger cars. For heavy vehicles tyre road noise is dominant for speeds over 60 km/h. Therefore the pavements are important for noise at both urban roads with speeds of approximately 50-60 km/h, as well as on national roads and motorways with higher speeds. The generation of noise when the tyres are rolling on a road surface is mainly determined by the surface texture and properties of the pavement.

There are different pavement types that can be used to reduce noise. The effect of noise reduction depends both on the pavement type used and on what noise reference levels that are used in each country. Therefore, the noise-reducing effect of the same pavement can vary from country to country. In countries where reference pavements with high noise levels are used, pavements that are considered ‘normal’ in other countries might be considered noise-reducing.

It is complicated and a highly specialized process to construct effective and durable noise-reducing pavements of good quality and with good performance, also in relation to traffic safety and that fulfil operating requirements such as winter maintenance. It requires the use of high quality materials, suitable skills of the contractor’s workforce as well as quality control during the construction process from mixing plant to construction site.

7.1 Conclusions

Based on the information in the subgroup report on the current stage of European knowledge regarding noise-reducing pavements, the following conclusions can be listed.

1. there are various types of noise-reducing pavements that can be used, all having their pros and cons;
2. generally there is a cost related to the use of noise-reducing pavements, either because the construction cost is higher and/or because the lifetime is shorter than for ‘normal’ pavements;
3. it is important to have a national reference pavement in relation to noise and to have a clear method defining the noise reduction;
4. use the average noise reduction over pavement lifetime as the noise reduction of a pavement;
5. have noise-reducing pavements included in a well-defined approach in the national noise prediction method;
6. rejuvenation may be a method to increase lifetime;
7. it is specialized work to construct noise-reducing pavements with decent durability;
8. some contractors have the experience to construct noise-reducing pavements;
9. NRAs can go to the Netherlands to obtain experiences with porous asphalt;
10. NRAs can go to Denmark, France, Switzerland the Netherlands to obtain experiences with thin layers;
11. NRAs can go to Germany or Austria to obtain experiences with concrete pavements with exposed aggregate structure;
12. NRAs go to Germany or Austria to obtain experiences with a noise optimized split mastic asphalt surface such as SMA-LA;

13. while maintaining road pavements, consider if it is relevant to apply a new noise-reducing pavement when changing an old pavement;
14. noise should be included as an active parameter in pavement management systems;
15. there is still a need for research and development to improve noise reduction, reduce annual noise increases, durability and costs to keep the satisfactory performance of other functionalities;
16. there are various methods for including noise in a tendering process, all having their pros and cons.

8 References

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

22-28 Avenue d'Auderghem
1040-Brussels
Tél. : + 32 (0) 27 71 2478
Email : information@cedr.eu
www.cedr.eu

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